University of Alberta

INFLUENCE OF SOIL CAP DEPTH AND VEGETATION ON RECLAMATION OF PHOSPHOGYPSUM STACKS IN FORT SASKATCHEWAN, ALBERTA

By

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ABSTRACT

This study quantified environmental parameters to develop reclamation strategies for phosphogypsum stacks. Research was conducted on phosphogypsum stack experimental plots established in 2006 (6 soil cap depths, 5 vegetation treatments), and soil capped slopes seeded in 1998. Significant root mass accumulations occurred at soil-phosphogypsum interfaces with 8, 15, 30 and 46 cm caps in 50% of cores. Peak water content occurred at this interface with all cap depths in fall 2010; trends differed in 2011. Maximum rooting depth increased with increased cap depth, root biomass did not. Vegetation performed better in capped than uncapped plots; cap depths ≥ 15 cm supported healthy vigorous plants. Vegetation on stacks had elevated fluorine, cobalt and nickel; plants from cap depths ≥ 8 cm had tissue concentrations safe for animal consumption. Snow metal concentrations increased with proximity to a neighbouring metal refinery. Nineteen years after capping and seeding stack slopes had 35 plant species.

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1. INTRODUCTION

1.1 Background

This research focuses on reclamation of phosphogypsum (PG) stacks under varying soil cap depths and vegetation treatments. Fort Saskatchewan, Alberta has four PG stacks awaiting reclamation. The site is next to a metal refinery and metal concentrations in the stacks are high relative to PG's inherent composition. Determining if some metals in the vicinity of the PG stacks come from outside sources will help in development of their reclamation plans because it will help differentiate possible impacts from PG alone relative to impacts from other products. Results from this research will be used to develop reclamation plans for PG stacks, including currently active stacks in Redwater, Alberta.

1.2 Phosphogypsum

1.2.1 Phosphogypsum Production

Phosphogypsum is an industrial by product created during phosphorous fertilizer production (Rutherford et al. 1994, Wissa 2003) by the wet acid method, which accounts for over 90% of phosphorous fertilizer production (Tayibi et al. 2009). In this method phosphate rock is mixed with sulphuric acid to produce phosphoric acid, the main component of phosphorous fertilizer. The equation for the process is: $Ca_5F(PO_4)_3 + 5H_2SO_4 + 10H_2O \rightarrow 3H_3PO_4 + 5CaSO_4{\cdot}2H_2O + HF$.

The wet acid method is economical, however, it produces PG at a rate of 5 tonnes per ton of phosphoric acid (Richardson et al. 1995, Rutherford et al. 1994). World wide PG production is estimated at 100-280 million tonnes annually (Tayibi et al. 2009). PG production is currently greatest in the United States of America, the former Union of the Soviet Socialist Republic, China, Africa and the Middle East.

Phosphate rock used for phosphorus fertilizer production is obtained from open pit or underground mining. Phosphate rock mines occur around the world, including the United States of America, Morocco, Tunisia, Jordan and Australia (Tayibi et al. 2009). Phosphate rock is typically of sedimentary origin, with deposits formed approximately 70 million years ago by plant and animal decay (Becker 1989). Phosphate rock is composed mainly of phosphate, fluorine and calcium. Source rock used for fertilizer production generally contains 23-40% phosphate (PO_4^{3-}), impurities, such as heavy metals and compounds including calcium oxide (CaO), silicon dioxide (SiO_2), fluorine (F), carbon dioxide (CO_2), sulphur trioxide (SO_3), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), magnesium oxide (MgO) and sodium oxide (Na_2O).

1.2.2 Phosphogypsum Properties

PG is composed mainly of solid gypsum ($CaSO_4 \cdot 2H_2O$), phosphoric acid, trace elements and small amounts of radionuclides (Rutherford et al. 1994, Thorne 1990). Composition varies greatly depending on the source rock, plant operation efficiency, PG age and weathering time. Impurities and compounds not in the fertilizer from the source rock become concentrated in PG. PG is a powdery off-white material with very low plasticity.

Phosphogypsum is over 90% gypsum and generally contains calcium oxide (CaO), sulphates, silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), phosphate (PO_4^{3-}) and fluorine (F) (Taha and Seals 1992). Impurities can include trace metals such as arsenic, silver, barium, cadmium, chromium, lead, mercury and selenium (Tayibi et al. 2009). Yttrium, light rare earth elements, and gold, selenium and strontium are common in PG. Impurities vary greatly depending on source rock origin. PG from central Florida source rock has higher antimony and arsenic concentrations than PG from Idaho igneous rock, and lower yttrium, zirconium, copper, barium and nickel than PG from South African source rock (May and Sweeney 1984, Tayibi et al. 2009).

Source rock for phosphorous fertilizer production has naturally occurring radioactivity due to uranium, radium and thorium (Rutherford et al. 1994, Tayibi et al. 2009). While most uranium and thorium in source rock ends up in fertilizer, approximately 80% of ^{226}radium is concentrated in PG causing radioactivity. The United States Environmental Protection Agency classifies PG as a technologically enhanced naturally occurring radioactive material, meaning industry created a material with concentrated radioactive materials that occur naturally in the environment (USEPA 2012).

The main source of radioactivity in PG is ^{226}radium which can produce radon gas (^{222}radon); smaller quantities of radioactive ^{238}uranium, ^{210}lead, ^{210}polonium, and ^{230}thorium are also found (Rutherford et al. 1994). PG radioactivity varies greatly depending on the source rock; ^{226}radon from PG from Sweden produces 15 Bq/kg of radioactivity while some Florida PG produces 1140 Bq/kg.

Fresh PG pH is below 3 and is considered an acidic by product due to residual phosphoric, sulphuric and hydrofluoric acids from the fertilizer production process. PG pH tends to increase with age and weathering. Vertical hydraulic conductivity of PG is 1×10^{-3} to 2×10^{-5} cm/s. Its free water content following filtration is usually 25-30% (SENES 1987), depending on weather conditions and on how long the stack has been draining. Solubility of PG depends on its pH and it is highly soluble in salt water (~4.1 g/L) (Guo et al. 2001). PG bulk density is 0.9-1.7 g/cm^3 and its particle density is 2.27-2.40 g/cm^3 (May and Sweeney 1984, SENES 1987, Tayibi et al. 2009). PG particle size is 0.250-0.045 mm in diameter, similar to that of fine sand or silt (May and Sweeney 1984). PG has a crystal structure with mainly rhombic and hexagonal forms (Tayibi et al. 2009).

1.2.3 Phosphogypsum Disposal

Over 85% of PG produced annually is disposed of on land or sea and approximately 15% is recycled (Tayibi et al. 2009). PG is either dry or wet stacked on land. Wet stacking is most common internationally; filtered PG is mixed with water and pumped into settling ponds (Wissa 2003) where solids settle and water is decanted and reused as process water for further fertilizer manufacturing. Solid material is placed in large stacks, typically adjacent to fertilizer production plants. Stack areas can be up to 1 million m^2 and tens of meters in height (Rutherford et al. 1995). PG stacks in Redwater, Alberta are currently the largest and only active stacks in Canada; they are wet stacked and expected to cover 300 ha and be 40 m in height at closure (Nichol 2010).

Wet stacked PG is now generally placed on a liner system to limit PG leachate movement to ground water. Current standards include liners that are generally geomembranes placed over a layer of compacted soil. In Florida composite liners, which meet specific criteria, are required under all PG stacks (Florida Department of Environmental Protection 1993). In Fort Saskatchewan, Alberta one PG stack was built on a clay liner and one on a high density polyethylene liner (Svarich 1999). The expansions of the Redwater, Alberta stacks were placed on a high density polyethylene liner system; however the older parts of the stacks are unlined and surrounded by a ground water intercept system (Jackson 2008, Nichol 2010). Water management is a key aspect of PG stack management and, depending on the local climate, stacks can contain internal drainage systems. Ponds and ditches often surround the stacks to collect excess water which can be re-used as process water.

Dry stacking is less common than wet stacking internationally (Wissa 2003). With dry stacking, PG is transported directly after filtration to the disposal and stacking location. Unlike wet stacking, no water is added to make slurry and decanted for reuse. Dry stacking is common in Jordan, Tunisia, Senegal and several former Soviet Union countries.

Discharging PG to water bodies is uncommon. It is currently done in Morocco and South Africa, where gypsum is mixed with sea water then discharged to the Atlantic Ocean (Wissa 2003). This option is currently politically and environmentally acceptable when the slurry is dilute and the discharge area is a very large water body with an uninhabited coast and strong currents to disperse waste quickly. It is not politically and environmentally acceptable to discharge PG slurries into smaller water bodies, such as rivers or lakes.

1.2.4 Phosphogypsum Reuse

Less than 15% of the PG produced annually world-wide is recycled for other uses (Tayibi et al. 2009). Due to the high volumes produced annually, substantial research has gone into its reuse options and into treatment options to increase reuse possibilities. Main recycling options for PG include use in agriculture for soil enhancement, construction and building applications and cement manufacturing. Fluorine and other impurities, including trace metals and radionuclides, limit its reuse.

In Canada reuse of phosphogypsum is regulated under the Canadian Guidelines for the Management of Naturally Occurring Radioactive Materials (NORM) (Health Canada 2000). With these guidelines, the material is classified by its radiological properties and placed in categories of reuse. The categories of reuse indicate material that can be used unconditionally, used as long as risk assessments indicate it is safe for the proposed use, or the material should not be reused. PG from Fort Saskatchewan, Alberta has concentrations of radium-226 of 0.4 to 0.8 Bq/g and the guidelines indicate that it can be reused provided detailed risk assessments indicate it is safe to do so for the proposed use (Health Canada 2000, Rutherford et al. 1995). SENES (2006) conducted detailed risk assessments for the reuse of PG from Agrium Fort Saskatchewan and concluded that it can be used safely in a wide variety of applications. Countries vary widely in their guidelines surrounding the reuse of PG and the United States Environmental Protection Agency has banned all uses of PG exceeding 370 Bq/Kg of radioactivity since 1992 due to health and environmental concerns (USEPA 2002).

PG is used in agriculture as a soil amendment to improve nutrient status and physical and chemical properties (Rutherford et al. 1994). PG can amend highly weathered, sodic, and calcareous soils. It contains nutrients from the source rock, such as calcium and phosphorus, which can benefit deficient soils. PG can amend some acidic soils by decreasing exchangeable and solution aluminum and increasing exchangeable and solution calcium. PG can amend sodic soils by replacing excess sodium with calcium on soil exchange complexes and promoting flocculation. PG is used by peanut growers in the southern United States to amend agricultural soils (US EPA 2012).

PG has been used for construction and building applications in place of natural gypsum and as a fly-ash lime reaction activator (Tayibi et al. 2009, Weiguo et al. 2007). Due to its impurities and radioactivity, its use in construction and building materials is limited. Its use for building materials was banned in 1990 by the United States and in the European Union it was discontinued in 1992. PG is currently used in Korea to make boards for house construction.

PG has been used in cement manufacturing in place of natural gypsum as a setting regulator (Singh 2002, Tayibi et al. 2009). The presence of impurities in PG makes it less desirable than natural gypsum for cement construction, but treatment prior to use can increase its suitability. PG can be used in road construction as a base material. Studies are ongoing for potential use and treatment options for PG due to the large volumes produced, the large areas used by stacks and the possible beneficial applications.

1.2.5 Phosphogypsum Environmental Hazards

PG stacks can pose environmental hazards and must be reclaimed according to local regulations. Possible environmental hazards include ground water contamination with fluoride, trace elements, acidity or radionuclides, radioactivity from radon gas and gamma radiation and atmospheric contamination by fluoride (Rutherford et al. 1994, Tayibi et al. 2009, Wissa 2003). Hazards can be substantially reduced with proper stack reclamation.

Infiltration of precipitation into PG stacks and stack seepage can cause trace elements, fluorine, acidity or radionuclides in the stacks to become mobile and move to ground water, soils and eventually into organisms (Rutherford et al. 1994, Tayibi et al. 2009, Wissa 2003). Trace metals in PG, which vary depending on source rock used, can include arsenic, silver, barium, cadmium, chromium, lead, mercury and selenium which can become mobile in water. The movement of trace elements to ground water is reduced in inactive stacks which have been washed free of process water relative to active stacks (Rutherford et al. 1994). The acidity of process water can increase trace element mobility to ground water. Proper reclamation of stacks and use of liners under stacks greatly reduce trace element movement from PG to ground water (Rutherford et al. 1994). The Operating Approval for the Fort Saskatchewan PG stacks indicates that regular ground water monitoring and reporting is required and that ground water below stacks should be within guidelines (Alberta Environment 2008).

Results of PG leachate studies are varied and indicate that in some circumstances ground water pollution from PG can occur, however with reclamation, liners and ground water intercepts it can be substantially reduced. Rutherford et al. (1995) found that although leachate from fresh PG with residual process water can contain elevated fluoride, uranium and cadmium, PG leachate that has been washed free of process water poses little environmental hazard, with the exception of slightly elevated fluoride concentrations. Haridasan et al. (2002) found that under field conditions leaching of radium from fresh PG stacks may be slow. SENES (1987) compared ground water quality near Alberta PG stacks to background concentrations and found that sulfate and fluoride were consistently elevated and calcium, phosphate and nitrogen species were elevated in some wells.

Radioactivity from radon gas and gamma radiation is associated with PG stacks (Rutherford et al. 1994). Most radium in source rock for fertilizer production is transferred to PG and is commonly found as radium-226 (Tayibi et al. 2009). The PG from Fort Saskatchewan, Alberta has concentrations of radium-226 of 0.4 to 0.8 Bq/g; the Canadian Guidelines for the Management of Naturally Occurring Radioactive Materials indicate that this PG can be reused provided detailed risk assessments indicate it is safe for the proposed use (Health Canada 2000, Rutherford et al. 1995). SENES (2006) conducted detailed risk assessments for reuse of PG from Agrium Fort Saskatchewan and concluded that it can be used safely in a variety of applications. Norlander (1988) studied PG tailings in Calgary, Alberta and determined that radon, dust, particulates and gamma radiation would prevent residential development in the stack area on both covered and uncovered PG stacks, but that alternative active land uses should be investigated.

Atmospheric contamination with PG dust is a hazard generally associated with active stacks, is uncommon in inactive stacks and usually eliminated in reclaimed stacks. Atmospheric contamination can occur if fine PG dust particles are blown into the air. The fine dust can contain fluoride and become inhaled or land on nearby surfaces and affect environmental receptors (Al Attar et al. 2012, Rutherford et al. 1994). Excess fluoride can interfere with plant functioning including photosynthesis and respiration and can cause toxic effects, including fluorosis, in herbivores (Al Attar et al. 2012, Wissa 2003). Crusts form on inactive and bare PG stacks which limit the volumes of fugitive dust.

1.2.6 Phosphogypsum Stack Reclamation

Phosphogypsum stacks must be reclaimed according to local regulations to decrease environmental hazards. Stack closure is regulated by local governments and varies with jurisdiction. It generally involves a cover that provides a stable substrate for revegetation, limits erosion and water infiltration and minimizes exposure pathways between PG and environmental receptors. Common cover systems for PG reclamation are revegetated soil layers over PG, amendments incorporated into the PG surface which allow revegetation, or high density polyethylene liners covered by revegetated soil caps (Wissa 2003).

Florida is one of the largest producers of phosphorous fertilizer worldwide and has developed comprehensive regulations regarding PG stack reclamation. In Florida annual precipitation is high and sinkhole development in PG stacks due to high water content was a problem. Their regulations address this problem and their specific climatic conditions. PG stack reclamation is governed by the

Florida Department of Environmental Protection and regulations are outlined in a Florida Administrative Code (Florida Department of Environmental Protection 1993, Patel 2002). In Florida the cover systems on the top of the stacks must include a 46 cm barrier soil layer below a 46 cm layer of soil or amended PG that can sustain vegetation and control erosion. The 46 cm barrier layer may be reduced to 30 cm if a very low permeability soil is used. Geomembrane covers overlaid by 61 cm soil caps can also be used, however geomembrane liners are costly. Cover system requirements on side slopes are site specific and must be able to support establishment and development of vegetation and minimize erosion of the final cover material.

Alberta regulations for all industries require that reclamation return land to a capability equivalent to that prior to disturbance (Alberta Environment 2010). Alberta does not have specific regulations for PG stack reclamation and sites must be assessed individually to develop reclamation plans based on stack characteristics, local climate and landscape. The Operating Approval for the Agrium Fort Saskatchewan PG stacks states that research options for the reclamation of the phosphogypsum stacks must continue to be investigated (Alberta Environment 2008). The default soil cap for phosphogypsum stack reclamation recommended by Alberta Environment is 1 m (2008). A cover system that limits the potential environmental hazards of PG and which does not require the costly and environmentally damaging excessive stripping of soil from surrounding areas is desired.

Use of phosphoric acid fertilizer increased exponentially in the 1960s during the green revolution, and since then researchers have been studying what to do with the PG by product. Leaving PG stacks bare and unreclaimed presents environmental hazards and therefore research on closure and reclamation planning for PG stacks to minimize environmental hazards has been conducted. Research areas include assessment of methods to revegetate stacks, amendments to improve PG for revegetation, optimum soil cap depth and synthetic cover systems. Local climate has a major effect on the activity of reclaimed PG stacks and therefore research into reclamation in specific climatic regions is necessary for final reclamation planning.

Norlander (1988) studied the reclamation of PG tailings in Calgary, Alberta with a focus on radon flux. He determined that radon, dust, particulates and gamma radiation will prevent residential development in the stack area on both covered and uncovered PG stacks, but that alternative active land uses should be investigated. Duenas et al. (2007) found that reclaimed phosphogypsum stacks produce substantially lower radon emissions that active stacks and that radon levels on reclaimed stacks are within the US EPA allowable limits.

Thorne (1990) studied reclamation of a PG tailings pond in Medicine Hat, Alberta with a focus on revegetation. She found that plants grown in bare PG accumulated elements elevated in PG including selenium, fluorine and cadmium in concentrations potentially toxic to wildlife. She determined that the majority of factors limiting plant growth on PG could be overcome by adding amendments, with the main exception of selenium hyper accumulation by vegetation.

Richardson et al. (1995) assessed the effects of various cover systems for PG stacks on soil, vegetation and water parameters in Florida. They found that runoff water quality and radon flux was substantially improved in revegetated PG stacks compared to unrevegetated PG stacks. PG stacks with amendments incorporated and PG with 15 cm soil caps both produced healthy vegetation with high cover. Amended PG with no cover, however, was considered likely to require more long term maintenance (fertilizer, mowing, herbicide) to maintain a desirable diverse vegetation community compared to the PG with a soil cap. Amended PG with no soil cap without periodic maintenance was likely to develop more weedy species with lower and inadequate cover for reclamation than PG with a soil cap. PG with a 15 cm soil cap produced half the radon emissions of PG with amendments incorporated.

Komnitsas et al. (1999) studied effects of amending PG to improve its fertility and grow vegetation on PG stacks in Romania. A vegetated cover on PG stacks reduced the major risks of the stacks, which are airborne dusts blowing onto nearby areas and dust inhalation by residents. They conducted a greenhouse study and concluded that mixing dolomite, kaolin and sewage sludge with PG, and a 15 cm soil cap improved substrate fertility and allowed successful vegetation growth. Addition of the above amendments or soil cap increased micronutrients, pH, water holding capacity and organic matter in the substrate creating a suitable plant growth medium for successful revegetation.

Gusev (2006) studied primary succession on PG piles in Belarus. He compared succession on PG piles 0-15, 15-30 and more than 30 years of age.

Without reclamation or amendments succession progressed slowly but steadily. Plant species diversity was relatively low compared to nearby undisturbed sites and only certain species were adapted to succession on PG piles. Succession was substantially quicker at the bottom of PG stack slopes than at mid and upper slope locations, likely because litter, soil and seeds from nearby locations were more easily deposited and accumulated there. In the first 15 years stacks generally had some young trees growing and a herbaceous layer of 1.1-4.5% on lower and mid slope positions, but no vegetation on upper slopes. Stacks over 30 years had mean herbaceous covers of 20-60%, young trees growing and litter layers over 0.5 cm thick on lower, mid and upper slopes. Reclamation should be conducted to speed stack revegetation to limit environmental hazards.

Hallin et al. (2008, 2010) studied the Agrium Fort Saskatchewan, Alberta PG stacks 8 years after reclamation of stack slopes with 15 cm of soil cover and revegetation. They characterized PG material and studied effects of soil cover and revegetation on infiltration and percolation, runoff water quantity and quality and plant community development. For most parameters the cover system was an effective reclamation strategy which minimized environmental hazards. There were some localized areas of concern warranting further investigation including quality of PG leachate and soil and plant tissue trace element concentrations.

Hallin (2008) found plant cover on stack slopes with a 15 cm soil cover was high and relatively consistent throughout the stacks and comprised mainly of grasses and ruderal species. Hallin found that plant tissues collected throughout the stacks contained elevated concentrations of nickel and fluorine compared to one reference sample, however further research and comparisons to background samples is required to substantiate her results. Concentrations of fluorine in the 15 cm soil cover, which was mixed with some PG, consistently exceeded Alberta Tier 1 soil remediation guidelines for a natural area land use, while nickel concentrations were over those guidelines in one third of the sample sites and cobalt exceeded criteria in approximately one fifth of samples. Run off water from the stacks exceeded the Canadian guidelines for aquatic life and drinking water criteria for several parameters.

Jackson et al. (2009, 2011) also studied the Fort Saskatchewan PG stacks to evaluate effects of various soil cap depths and vegetation mixes on plant community development, water quality and quantity, radon gas, gamma radiation and hydrogen fluoride emissions. Vegetation cover, biovolume, health and height were greater on capped plots than uncapped plots and these parameters were not significantly affected by cap depths 8 cm or over. In cap depths 30 cm or lower subsurface water quality exceeded the Canadian Environmental Quality Guidelines (aquatic life) and Alberta Tier 1 Soil and Groundwater Remediation Guidelines (industrial land use) for several parameters. There was not enough water collected in cap depths 30 cm or over to assess water quality. There were some correlations between cap depth and radon concentration and gamma radiation but not hydrogen fluorine emissions. Gamma and radon emissions from PG stacks exceeded background levels but were not considered hazardous to humans; hydrogen fluoride emissions did not exceed background levels.

1.3 Metal Deposition From Industrial Sources

Cumulative effects of heavy metal deposition from industrial sources onto the earth's surface can negatively affect biota. Heavy metal pollution is common where there is metal mining and can occur around metal refineries. Although some metals are biologically important to humans and animals, most are toxic at relatively low concentrations, including nickel and cobalt. Excessive intake of heavy metals can interfere with enzyme activity in plants, humans and other organisms causing toxic effects and death (Duruibe et al. 2007). Understanding metal deposition sources and control measures is of environmental significance.

The Sudbury, Ontario area is one of the best known examples of large scale metal mining and smelting and the negative environmental consequences (Nkongolo et al. 2008). Nickel and copper have been mined and smelted in the area for over 80 years. Sulphur dioxide emissions and metal particulate deposition from smelters have caused vegetation denudation for over 260 km^2, soil acidification, persistent erosion issues, lake acidification and fish die-off (Hutchinson and Whitby 1977, Negusanti 1995).

Metal concentrations in soils and vegetation decreased exponentially with distance from Sudbury area metal smelters (Hutchinson and Whitby 1977). Sulphur dioxide and metal emissions from smelters decreased substantially in the last 30 years due to control measures (Nkongolo et al. 2008). Although soil metal concentrations are now significantly lower than in the 1980s, soil metals are persistent and will likely take hundreds of years to reach background concentrations (Hutchinson and Symington 1997, Nkongolog et al. 2008).

In Rouyn-Noranda, Quebec studies have been conducted on the effects of a copper smelter on various matrices in the surrounding area, including peat moss, snow, soil, lake water and lake sediments (Bonham-Carter et al. 2006, Telmer et al. 2004, and Zdanowicz et al. 2006). Bonham-Carter et al. (2006) found that all of the media analyzed had exponential increases in copper, lead and zinc near the smelter compared to background concentrations, indicating the smelter was the point source of metal impacts. Concentrations of smelter related metals reached background concentrations approximately 65 km from the smelter. Within 5 km from the smelter, smelter related metals were up to 1000 times higher than local background concentrations.

Kelly et al. (2010) studied effects of oil sands developments in northern Alberta on concentrations of various elements in the snowpack. Bitumen upgraders and local oil sands developments were point sources of several elements including lead, mercury, nickel, chromium and copper, which decreased exponentially with distance from those sources.

Gregurek et al. (1998) studied snow metal concentrations around nickel plants in Russia that had been operating for over 60 years. Heavy metals and other elements in the snow around the plants were 10,000-100,000 times higher than background concentrations and contained the same fingerprints as the ores used in the plants. Concentrations of nickel in the snow near the plant were 1,110-3,830 µg/L. The ecosystem surrounding the plants was severely impacted and vegetation was no longer growing for hundreds of km^2 around the plants.

Teper (2009) studied impacts of open tailings ponds from zinc-lead smelting refineries in Poland on forests in the surrounding area. Significant quantities of dust with chemical compositions similar to that of the tailing pond but different from the environmental background were found on pine needles surrounding the tailings pond. Higher concentrations were found closer to the tailings ponds than further away, indicating material from the tailings pond was being deposited in the surrounding areas.

Ceburnis et al. (2002) assessed metal concentrations in snow and moss around two electric thermal power stations and a cement factory in Lithuania. The pattern of metal concentration in snow and moss around the stations was exponentially higher near the center than at locations further away. Wind direction affected distribution of emitted elements around the smelter with concentrations slightly higher in the direction of the prevailing wind than in other directions. At distances approximately 20 km from the source, source metals became indistinguishable from background values.

Ceburnis et al. (2002) created a semi empirical model of depositional pattern of metals around point sources of pollution to estimate the amount of metals being emitted from them. Values for the parameters in their models changed with the specific metal (nickel, chromium, vanadium) and with stations. General trends were similar for all metals and stations or factories assessed, however average concentrations and the exact shape of the curves differed. Ceburnis et al. stressed that to use the model to characterize the metal deposition curve around specific stations many samples needed to be taken close to the point source compared to locations further away because major changes in metal concentration occur close to the source.

Zajac and Grodzinska (1982) assessed snow metal concentrations around a highly industrial area in Poland containing iron and steel mills. Snow metal concentrations decreased exponentially with distance from the source. Both wet and dry deposition were factors in snow metal accumulation; meaning deposition occurred from industrial dust blown onto the snow and from emissions caught in falling snow. Time of sampling significantly affected concentrations because of differing meteorological factors, including amount of snowfall, temperature and wind direction and velocity. Longer durations of snow cover and lower volumes of snow cover had higher concentrations of metals.

Agrium in Fort Saskatchewan is located in a highly industrial area and is adjacent to a metal refinery to the south. Metal concentrations on the stacks are higher than expected based on the PG's inherent composition. PG is derived from source rock from Florida, and this PG typically has relatively low concentrations of cobalt, copper and nickel (2, 8 and 2 mg kg^{-1} respectively) compared to PG from other source rocks (May and Sweeny 1984, Rutherford et al. 1994). Samples from the Fort Saskatchewan PG stacks indicate that cobalt, copper and nickel are often substantially higher in surface samples than in locations deeper in the profile, indicating metals may be accumulating on the surface of the stacks (Unpublished data). Emissions and material blown from the tailings pond of the neighboring metal refinery are possible sources of metals on Agrium property. Determining the point source of metals on Agrium property is important in developing control measures to reduce metal contamination and in helping to develop a reclamation plan for the Agrium PG stacks.

1.4 Research Objectives

This research will be part of a general environmental risk assessment for PG stacks at Agrium in Fort Saskatchewan, Alberta. It will assess effects of soil cap depth and plant species on water, vegetation and soil parameters. It will assess whether metals on the stacks and in the stack vicinity are coming from outside sources. It will assist in development of a reclamation plan which minimizes environmental hazards and will contribute to a cost effective analysis. The information gained will be used for developing reclamation plans for the inactive PG stacks at Agrium in Fort Saskatchewan and for future PG stack reclamation, including the Redwater, Alberta PG stacks. This research builds on that of Hallin (2008) and Jackson (2009) conducted at the same site.

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2. INFLUENCE OF SOIL CAPPING DEPTH ON REVEGETATION OF PHOSPHOGYPSUM STACKS IN FORT SASKATCHEWAN, ALBERTA

2.1 Introduction

Phosphogypsum (PG) is a by product created during production of phosphorous fertilizer by mixing phosphate rock with sulphuric acid to produce phosphoric acid, the main component of phosphorous fertilizer (Rutherford et al. 1994, Wissa 2003). PG is composed mainly of solid gypsum ($CaSO_4{\cdot}2H_2O$), phosphoric acid, trace elements and small amounts of radionuclides (Rutherford et al. 1994, Thorne 1990). At least 80 countries currently have phosphogypsum stacks, including Canada and the United States (Florida Institute for Phosphate Research 2010). PG is produced at a ratio of 5 tons of phosphogypsum for every ton of phosphorus fertilizer (Rutherford et al. 1994, SENES 1987). The most common disposal method internationally is wet stacking whereby filtered PG is mixed with water and pumped into settling ponds (Wissa 2003). The water is decanted and solid material is placed in stacks. Stacks can cover areas up to 1 million m^2 and reach tens of meters in height (Rutherford et al. 1995).

PG stacks can pose environmental hazards, which can be substantially reduced through reclamation. Potential environmental hazards include ground water contamination with fluoride, trace elements, acidity or radionuclides, radon gas and gamma radiation, and atmospheric contamination by fluoride (Rutherford et al. 1994, Tayibi et al. 2009, Wissa 2003). For example, SENES (1987) found that while active stacks increased ambient and foliage fluoride concentrations nearby, this did not occur when the production plant and stacks became inactive

Stack closure is regulated by local governments, varying with jurisdiction. It involves covering the stack to provide a stable substrate for revegetation, limit erosion and water infiltration and minimize exposure pathways between PG and environmental receptors. The cover is generally a revegetated soil layer but can be a high density polyethylene liner (Wissa 2003). Alberta regulations require all industries to reclaim to predisturbance equivalent capability (Alberta Environment 2010b). Alberta does not have specific regulations for PG stack reclamation and sites must be assessed individually to develop reclamation plans based on stack characteristics, local climate and landscape (Alberta Environment 2010b).

PG stack reclamation has been studied in various locations. Plants growing in bare PG derived from Idaho rock in Medicine Hat, Alberta accumulated elements elevated in PG including selenium, fluorine and cadmium in potentially toxic concentrations for wildlife (Thorne 1990). Most factors limiting plant growth, except selenium hyper accumulation by vegetation, were overcome by adding amendments. In a greenhouse study in Romania, mixing dolomite, kaolin and sewage sludge with PG and capping with 15 cm of soil increased micronutrients, pH, water holding capacity and organic matter creating a suitable substrate for revegetation (Komnitsas et al. 1999).

At Fort Saskatchewan, Alberta, PG stack slopes covered with 15 cm of soil and revegetated were assessed after 8 years (Hallin et al. 2008, 2010). Plant cover was high and relatively consistent throughout the stacks and comprised mainly of grasses and ruderal species. Plant tissue contained elevated concentrations of nickel and fluorine relative to a single reference sample. Fluorine concentrations in the soil cover, which was mixed with some PG, consistently exceeded Alberta soil quality criteria guidelines, while guidelines were exceeded for nickel in one third of the samples and cobalt in one fifth of samples. On the same sites Jackson et al. (2009, 2011) found vegetation cover, biovolume, health and height were higher on capped plots than uncapped plots, but were not significantly affected by cap depths 8 cm or over.

Reclamation may occur naturally, but over long periods of time. In Belarus, Gusev (2006) studied 0-15, 15-30 and > 30 year old PG stacks. Without reclamation or amendments succession was slow but steady. Plant species diversity was low relative to undisturbed sites. Succession was substantially quicker at the bottom of stack slopes than at mid and upper locations, likely because litter, soil and seeds from nearby locations were more easily deposited and accumulated. In the first 15 years stacks generally had some young trees and a herbaceous cover of 1.1-4.5% on lower and mid slopes, but no vegetation on upper slopes. By 30 years herbaceous cover was 20-60%, with young trees and litter layers over 0.5 cm thick on lower, mid and upper slopes.

The Operating Approval for Agrium Fort Saskatchewan states that research options for reclamation of the phosphogypsum stacks must continue to be investigated (Alberta Environment 2008). A cover system limiting potential environmental hazards of PG which does not require environmentally damaging stripping of topsoil from surrounding areas is desired. This research will be part of a general environmental risk assessment for the Agrium Fort Saskatchewan PG stacks. It will assess effects of soil cap depth and vegetation on water, vegetation and soil. It will help to develop a reclamation plan for the inactive PG stacks at Agrium in Fort Saskatchewan and for future PG stack reclamation in other jurisdictions.

2.2 Research Objectives

The objective of this research was to quantify potential environmental risks posed by the Agrium phosphogypsum stacks in Fort Saskatchewan, Alberta. It is part of a general risk assessment to assist in development of recommendations for phosphogypsum stack reclamation. Specific research objectives are to determine the following.

- Whether soil cap depth affects plant growth, development and health.
- Whether plants root into phosphogypsum and if so whether rooting into phosphogypsum affects plant growth, development and health.
- Whether plants take up trace elements from phosphogypsum and whether this is affected by species and cap depth.
- Whether seeded plant species have persisted and whether unseeded species have encroached on to the study site.

2.3 Materials And Methods

2.3.1 Site Description

Fort Saskatchewan is located approximately 30 km northeast of Edmonton, Alberta (53º 43’ N and 113º 13’ W) in an industrial area with over 40 large companies (Alberta’s Industrial Heartland Association 2012, City of Fort Saskatchewan 2012) (Figure 2.1). Residential communities occur on the west side and Fort Saskatchewan’s population is approximately 19,000 (Figure 2.2).

The research site is in the Central Parklands Natural Subregion of Alberta within the Aspen Parkland, Ecoregion, between the Dry Mixedwood Natural Subregion to the north and west and Foothills Fescue, Foothills Parkland and Northern Fescue Natural Subregions to the south (Natural Regions Committee

2006). Most of the Subregion is cultivated and inhabited with small sections of native aspen and prairie vegetation. Non native species such as *Bromus inermis* L. (smooth brome) and *Agropyron repens* L. (quack grass) are dominant. Average annual precipitation is 440 mm with 75% falling during the growing season. Frost free days average 109 per year with average temperatures of -14 and 17 °C in January and July, respectively (Environment Canada 2012).

Dominant soils are black chernozems with small proportions of dark gray chernozems and significant areas of solonetzic soils (Natural Regions Committee 2006). Elevation averages 620 m above sea level and and the land is hummocky with gently rolling hills. Lacustrine and fluvial deposits are common and significant eolian deposits can be found. The Belly River formation, consisting of sandstone, siltstone, mudstone and ironstone beds, forms the bedrock in the Fort Saskatchewan area (Hamilton et al. 2005).

Agrium is located in the industrial district in eastern Fort Saskatchewan. It is bordered by the North Saskatchewan River to the north and agricultural land to the south (Figure 2.2). Dow Chemical Inc., a plastic and chemical products manufacturing facility, is located east of Agrium; Sherritt International, a metallurgical services and metal refinery company, is located to the south (Alberta's Industrial Heartland 2012). Agrium specializes in nitrogen, phosphorus, potash and micronutrient fertilizer production (Agrium 2012). Phosphorous fertilizer was produced at their Fort Saskatchewan facilities from 1965-1991 and it currently produces nitrogen fertilizers (Svarich 1999).

Phosphogypsum was stacked on Agrium property for 26 years with approximately 5 million tonnes of dihydrate PG in four stacks on a 35 ha area (Svarich 1999). Stack 1, next to the Fort Saskatchewan River, covers 9.3 ha and was built on a high density polyethylene liner (Figure 2.2). Stack 2, south of stack 1 covers 8.5 ha and was built on a clay liner. Both stacks have settling basins of 4.7 ha. Stacks 1 and 2 were decommissioned in 1991 when phosphate fertilizer production at Agrium Fort Saskatchewan ceased. Florida phosphate rock is the source rock for all PG on site (Nichol 2012).

In summer 1998 approximately 15 cm of topsoil was placed on the side slopes of PG Stacks 1 and 2 (Nichol 2012, Hallin 2008). A non native seed mix composed mainly of *Bromus inermis* and *Brassica napus* L. (canola) was seeded on the stack slopes (Nichol 2012). The research plots are located in the basin of

Stack 1. The stack settling basins are located on top of the stacks, recessed within the stacks by approximately 10 m, and their surfaces are relatively flat. Where PG is bare and exposed a surface crust has formed.

2.3.2 Experimental Design

Eighteen experimental research plots, established in October 2006, were located in the basin of Stack 1 with varying soil cap depth and vegetation treatments (Figure 2.3). Plots are 50 m long by 10 m wide and composed of uncapped plots and capped plots with soil cap depths of 8, 15, 30, 46 and 91 cm (Jackson 2009). Three replicates of each depth occur in a randomized complete block design. The soil for the cap depth plots was acquired from the Petrocan plant east of Fort Saskatchewan. The soil was characterized as a sandy loam to loamy sand with good general soil qualities (low sodium, high calcium, low electrical conductivity, low sodium adsorption ratio) (Jackson 2009).

Plots were divided into five 10 x 10 m subplots. Four subplots were seeded in June 2007 with monocultures of *Agrostis stolonifera* L. (redtop), *Festuca ovina* L. (sheep fescue), *Deschampsia caespitosa* (L.) Beauv. (tufted hair grass) and *Agropyron trachycaulum* (Link) Malte ex H.F. Lewis (slender wheat grass). One was seeded with a mix of these grasses and *Trifolium hybridum* L. (alsike clover). Species were selected for origin, germination, establishment, erosion control, palatability, acidity tolerance, water and nutrient requirements (Jackson 2009).

2.3.3 Meteorological Conditions

A Campbell Scientific meteorological station with a CR10X data logger was installed on Stack 1 in 2006 in the centre of basin 1 between two research plots (Jackson 2009). The station records air temperature (°C) and relative humidity (%) with a HMP45C Vaisala relative humidity and temperature probe, total rainfall (mm) with a TE525WS Texas Electronics 20 cm tipping bucket rain gauge and a manual rain gauge, wind speed (m/s) and direction with a 05103-10 RM Young wind monitor and total solar radiation (kW) with a Kipp and Zonen silicon pyranometer. Data are recorded hourly and downloaded regularly. No data are available from late November 2010 to late April 2011 due to technical difficulties. Meteorological data for the years of this study were compared to the Fort Saskatchewan climate normals for 1971-2000 (Environment Canada 2012).

2.3.4 Vegetation Assessment

Vegetation was assessed in 0.1 m^2 quadrats (0.5 m x 0.2 m) June 30 to July 7 2011 in three random locations per subplot (3 quadrats x 3 replicates x 30 treatments for a total of 270 quadrats). Species composition, relative abundance, average biomass, height, health, stage of physiological development and ground cover were assessed. Within each quadrat all plant species were identified, then total canopy cover and canopy cover by species estimated. Within 2 cm of the ground live vegetation, bare ground, rocks, litter, standing litter and moss cover were estimated. Height of three randomly selected individuals of each species was measured from ground surface to stretched tip with a meter stick.

Species health was determined using a three point scale, with a value of 1 was for necrotic plants (< 25% live green material), 2 for plants exhibiting chlorosis, necrosis or wilting (25 to 75% live green material) and 3 for healthy plants (> 75% live green material). Physiological development for each species was determined on a three point scale with a value of 1 for a rosette or immature plant, 2 a plant close to flowering or flowering and 3 a plant that set seed. Biomass was determined by clipping vegetation 2.5 cm above ground surface, placing it in a labeled paper bag, oven drying at 80 °C for 48 hours then weighing

Geoprobe soil cores were taken in July 2010 in each of the 18 *Agropyron trachycaulum*, *Festuca ovina* and *Deschampsia caespitosa* subplots for a total of 54 cores. Species were chosen for rooting patterns; *Agropyron trachycaulum* with shallow fibrous roots, *Festuca ovina* with dense, deep roots and *Deschampsia caespitosa* with extensive horizontal and vertical roots (Looman 1983, United States Department of Agriculture 2010). Sample locations were randomly determined and cores were taken below the nearest individual of the desired species.

The geoprobe, a mechanical direct push machine, was used to collect soil cores 1 m deep and 7.6 cm in diameter. Cores were removed from the ground, placed in thick plastic sheaths, and wrapped and sealed with plastic, then stored in a cooler at 3 °C. In the laboratory cores were removed from the plastic, pried apart and examined. Soil depth and maximum root depth were measured. Any layer in the soil or PG where roots had accumulated by approximately 75% more than other layers in the core where roots were present was considered a root mass accumulation; these were determined visually and their locations noted.

Soil and phosphogypsum were separated and placed in successively smaller sieves to remove roots from the substrate. Roots were washed with tap water over fine sieves to remove any remaining substrate. Roots were placed in paper bags, dried at 80 °C for 48 hours and weighed to determine biomass.

2.3.5 Soil and Phosphogypsum Analyses

Soil and phosphogypsum were sampled in the research plots and in offsite reference locations to assess substrate pH and trace element concentrations. Substrates were sampled in July 2010 and September 2011 for trace element assessment and in September 2011 for pH. Samples were taken in each of the three research plot replicates and three replicates were taken in seven offsite reference locations. Separate samples were collected for the two analyses from the same locations for a total of 39 samples.

Reference sites outside Agrium Fort Saskatchewan were compared with samples taken from the research plots. Reference locations were selected with vegetation similar to that in the research plots. Fort Saskatchewan River valley sites (0.3 km north west of and 0.7 km north east of Agrium) were located near Agrium to provide background values for the area. The Petrocan plant in Fort Saskatchewan was capped with the same topsoil as the research plots at Agrium. The Edmonton River valley sites (south of the river and north of the river) were in the same natural subregion as Agrium. Ellerslie Research site was in the same natural subregion and located on the outskirts of a city, like Agrium.

Samples were taken with an auger to a depth of 15 cm (where most roots were) and placed in air tight plastic bags and stored in coolers at 3 °C. Samples for pH analysis were taken to ALS Laboratories in Edmonton and pH was determined by the saturated paste method (Canadian Society of Soil Science 2006). Samples for trace elements were dried at 40 °C to constant weight, finely ground, placed in sealed plastic bags, then sent to the Becquerel Laboratory in Ontario for determination of concentrations of 37 elements (Table 2.1) with neutron activation analysis (Becquerel Laboratories Inc. 2009, Simpson 2012).

Concentrations of elements assessed in soil and PG samples were compared to the Tier 1 soil remediation guidelines (Alberta Environment 2010a). Since the planned land use of the site is walking trails, the natural area Tier 1 land use guidelines were used. The industrial area land use type was also used for comparison because the site is expected to remain an industrial site for many years before it is potentially open to the public as walking trails.

2.3.6 Vegetation Tissue Trace Element Analyses

Vegetation was sampled for trace element analysis in July 2012 at the research and reference sites. *Agropyron trachycaulum, Festuca ovina, Agrostis stolonifera* and *Medicago sativa* L. (alfalfa) were selected as they occurred in large numbers and represented grass and forb vegetation. Samples were collected in all three replicates of all research plots. The same seven offsite reference locations that used for substrate sampling were used for the vegetation tissue sampling to facilitate correlation analyses. Species sampled at the research site were found in at least one of the reference locations and sampled with the exception of *Festuca ovina* which was substituted with *Festuca saximontana* Rydb (Rocky Mountain Fescue).

At each sampling location, biomass of three random individuals of the desired species was cut 2 cm above ground and composited into one sample. Samples were placed in brown paper bags, washed with deionized water, dried at 80 °C for 48 hours, ground to 10-15 mm (Baldwin et al. 2009) then sent to Becquerel Laboratories in Mississauga, Ontario. Concentrations of 37 elements (Table 2.1) were determined with neutron activation analysis (Becquerel Laboratories Inc. 2009, Simpson 2012).

Elevated concentrations of elements in vegetation from the research plots were compared to literature values for normal plant tissue (United States National Research Council 2005, Kabata-Pendias 2011) and maximum tolerable concentrations for animals. Maximum tolerable levels compiled by the United States National Research Council are defined for each element and animal group as the dietary level that, when fed for a defined period of time, will not impair animal health and performance (2005). Maximum tolerable levels for rodents, poultry and cattle were chosen for comparison.

2.3.7 Statistical Analyses

Data were compiled in Excel and means calculated for each replicate when more than one sample was taken per replicate. Health and development data for each treatment were converted to percentages of each species within each category. In the mix treatment average health and development values were calculated for all four species combined for each treatment. Detection limits were sample specific and therefore average detection limits were calculated for each element. The detection limits for some elements in *Agropyron trachycaulum* tissue samples were artificially raised due to the addition of a bromine tracer on those plots and in these cases it was not included in the mean detection limit.

Statistical software programs SAS and SPSS were used for analyses. Values from uncapped controls (0 cm) were compared to capped samples (8-91 cm) with Mann Whitney tests. Two-way analysis of variance was conducted to determine if vegetation and soil were affected by cap depth, reference location and vegetation treatment. Tukey's post hoc multiple comparisons were conducted with Bonferoni correction (Dytham 2011). Where data were non-normal the nonparametric Scheirer-Ray-Hare extension of the Kruskal-Wallis test was used (Elliott and Hynan 2011).

2.4. Results And Discussion

2.4.1. Meteorological Conditions

Total precipitation from January to July 2010 (period most affecting 2010 plant parameters) was 295 mm. Average temperature on the PG stack for this period was 3.7 °C. Mean wind speed was 2 m/s and mean direction was south (186.5°N). Average relative humidity was 69%. Data for this period were similar to climate normals for the area (data not shown) (Environment Canada 2012).

Total precipitation from May to July 2011 inclusive was 301.2 mm, 30% higher than the climate normal for Fort Saskatchewan of 230.9 mm (Environment Canada 2012). This could cause plants to have higher biomass, height and health compared to an average year because water is usually the limiting growth factor in the aspen parkland natural subregion. Average temperature was 14.6 °C. Mean wind speed from May to July was 2.6 m/s and mean direction was south (180.6 °N). Average relative humidity was 62%.

2.4.2 Above Ground Plant Response

Above ground vegetation consistently responded significantly and positively to capping (Tables 2.2, 2.3). Total cover was significantly greater with capping than without and significantly greater with ≥ 15 cm than 8 cm caps (Figure 2.4). Vegetation treatment did not significantly affect total canopy cover. There were no significant interactions detected among vegetation treatments and cap depths.

Seeded canopy cover was significantly greater on PG with capping than without and there was no significant difference in seeded cover with cap depth (Figure 2.5, Tables 2.2, 2.3). No seeded vegetation was found in uncapped PG. There was no significant interaction effect of species and cap depth. Vegetation treatment had a significant effect on seeded cover, with *Agrostis stolonifera* and *Deschampsia caespitosa* covers significantly less than the other species.

Above ground biomass was significantly greater with capping than no capping (Figure 2.6, Tables 2.2, 2.3). Biomass was numerically less with 8 cm caps than greater cap depths. Caps ≥ 15 cm had similar above ground biomass. Vegetation treatment had no significant effect on above ground biomass, and there was no significant interaction between vegetation treatment and cap depth.

Height of seeded and unseeded species was similar with caps ≥ 8 cm, and significantly lower with no cap (Figure 2.7, Tables 2.2, 2.3). Health and development could not be determined for uncapped plots because of the low vegetation. Vegetation on 8 cm caps was moderately healthy to healthy (Tables 2.2, 2.3). Most plants on caps ≥ 15 cm were healthy. Most plants on all cap depths were flowering or close to flowering but had not set seed (78-93%) and a small number had set seed (0-19%) (Tables 2.2, 2.3).

Bare ground was high on uncapped plots (95%), considerably less on 8 cm caps (11%) and very low on 15 caps (1%) (Tables 2.4, 2.5). With caps ≥ 8 cm litter cover was high (85-94%). Standing litter and vegetation covered 2-7% of ground on caps 8 cm and greater. Feces, wood and moss were 1% or less of ground cover on all treatments.

The improvement of above ground vegetation parameters with soil capping is consistent with other studies (Komnitsas et al. 1999, Richardson et al. 1995). Jackson (2009) studied the same plots in Fort Saskatchewan and found capped plots had significantly higher cover, biovolume, health and height than uncapped plots. One year after capping and seeding cap depths ≥ 8 cm did not affect above ground vegetation in Jackson's study, whereas in the current study, four years after capping and seeding, cap depths ≥ 15 cm did not affect above ground vegetation parameters. Hallin et al. (2008, 2010), similar to this study, found a 15 cm soil cap on stack side slopes provided for high cover vegetation consistently on the stacks. Richardson et al. (1995) found a 15 cm soil cap on stacks in Florida was adequate to grow healthy vegetation with high cover.

2.4.3 Seeded Species Response

Seeded species had significantly higher cover, biomass and height on capped than uncapped plots. Total canopy cover was significantly higher on caps ≥ 15 cm than 8 cm and seeded canopy cover (cover of seeded species alone) was similar on caps ≥ 8 cm. Biomass was slightly lower on 8 cm caps than caps ≥ 15 cm, which were similar. Height was similar for caps ≥ 8 cm. Health was slightly lower on 8 cm caps compared to caps ≥ 15 cm, which were similar.

Seeded species generally responded according to their inherent properties. *Agropyron trachycaulum, Festuca ovina,* and the species mix had significantly higher seeded canopy cover than *Deschampsia caespitosa* and *Agrostis stolonifera.* Mix canopy cover was similar to that of *Festuca ovina* and *Agropyron trachycaulum* and significantly higher than that of other monocultures (Figure 2.5, Table 2.2). *Agropyron trachycaulum* and *Festuca ovina* had greatest cover in this treatment; *Agrostis stolonifera* and *Deschampsia caespitosa* were sparsely present and *Trifolium hybridum* was only found in one quadrat. Seeded species had similar cover to their monoculture plots, indicating their abundance was not due to competition among seeded plants.

Agropyron trachycaulum has strong seedling vigour and high establishment and provides high, quick cover, as on this site. *Festuca ovina* was recently identified as a potentially invasive species with high longevity and persistence (Neville 2009), supported by the fact that it was only moderately established in 2007 (Jackson 2009) and increased considerably through to 2011. It formed dense tufts with high cover, consistent with its typical growth pattern (Johnson et al.1995). *Agrostis stolonifera* had moderate first year survival and low cover relative to most other species consistently over time (Jackson 2009). This may be partially attributed to its inherent slender stems, small canopy cover and small grains (Johnson et al. 1995). *Deschampsia caespitosa* had low first year survival (Jackson 2009), and typically has narrow leaves, thin stalks and fine seed heads (Johnson et al.1995) contributing to its low cover in 2011. It requires mesic conditions and poor performance could be attributed to low soil water.

2.4.4 Unseeded Species Response

Unseeded species comprised a larger part of canopy cover than seeded species on all cap depths (Figure 2.5). It was significantly lower without caps than with, lower with 8 cm than ≥ 15 cm caps and significantly lower than with 30 and 91 caps. Unseeded species were more prevalent in *Agrostis stolonifera* and *Deschampsia caespitosa* than *Festuca ovina*, *Agropyron trachycaulum* and mix treatments as they had less competition from seeded species.

There were 22 unseeded species in the experimental plots, 7 grasses, 14 forbs and 1 tree (Table 2.6). *Medicago sativa* was the most abundant unseeded species as plot soil was seeded with it and it was likely in the seed bank. *Bromus inermis* Leyss, *Poa pratensis* L. (Kentucky bluegrass), *Chenopodium album* L. (lambs quarters), *Crepis tectorum* L. (narrow leaf hawksbeard), *Descurainia sophia* (L.) Webb. (flixweed) and *Kochia scoparia* (L.) Roth (Kochia) were abundant. *Puccinellia nuttalliana* (Schult.) Hitchc. (Nuttall's alkali grass), adapted to high salts, was most abundant without caps, and in bare PG between plots.

2.4.5 Below Ground Plant Response

No roots were found in uncapped plots (Figures 2.8, 2.9, Tables 2.7, 2.8). Vegetation treatment had no significant effect on rooting depth and all species had significantly increasing maximum root depth with increasing cap depth. Total root biomass was significantly lower without caps than with caps and there were no significant differences in root biomass with caps ≥ 8 cm (Figure 2.9). Root biomass was numerically highest in 8 cm caps (Table 2.8). Root biomass in soil was much higher than in PG for all cap depths and few roots grew into PG.

Root accumulations consisting of a layer of fine roots approximately 0.5 cm thick (Figure 2.10) occurred at the soil-PG interface in 50% of the cores from 8 to 46 cm caps (Tables 2.7, 2.8). They did not occur in 91 cm caps, likely because maximum root depth did not reach the interface. In some cores with cracks through the PG, roots accumulated in the cracks. Thick tap roots were rarely found in the interface accumulations and tap roots were sometimes found below the interface in PG. Root accumulations at the interface could occur due to increased water at the interface, increased bulk density of the PG which makes it difficult to penetrate, lack of nutrients in PG, a higher concentration of elements unfavourable to root growth in PG, or combinations thereof.

Roots were deepest for *Festuca ovina* and shallowest for *Deschampsia caespitosa* (Figure 2.8, Table 2.7). For all three species, root depth increased with increased cap depth and root biomass was similar on all caps ≥ 8 cm (Figure 2.9, Table 2.7). *Agropyron trachycaulum* and *Deschampsia caespitosa* root biomass were similar and significantly lower than that of *Festuca ovina*. Root biomass of all species was low in PG and root mass accumulations occurred at the soil-PG interface of cores from 8-46 cm caps.

Few studies assessed plant rooting in PG with a soil cap, with this study the first to note root mass accumulations at the soil-PG interface. Richardson et al. (1995) found plants that naturally established on PG stacks typically had very shallow roots systems and were easily uprooted. Herbaceous plant roots occasionally followed cracks in the PG to greater depths.

Hallin et al. (2010) found plants on side slopes of Fort Saskatchewan PG stacks 8 years after soil capping were often rooting into PG by over 20 cm. The long time since capping, and slopes which are typically less compacted than basins and incur more erosion, could lead to increased mixing of soil and PG at the interface, creating a more hospitable rooting medium.

2.4.6 Soil Analyses

Of 37 elements assessed, 7 were three or more times higher and 8 were three or more times lower in uncapped plots relative to reference soils (Figure 2.11, Tables 2.9, A1). This PG was bare and exposed for 20 years and therefore different in composition than fresh PG due to volatilization, leaching and deposition from the atmosphere. Exposed PG pH was 5.0, lower than the 7.4 of reference soils (Figure 2.12, Table 2.9) and the slightly acidic or neutral soil pH considered optimum for most plant growth (Government of Alberta 2003, Taiz and Zeiger 2010). Caps ≥ 15 cm had optimum range pH in the upper 15 cm.

Fluorine was most highly elevated in PG with concentrations 31 times greater than that in reference soils. High fluorine is typical of PG (Rutherford et al. 1994, Wissa 2003). Relative to reference soils, lutetium, cobalt, terbium, lanthanum, europium and nickel were 3 to 5 times higher and arsenic, thorium, bromine, scandium, barium, sodium, iron and cesium were 3 to 6 times lower in PG than reference soils. Most differences occurred in the upper 15 cm of caps < 30 cm deep (Table 2.9).

Cobalt concentrations in the upper 15 cm of uncapped plots and 1/3 of samples from 8 cm caps exceeded natural area Tier 1 soil remediation guidelines (Alberta Environment 2010a) (Table 2.9). None exceeded Tier 1 industrial area guidelines. Reference soils slightly exceeded the Tier 1 natural area fluorine guideline. Fluorine concentrations in uncapped and 8 cm capped plots exceeded the industrial area Tier 1 guideline. Nickel concentrations exceeded Tier 1 natural and industrial area guidelines in uncapped plots and in 1/3 of the 8 cm caps.

Nickel, cobalt and iron could originate from a neighboring metal refinery and tailings pond (Chapter 4). Based on the literature and sampling, metal concentrations on stacks are higher than expected for PG composition. The PG is derived from Florida source rock, which typically has low concentrations of cobalt, copper and nickel (2, 8, 2 mg kg^{-1}, respectively) relative to PG from other source rocks (May and Sweeney 1984, Rutherford et al. 1994). Data from PG stacks indicate cobalt, copper and nickel are often substantially higher in the surface than deep in the profile, indicating metals may be accumulating on stack surfaces (Unpublished data). Metal refinery stack emissions and material blown from refinery tailings ponds are possible sources of metals on Agrium property.

2.4.7 Plant Tissue Trace Elements

Trace element analyses could not be performed on uncapped vegetation due to insufficient amounts of material. Relative to references, 3 of 37 elements (cobalt, fluorine, nickel) were elevated in some plant tissue (Tables 2.10, A.2.2, A.2.3, A.2.4, A.2.5 and A.2.6). Cobalt decreased with increasing cap depth with significantly higher than reference concentrations in tissue from 8, 15, 30 and 46 cm caps (Figure 2.13). Although *Medicago sativa* tissue had numerically higher cobalt than other species, differences were not significant among species (Tables 2.11, 2.12). Cobalt concentrations from all cap depths were below maximum tolerable limits for rodents, poultry and cattle (Table 2.10).

Fluorine and nickel were elevated relative to references in some tissue from research plots, however, statistical analyses were not conducted because many samples were below detection limits (Table 2.10). Fluorine was elevated in grasses from 8 cm caps relative to references; the mean fluorine in grasses from 8 cm caps was within the normal range for plants, however some plants from this depth contained fluorine above the normal range (Table 2.11). *Medicago sativa* tissue fluorine was elevated relative to the references but still within the normal range (Table 2.12). Fluorine concentrations were not elevated in plants from cap depths ≥ 15 cm. Fluorine in vegetation was below maximum tolerable limits for animals (Table 2.10) (United States National Research Council 2005).

Medicago sativa and *Agrostis stolonifera* nickel concentrations were higher in tissue from research plots than reference sites (Tables 2.10, 2.11, 2.12). There was no trend in tissue nickel concentration with cap depth. *Agropyron trachycaulum* nickel concentrations could not be accurately assessed because of high bromine due to a tracer placed by an MSc student which interfered with nickel assessment and raised its detection limit (Christensen 2012, Simpson 2012). *Festuca ovina* reference tissue contained more nickel than other reference tissues, likely due to the close proximity to the metal refinery and tailings pond. Nickel concentrations from all caps were all below maximum tolerable limits for rodents, poultry and cattle (Tables 2.10, 2.11, 2.12).

Elevated nickel and cobalt in tissue from the research plots is potentially due in part to metals originating from the neighbouring metal refinery and tailings pond which have been deposited on the PG stacks. Nickel, cobalt and iron concentrations are substantially higher near the tailings pond than at locations further away indicating the pond is likely a source of metals (See Chapter 4).

Cobalt concentrations were not significantly different among species (Figure 2.13, Table A.2.4). In *Agrostis stolonifera* cobalt concentrations were highest in 8 cm caps followed by 15 and 30 cm caps and below detection in 46 and 91 cm caps and references (Figure 2.13). *Agrostis stolonifera* nickel concentrations were elevated in all caps relative to references, with no cap depth trend. *Agrostis stolonifera* fluorine concentrations were highest in 8 cm caps and similar to references in caps ≥ 15 cm.

Agropyron trachycaulum tissue cobalt concentration was higher in research plots than references and generally decreased with increasing cap depth (Figure 2.13, Table A.2.3). *Agropyron trachycaulum* fluorine concentrations were highest in 8 cm caps and similar to references in caps ≥ 15 cm.

Festuca ovina tissue cobalt concentration decreased with increasing cap depth and was lower on references than research plots (Figure 2.13, Table A.2.5). *Festuca ovina* reference tissues had higher cobalt and nickel than the other three species, likely since its reference location was closer to the neighbouring metal refinery than other references. *Festuca ovina* fluorine was slightly elevated in 8 cm caps relative to references but was within the normal range in vegetation from all cap depths. There was no trend in tissue nickel concentration with cap depth.

Medicago sativa had slightly higher cobalt concentrations than grasses (Table A.2.6). Cobalt decreased with cap depth and was lower in references than plots (Figure 2.13). *Medicago sativa* was not elevated in fluorine in any of the caps. *Medicago sativa* nickel concentrations were lower in references than plots with no trend for cap depth.

Hallin (2008) assessed tissue concentrations of 37 elements from plants on Fort Saskatchewan PG stack slopes with a 15 cm soil cap. They contained elevated fluorine and nickel compared to a reference sample but, potentially due to a small sample size, did not contain elevated cobalt. Similar to this study, other studies indicate that radionuclides including uranium and radium are not elevated in plants grown on PG (Al-Oudat et al. 1998, Thorne 1990).

Other studies found some different elements accumulated by plants in PG compared to this study, which may be due to different PG elemental composition. Thorne (1990) found vegetation in bare PG accumulated selenium, fluorine and cadmium and vegetation in amended PG accumulated selenium. Unlike this study, elements were taken up in concentrations potentially toxic to wildlife. Gorbunov et al. (1992) found strontium was consistently accumulated by plants when PG was applied at 60 tons/ha to soil; slight accumulations of zinc, bromine, hafnium, lead, calcium, scandium, lanthanum, rubidium, caesium, cerium and antimony occurred in the tissues of some species.

2.4.8 Reclamation Applications

A soil cap ≥ 15 cm was adequate to grow healthy, vigorous vegetation. A ≥ 46 cm cap was required to meet natural area Tier 1 guidelines in the upper 15 cm of substrate in all samples for 37 trace elements. A ≥ 8 cm cap was required to meet industrial area Tier 1 guidelines in the upper 15 cm of substrate in all samples for 37 trace elements. Based on current concentrations of cobalt and nickel on the stack (significant quantities from a neighbouring metal refinery) a ≥ 15 cm cap was needed for vegetation with fluorine tissue concentrations similar to references and a ≥ 91 cm cap was needed for vegetation with cobalt concentrations similar to references and within the normal range for plants. However an 8 cm cap was adequate for vegetation with concentrations of 37 trace elements safe for animal consumption based on values set by the United States National Research Council (2005).

A mix of grasses and legumes is recommended for PG stack reclamation to blend with surrounding vegetation. *Agropyron trachycaulum* is recommended as it had high cover and health five years after seeding. *Agrostis stolonifera* was performing well and is tentatively recommended if longer term assessments confirm its success. *Medicago sativa* performed well and could be considered in future reclamation plans. *Deschampsia caespitosa* and *Trifolium hybridum* are not recommended for PG reclamation as five seasons after seeding they had very low cover and were being outcompeted by unseeded species. *Deschampsia caespitosa* likely requires more water and *Trifolium hybridum* likely requires more sunlight and does not have high tolerance for salts or acidity. *Festuca ovina* was performing well, however recent studies in other ecosystems indicate it can be highly invasive and should not be used in reclamation (Neville 2009).

Based on their inherent properties, several species are recommended for future studies of PG stack reclamation. *Festuca saximontana* Rydb. (rocky mountain fescue) is not as invasive as *Festuca ovina* but has many similar characteristics (Neville 2009). Native species *Koeleria macanthra* (Ledeb.) Schult. (june grass) or *Nassella viridula* (Trin.) Barkworth (green needle grass) are recommended. *Koeleria macanthra* is adaptable to a wide range of conditions and *Nassella viridula* is vigorous once established (Knudson 2005). *Lotus corniculatus* L. (birdsfoot trefoil) or *Vicia americana* Muhl. Ex Willd. (American vetch) could replace *Trifolium hybridum. Lotus corniculatus* fixes nitrogen and is tolerant of moderate salinity and acidity (Bush 2002). *Vicia americana* fixes nitrogen and grows well in grass mixes (Kirk and Belt 2010). These species could be assessed for phosphogypsum stack reclamation to create a vegetation mix on stacks that is healthy, vigorous and self-sustaining.

2.5. Conclusions

- Vegetation performed better in capped plots than uncapped plots for all parameters assessed.

- Cap depths ≥ 15 cm supported the most healthy vigorous plant growth; 8 cm caps were adequate for plant growth and development.
- Plant roots grew successfully in caps ≥ 8 cm; roots had similar biomass in caps ≥ 8 cm but increased in maximum root depth with increasing cap depth.
- Few roots grew in PG and fine root mass accumulations formed at the soil-PG interface; roots may grow better in the interface due to higher water content or may be unable to move deeper due to PG properties.
- *Agropyron trachycaulum*, *Festuca ovina* and *Agrostis stolonifera* were growing well on the stack; *Deschampsia caespitosa* and *Trifolium hybridum* were not.
- A cap depth of 8 cm was adequate to grow vegetation with tissue concentrations of 37 trace elements that are safe to eat by animals based on values set out by the United States National Research Council (2005).
- Fluorine, cobalt and nickel were elevated in some plants on the research plots relative to references; cap depth affected tissue fluorine and cobalt concentrations but not nickel
- Tissue fluorine was similar to references with cap depths ≥ 15 cm and tissue cobalt generally decreased with increasing cap depth and was within the normal range in the 91 cm cap depth.
- *Medicago sativa* had higher tissue cobalt than grasses; broad leaved plants with tap roots may take up more cobalt than grasses with fine roots.
- Unseeded canopy cover was higher than seeded canopy cover for all cap depths and 22 unseeded species encroached on the plots.

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Figure 2.1 Map of location of Fort Saskatchewan in Alberta, Canada (Adapted from GreenField Development Corp. 2009).

Figure 2.2 Aerial view of Agrium facilities and phosphogypsum stacks in Fort Saskatchewan, Alberta (Adapted from Google Inc. 2012).

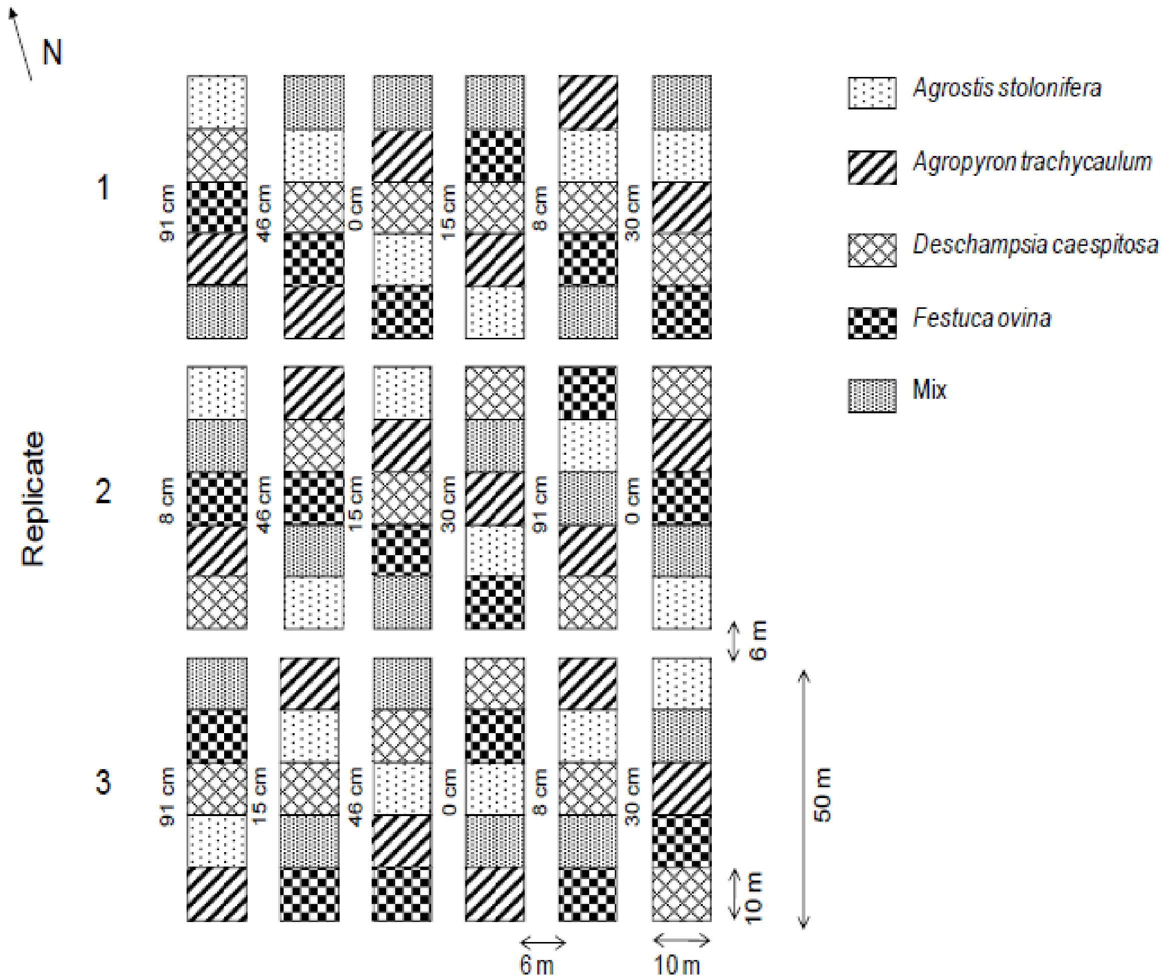

Figure 2.3 Experimental research plots at Agrium, Fort Saskatchewan, Alberta (Jackson 2009).

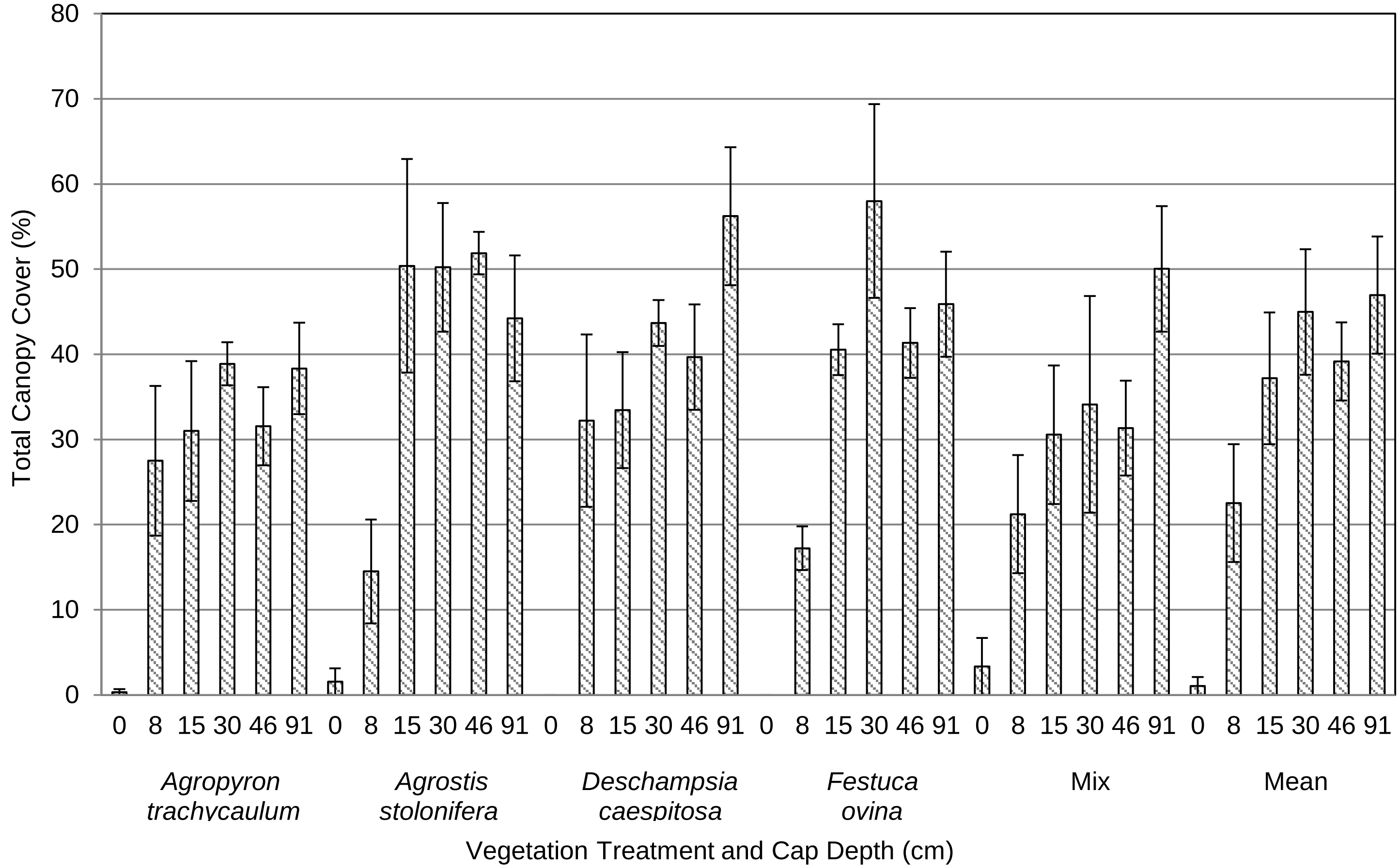

Figure 2.4 Total canopy cover on research plots at Agrium Fort Saskatchewan, Alberta in 2011.

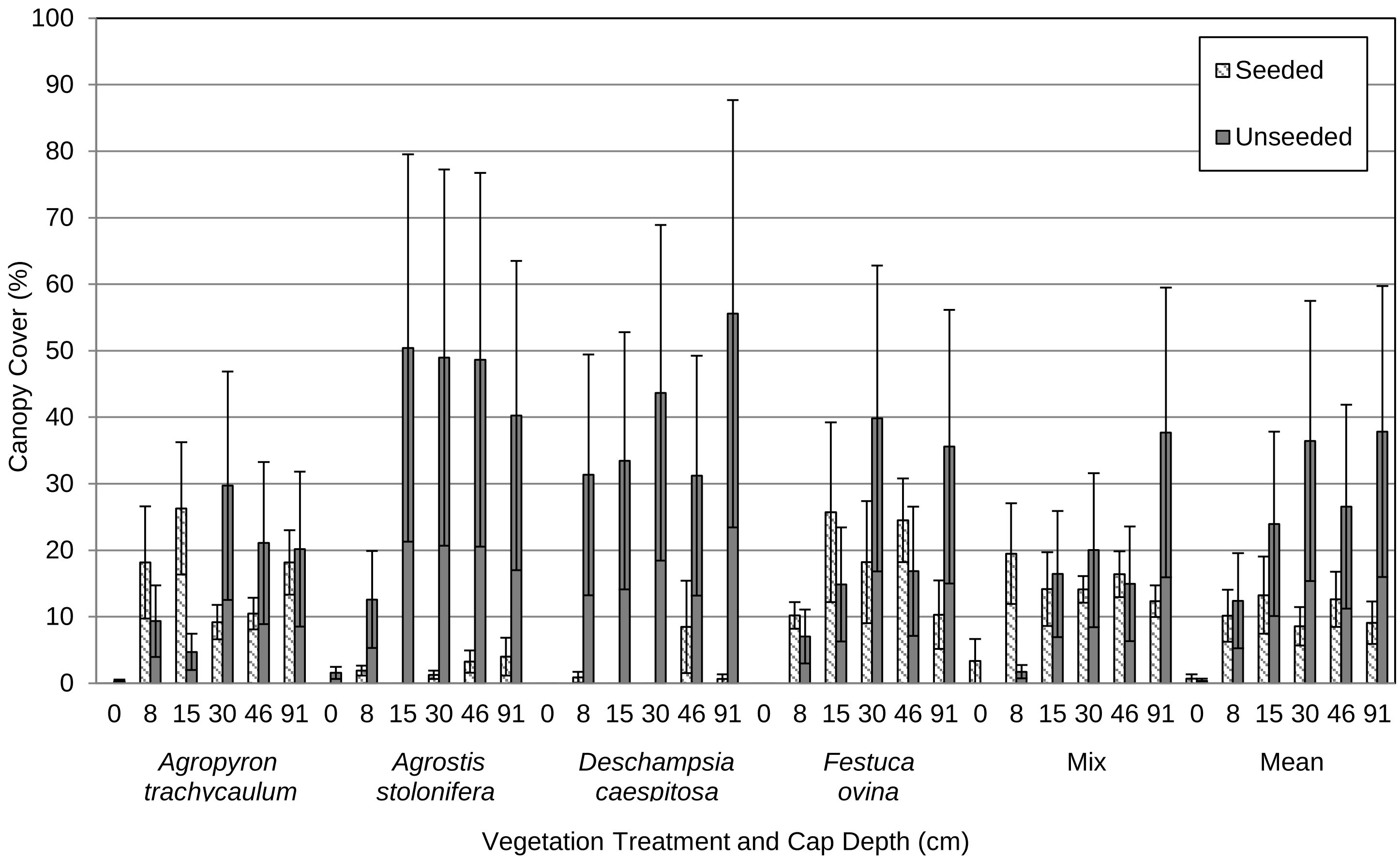

Figure 2.5 Canopy cover of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta in 2011.

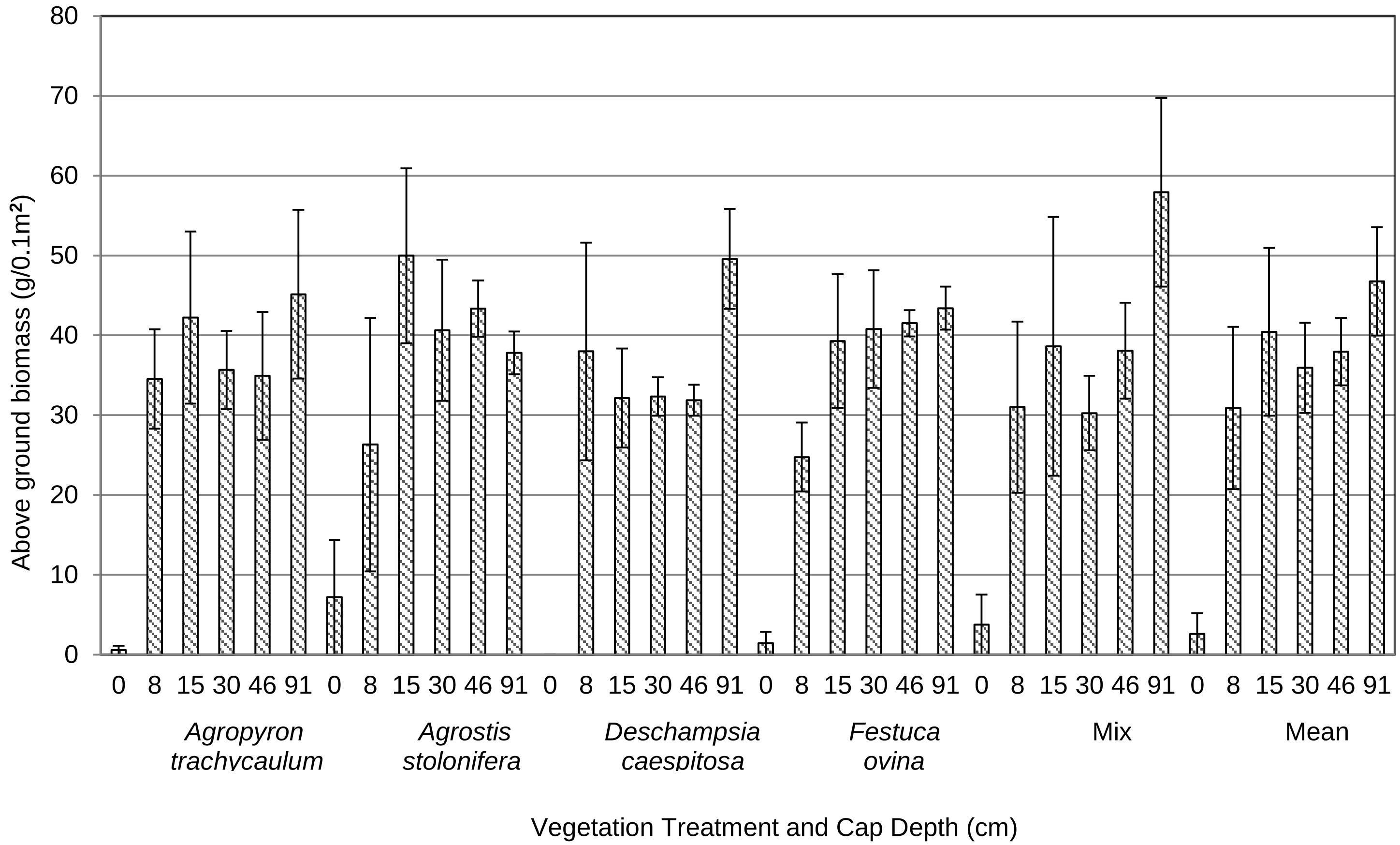

Figure 2.6 Above ground biomass on research plots at Agrium Fort Saskatchewan, Alberta in 2011.

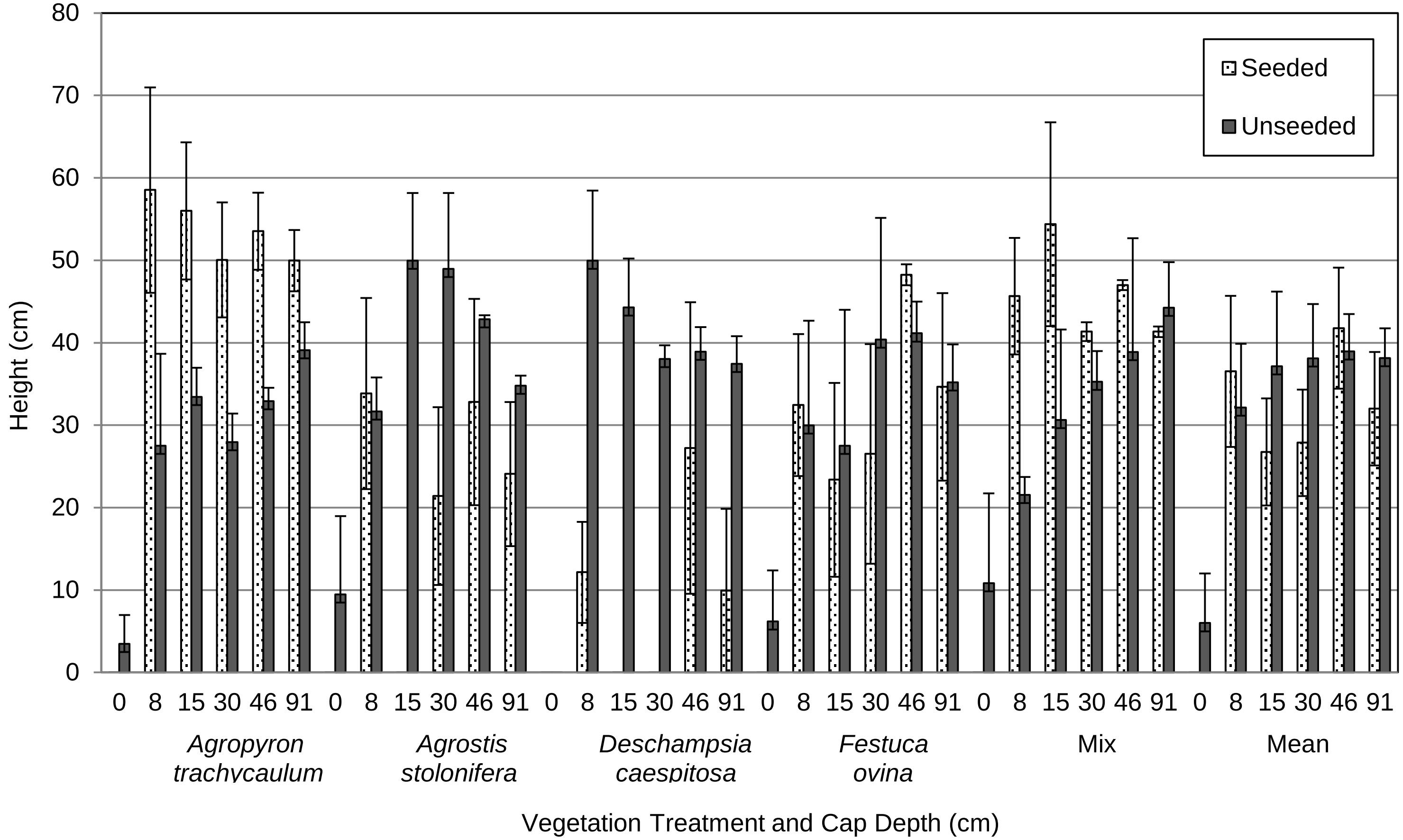

Figure 2.7 Height of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta in 2011.

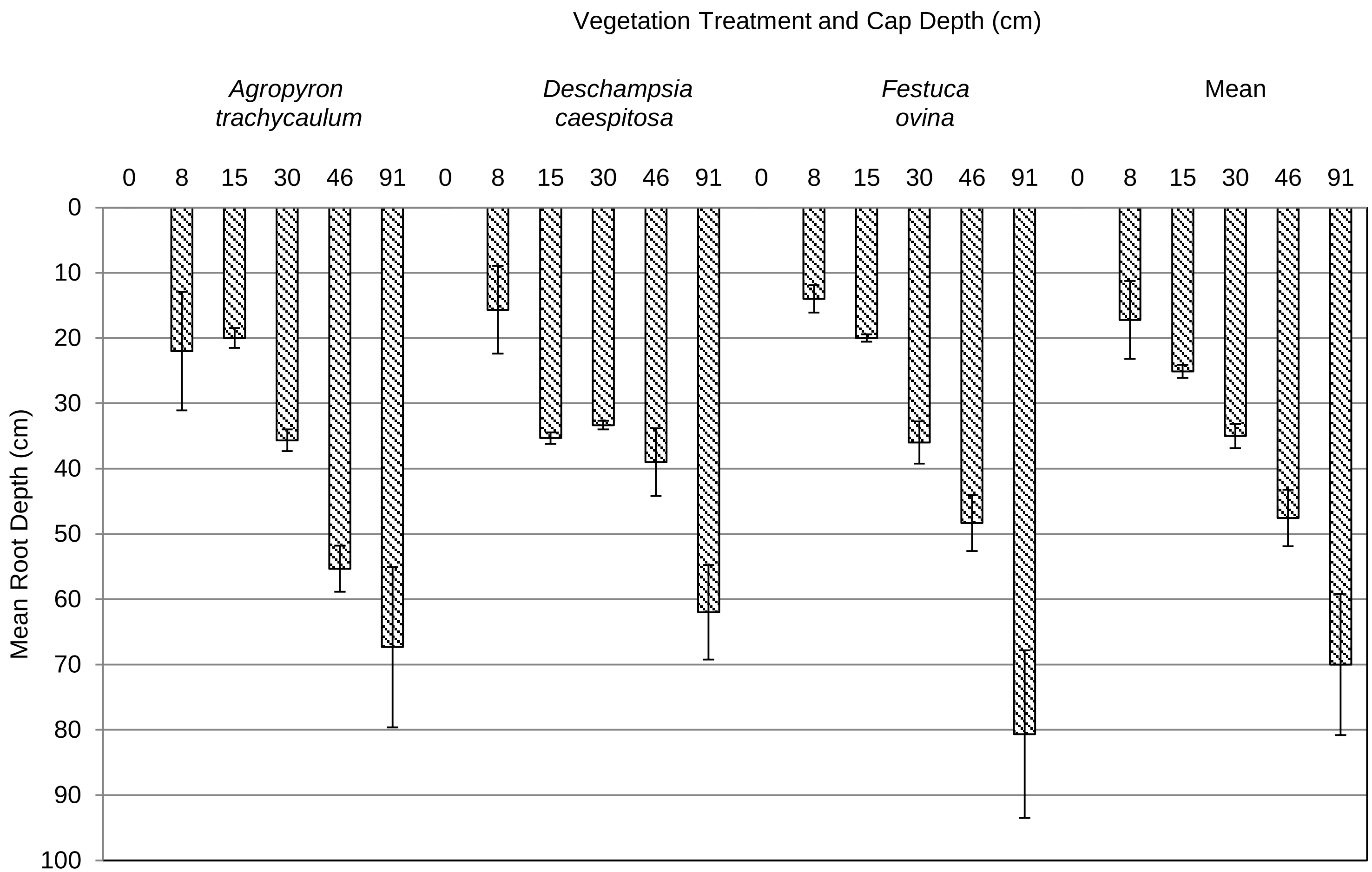

Figure 2.8 Maximum root depth of vegetation on research plots at Agrium Fort Saskatchewan, Alberta in 2010.

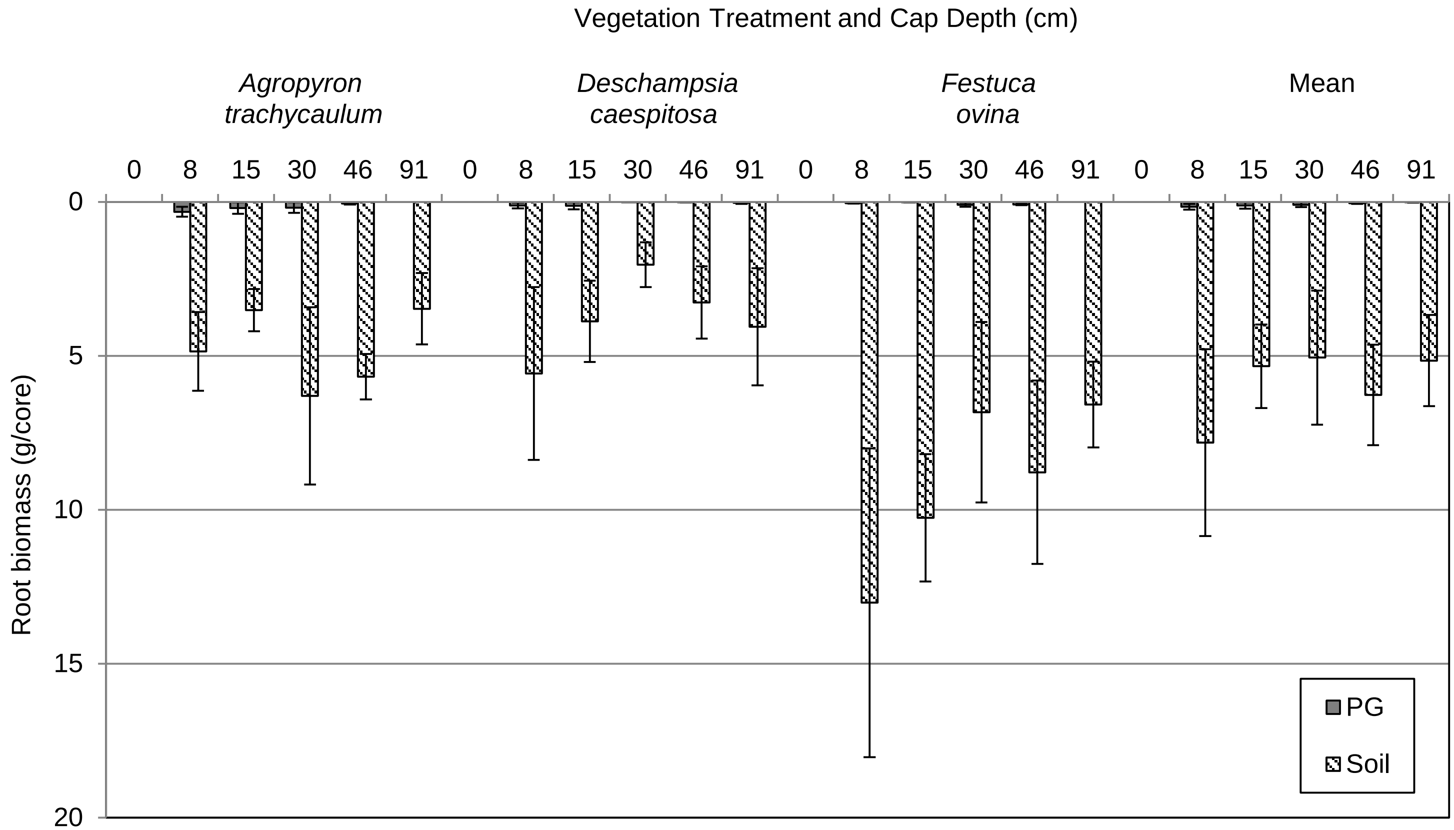

Figure 2.9 Root biomass in phosphogypsum and soil in research plots at Agrium Fort Saskatchewan, Alberta in 2010.

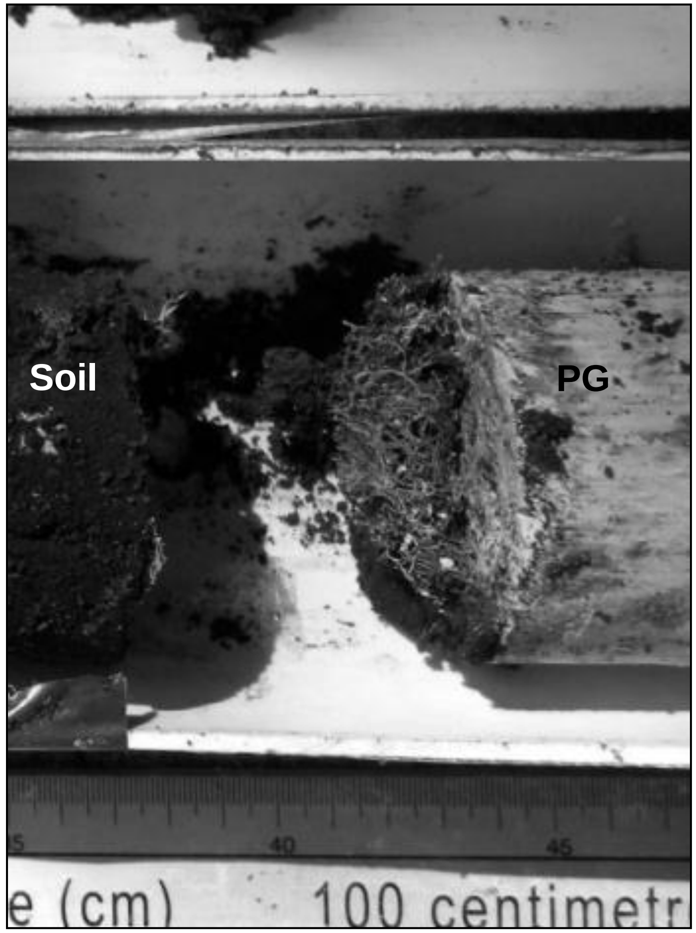

Figure 2.10 Picture of a root mass accumulation at the soil-PG interface in a soil core.

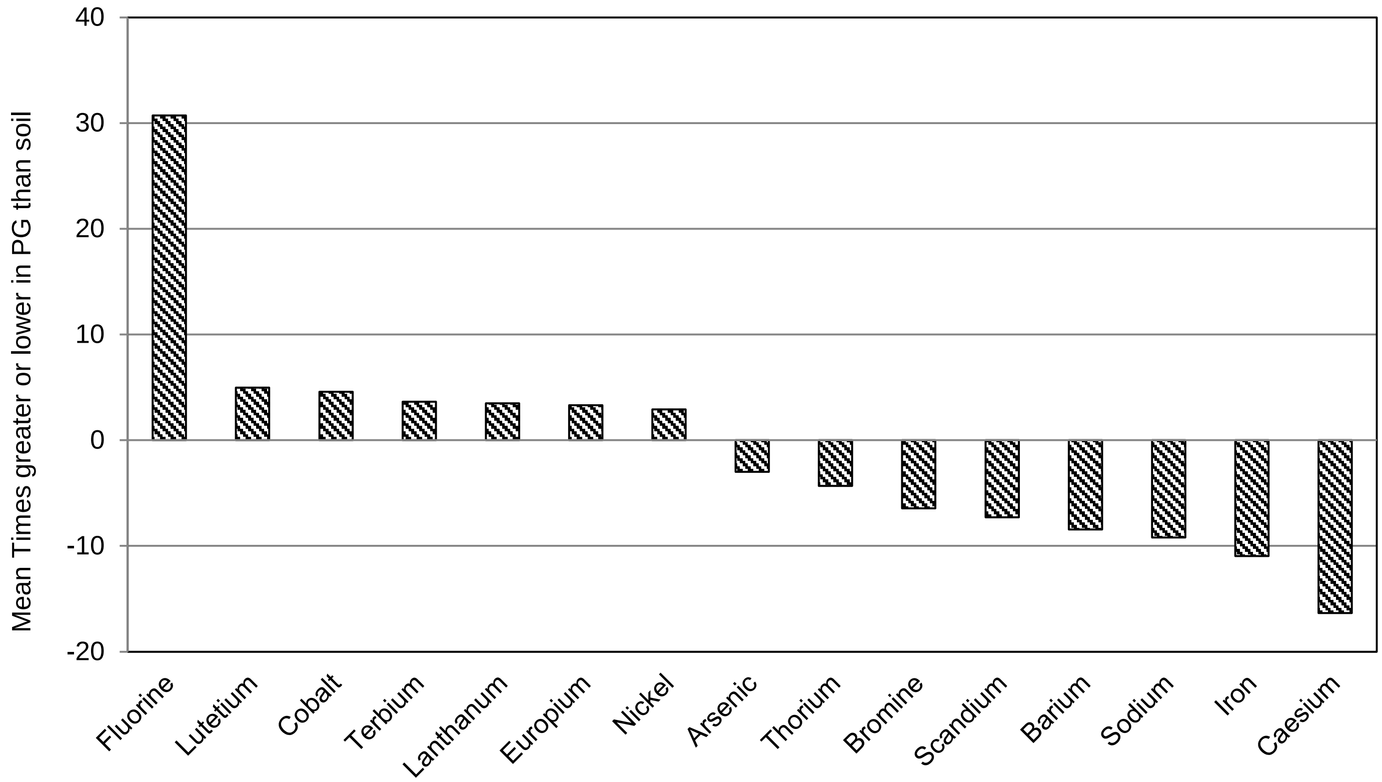

Figure 2.11 Elements elevated or lowered in bare exposed PG relative to reference soils at Agrium Fort Saskatchewan, Alberta in 2010 and 2011.

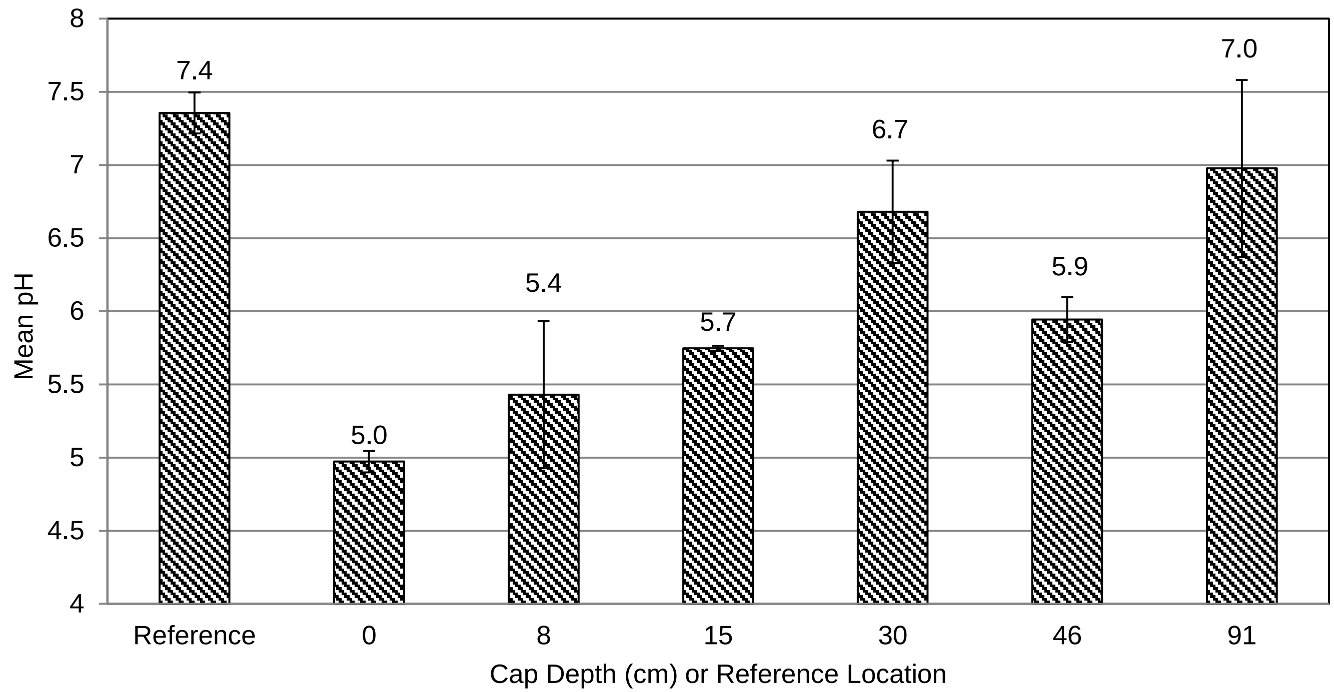

Figure 2.12 Substrate pH in top 15 cm on research plots at Agrium Fort Saskatchewan, Alberta and in reference locations.

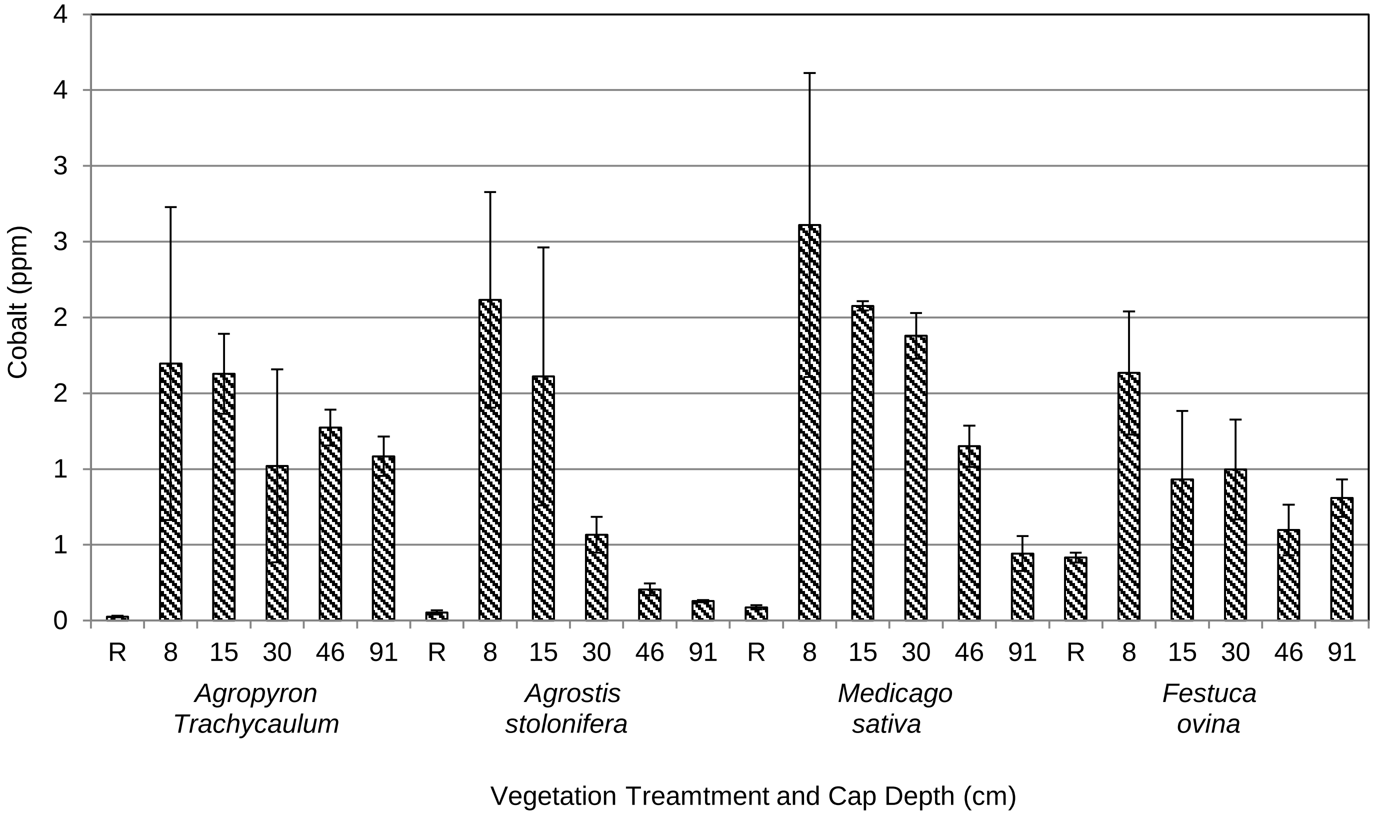

Figure 2.13 Cobalt concentration in vegetation tissue on research plots at Agrium Fort Saskatchewan, Alberta.

Table 2.1. Elements assessed with neutron activation in soil and vegetation samples.

Elements Assessed				
Antimony	Cobalt	Lutetium	Selenium	Tungsten
Arsenic	Europium	Mercury	Silver	Uranium
Barium	Fluorine	Molybdenum	Sodium	Ytterbium
Bromine	Gold	Nickel	Tantalum	Zinc
Cadmium	Hafnium	Potassium	Tellurium	Zirconium
Caesium	Iridium	Rubidium	Terbium	
Cerium	Iron	Samarium	Thorium	
Chromium	Lanthanum	Scandium	Tin	

Table 2.2. Vegetation above ground characteristics on research plots at Agrium Fort Saskatchewan, Alberta

Cap Depth (cm)	Vegetation Treatment	Total Canopy Cover (%)†	Seeded Canopy Cover (%)†	Above Ground Biomass (g/quadrat)†	Height (cm)	Health (%)‡			Development (%)‡		
						1	2	3	1	2	3
0	*Agropyron trachycaulum*	0 (0)	0 (0)	0.6 (0.6)	-	-	-	-	-	-	-
	Agrostis stolonifera	2 (2)	0 (0)	7.2 (7.2)	-	-	-	-	-	-	-
	Deschampsia caespitosa	0 (0)	0 (0)	0.0 (0.0)	-	-	-	-	-	-	-
	Festuca ovina	0 (0)	0 (0)	1.4 (1.4)	-	-	-	-	-	-	-
	Mix	3 (3)	3 (3)	3.8 (3.8)	-	-	-	-	-	-	-
8	*Agropyron trachycaulum*	28 (9)	18 (8)	34.5 (6.2)	59 (12)	0	11	89	0	89	11
	Agrostis stolonifera	15 (6)	2 (1)	26.3 (15.9)	34 (12)	0	0	100	0	100	0
	Deschampsia caespitosa	32 (10)	1 (1)	38.0 (13.6)	12 (6)	0	50	50	0	50	50
	Festuca ovina	17 (3)	10 (2)	24.8 (4.3)	32 (9)	0	33	67	0	72	28
	Mix	21 (7)	19 (8)	31.0 (10.7)	46 (7)	0	15	85	15	80	6
15	*Agropyron trachycaulum*	31 (8)	26 (10)	42.2 (10.8)	56 (8)	0	17	83	0	83	17
	Agrostis stolonifera	50 (13)	0 (0)	50.0 (11.0)	-	-	-	-	-	-	-
	Deschampsia caespitosa	33 (7)	0 (0)	32.1 (6.2)	-	-	-	-	-	-	-
	Festuca ovina	41 (3)	26 (14)	39.3 (8.4)	23 (12)	0	0	100	0	100	0
	Mix	31 (8)	14 (6)	38.6 (16.2)	54 (12)	11	0	89	6	94	0
30	*Agropyron trachycaulum*	39 (3)	9 (3)	35.7 (4.9)	50 (7)	0	0	100	11	89	0
	Agrostis stolonifera	50 (8)	1 (1)	40.6 (8.8)	21 (11)	0	0	100	0	100	0
	Deschampsia caespitosa	44 (3)	0 (0)	32.3 (2.4)	-	-	-	-	-	-	-
	Festuca ovina	58 (11)	18 (9)	40.8 (7.4)	27 (13)	0	0	100	0	83	17
	Mix	34 (13)	14 (2)	30.3 (4.7)	41 (1)	0	0	100	6	94	0
46	*Agropyron trachycaulum*	32 (5)	10 (2)	34.9 (8.0)	54 (5)	0	22	78	11	89	0
	Agrostis stolonifera	52 (2)	3 (2)	43.4 (3.5)	33 (13)	0	0	100	0	100	0
	Deschampsia caespitosa	40 (6)	8 (7)	31.9 (1.9)	27 (18)	0	0	100	0	33	67
	Festuca ovina	41 (4)	24 (6)	41.5 (1.6)	48 (1)	0	0	100	0	100	0
	Mix	31 (6)	16 (3)	38.1 (6.0)	47 (1)	0	6	94	6	83	11
91	*Agropyron trachycaulum*	38 (5)	18 (5)	45.2 (10.6)	50 (4)	11	11	78	22	78	0
	Agrostis stolonifera	44 (7)	4 (3)	37.8 (2.7)	24 (9)	0	0	100	0	100	0
	Deschampsia caespitosa	56 (8)	1 (1)	49.6 (6.3)	10 (10)	*	*	*	*	*	*
	Festuca ovina	46 (6)	10 (5)	43.4 (2.7)	35 (11)	0	0	100	0	100	0
	Mix	50 (7)	12 (2)	57.9 (11.8)	41 (1)	0	6	94	6	94	0

Data are means with standard errors in brackets.
3 ≤ n ≤ 9 for all treatments except mix where 3 ≤ n ≤ 45; †n = 9.
-Data not available; *Incomplete data set available for calculation of mean.
‡Data are % of plants in category. Health categories: 1 = < 25 % live green material, 2 = 25 to 75 % live green material, 3 = > 75 % live green material.
Development categories: 1 = rosette or immature plant, 2 = plant close to flowering or flowering, 3 = plant has set seed.

Table 2.3. Overall above ground vegetation characteristics on research plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Total Canopy Cover (%)†	Seeded Canopy Cover (%)	Above Ground Biomass (g/quadrat)†	Height (cm)	Health (%)‡			Development (%)‡		
					1	2	3	1	2	3
0	1 (1)	1 (1)	2.6 (2.6)	-	-	-	-	-	-	-
8	23 (7)	10 (4)	30.9 (10.2)	37 (9)	0	22	78	3	78	19
15	37 (8)	13 (6)	40.4 (10.5)	27 (6)	4	6	91	2	93	6
30	45 (7)	9 (3)	35.9 (5.6)	28 (6)	0	0	100	4	92	4
46	39 (5)	13 (4)	37.9 (4.2)	42 (7)	0	6	94	3	81	16
91	47 (7)	9 (3)	46.8 (6.8)	32 (7)	3	4	93	7	93	0

Data are means with standard errors in brackets.
$10 \leq n \leq 15$; †$n = 15$.
-Data not available.
‡Data are % of plants in category. Health categories: 1 = < 25 % live green material, 2 = 25 to 75 % live green material, 3 = > 75 % live green material.
Development categories: 1 = rosette or immature plant, 2 = plant close to flowering or flowering, 3 = plant has set seed.

Table 2.4. Ground cover on research plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Vegetation Treatment	Ground Cover (%)				
		Vegetation	Moss	Bare	Litter	Standing Litter
0	*Agropyron trachycaulum*	0 (0)	0 (0)	100 (0)	0 (0)	0 (0)
	Agrostis stolonifera	0 (0)	0 (0)	94 (6)	6 (6)	1 (1)
	Deschampsia caespitosa	0 (0)	0 (0)	100 (0)	0 (0)	0 (0)
	Festuca ovina	0 (0)	0 (0)	100 (0)	0 (0)	0 (0)
	Mix	1 (1)	0 (0)	81 (19)	18 (18)	0 (0)
8	*Agropyron trachycaulum*	3 (1)	0 (0)	3 (1)	94 (1)	3 (0)
	Agrostis stolonifera	3 (1)	0 (0)	11 (5)	87 (5)	2 (1)
	Deschampsia caespitosa	5 (1)	0 (0)	18 (9)	77 (8)	3 (0)
	Festuca ovina	4 (0)	0 (0)	12 (12)	84 (12)	3 (1)
	Mix	4 (1)	0 (0)	12 (11)	85 (10)	3 (1)
15	*Agropyron trachycaulum*	4 (1)	0 (0)	6 (6)	90 (6)	4 (1)
	Agrostis stolonifera	5 (2)	0 (0)	0 (0)	95 (2)	2 (1)
	Deschampsia caespitosa	4 (1)	0 (0)	0 (0)	96 (1)	2 (0)
	Festuca ovina	7 (2)	0 (0)	0 (0)	93 (2)	5 (1)
	Mix	4 (1)	0 (0)	0 (0)	96 (1)	3 (1)
30	*Agropyron trachycaulum*	4 (0)	7 (7)	1 (1)	79 (15)	18 (16)
	Agrostis stolonifera	5 (1)	0 (0)	0 (0)	94 (1)	3 (1)
	Deschampsia caespitosa	4 (0)	0 (0)	0 (0)	96 (0)	3 (0)
	Festuca ovina	8 (1)	0 (0)	2 (2)	90 (3)	3 (1)
	Mix	5 (1)	0 (0)	0 (0)	94 (1)	2 (0)
46	*Agropyron trachycaulum*	4 (0)	0 (0)	0 (0)	96 (1)	2 (1)
	Agrostis stolonifera	5 (1)	0 (0)	0 (0)	95 (1)	2 (0)
	Deschampsia caespitosa	5 (1)	0 (0)	1 (1)	95 (1)	3 (1)
	Festuca ovina	10 (2)	0 (0)	0 (0)	90 (2)	3 (1)
	Mix	4 (0)	0 (0)	2 (2)	94 (2)	3 (0)
91	*Agropyron trachycaulum*	4 (1)	0 (0)	1 (0)	95 (1)	2 (1)
	Agrostis stolonifera	4 (0)	0 (0)	3 (1)	93 (1)	2 (0)
	Deschampsia caespitosa	6 (1)	0 (0)	3 (1)	92 (2)	2 (1)
	Festuca ovina	15 (10)	0 (0)	0 (0)	85 (10)	2 (1)
	Mix	6 (1)	0 (0)	0 (0)	94 (1)	2 (1)

Data are means with standard errors in brackets.
n = 3.

Table 2.5. Overall ground cover characteristics on research plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Ground Cover (%)				
	Vegetation	Moss	Bare	Litter	Standing Litter
0	0 (0)	0 (0)	95 (5)	5 (5)	0 (0)
8	4 (1)	0 (0)	11 (8)	85 (7)	3 (1)
15	5 (1)	0 (0)	1 (1)	94 (2)	3 (1)
30	5 (1)	1 (1)	1 (1)	91 (4)	6 (4)
46	5 (1)	0 (0)	1 (1)	94 (1)	3 (1)
91	7 (2)	0 (0)	1 (1)	92 (3)	2 (1)

Data are means with standard errors in brackets.
n = 15 for all treatments.

Table 2.6. Plant species on research plots at Agrium Fort Saskatchewan, Alberta.

Category	Scientific name	Common Name
Grasses	*Agropyron repens* (L.) Beauv.	Quack grass
	Agropyron trachycaulum (Link) Malte ex. H.F. Lewis	Slender wheat grass
	Agrostis stolonifera L.	Redtop
	Bromus inermis Leyss.	Smooth brome
	Deschampsia caespitosa (L.) P. Beauv.	Tufted hair grass
	Festuca ovina L.	Sheep fescue
	Poa compressa L.	Canada blue grass
	Poa palustris L.	Fowl blue grass
	Poa pratensis L.	Kentucky blue grass
	Poa secunda J. Presl	Sandberg blue grass
	Puccinellia nuttalliana (Schult.) Hitchc.	Nuttall's alkali grass
Forbs	*Achillea millefolium* L.	Yarrow
	Axyris amaranthoides L.	Russian pigweed
	Chenopodium album L.	Lamb's quarters
	Crepis tectorum L.	Narrow leaved hawk's beard
	Descurainia sophia (L.) Webb.	Flixweed
	Kochia scoparia (L.) Roth	Kochia
	Linaria vulgaris Mill.	Toadflax
	Medicago sativa L.	Alfalfa
	Polygonum convolvulus L.	Wild buckwheat
	Silene pratensis (Rafn) Godron & Gren.	White cockle
	Taraxacum officinale Weber	Dandelion
	Thlapsi arvense L.	Stinkweed
	Trifolium hybridium L.	Alsike clover
	Urtica dioica L.	Stinging nettle
Trees	*Populus tremuloides* Michx.	Trembling aspen

Table 2.7. Vegetation below ground characteristics on research plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Vegetation Treatment	Maximum Root Depth (cm)	Total Root Biomass (g/core)	Root Biomass in Soil (g/core)	Root Biomass in PG (g/core)	Interface Root Accumulations (% of cores)
0	*Agropyron trachycaulum*	0 (0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0
	Deschampsia caespitosa	0 (0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0
	Festuca ovina	0 (0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0
8	*Agropyron trachycaulum*	22 (9)	5.2 (1.9)	4.9 (1.3)	0.3 (0.2)	67
	Deschampsia caespitosa	16 (7)	5.7 (2.8)	5.6 (2.8)	0.1 (0.1)	33
	Festuca ovina	14 (2)	13.1 (5.6)	13.0 (5.0)	0.0 (0.0)	67
15	*Agropyron trachycaulum*	20 (2)	3.7 (1.2)	3.5 (0.7)	0.2 (0.2)	67
	Deschampsia caespitosa	35 (1)	4.0 (1.6)	3.9 (1.3)	0.1 (0.1)	33
	Festuca ovina	20 (1)	10.3 (3.7)	10.3 (2.1)	0.0 (0.0)	33
30	*Agropyron trachycaulum*	36 (2)	6.5 (3.1)	6.3 (2.9)	0.2 (0.2)	67
	Deschampsia caespitosa	33 (1)	2.0 (0.8)	2.0 (0.7)	0.0 (0.0)	33
	Festuca ovina	36 (3)	6.9 (3.1)	6.8 (2.9)	0.1 (0.1)	67
46	*Agropyron trachycaulum*	55 (4)	5.7 (1.8)	5.7 (0.7)	0.1 (0.0)	67
	Deschampsia caespitosa	39 (5)	3.3 (1.6)	3.3 (1.2)	0.0 (0.0)	33
	Festuca ovina	48 (4)	8.9 (3.5)	8.8 (3.0)	0.1 (0.0)	33
91	*Agropyron trachycaulum*	67 (12)	3.5 (1.4)	3.5 (1.2)	0.0 (0.0)	0
	Deschampsia caespitosa	62 (7)	4.1 (2.2)	4.1 (1.9)	0.0 (0.0)	0
	Festuca ovina	81 (13)	6.6 (2.2)	6.6 (1.4)	0.0 (0.0)	0

Data are means with standard errors in brackets.
n = 3 for all treatments.

Table 2.8. Overall below ground vegetation characteristics on research plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Maximum Root Depth (cm)	Total Root biomass (g/core)	Root Biomass in Soil (g/core)	Root Biomass in PG (g/core)	Interface Root Accumulations (% of cores)
0	0 (0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0
8	17 (6)	8.0 (3.4)	7.8 (3.0)	0.2 (0.1)	56
15	25 (1)	5.5 (2.2)	5.3 (1.4)	0.1 (0.1)	44
30	35 (2)	5.2 (2.3)	5.1 (2.2)	0.1 (0.1)	56
46	48 (4)	6.3 (2.3)	6.3 (1.6)	0.0 (0.0)	44
91	70 (11)	5.2 (1.9)	5.2 (1.5)	0.0 (0.0)	0

Data are means with standard errors in brackets.
n = 9 for all treatments.

Table 2.9. Elements elevated in bare PG or cap soil relative to soil quality guidelines and reference locations and substrate pH at Agrium Fort Saskatchewan, Alberta.

Element	Test	Tier 1		Cap Depth (cm) or Reference						
		Nat. (ppm)	Ind. (ppm)	Reference	0	8	15	30	46	91
Cobalt	% ADL			100	100	100	100	100	100	100
	ppm	20	300	5.96 (0.4)	27.20 (4.5)	14.03 (4.0)	6.64 (1.9)	3.33 (0.6)	4.14 (0.5)	5.03 (0.3)
Fluorine	% ADL			100	100	100	100	100	100	100
	ppm	200	2000	270.48 (17.0)	8310.00 (871.7)	4593.33 (308.5)	995.00 (754.1)	196.67 (52.4)	210.67 (10.7)	177.00 (39.6)
Nickel	% ADL			100	100	100	100	100	100	67
	ppm	50	50	25.03 (2.2)	73.27 (11.9)	40.63 (15.6)	27.12 (11.8)	13.26 (1.7)	12.03 (1.9)	13.77 (3.2)
Europium	% ADL			86	100	100	33	67	33	33
	ppm			0.79 (0.1)	2.61 (0.7)	1.21 (0.1)	<0.45[1]	0.45 (0.0)	<0.45[2]	<0.45[3]
Lanthanum	% ADL			100	100	100	100	100	100	100
	ppm			20.37 (1.2)	70.99 (20.3)	31.91 (3.6)	13.99 (0.6)	11.73 (0.3)	13.60 (0.6)	13.20 (0.2)
Lutentium	% ADL			86	67	67	33	67	33	33
	ppm			0.11 (0.0)	0.55 (0.0)	0.43 (0.0)	<0.03[4]	0.05 (0.0)	<0.03[5]	<0.03[6]
Terbium	% ADL			100	100	100	100	100	100	100
	ppm			0.39 (0.0)	1.44 (0.3)	0.66 (0.1)	0.31 (0.0)	0.22 (0.0)	0.28 (0.0)	0.26 (0.1)
pH	pH			7.35 (0.14)	4.97 (0.07)	5.43 (0.50)	5.75 (0.02)	6.68 (0.35)	5.94 (0.15)	6.97 (0.60)

Concentration data are means for all samples above detection limit with standard error in brackets.
% ADL = percent of samples above detection limit.
Land Use Types: Nat. = Natural Area, Ind. = Industrial area, Res./Park. = Residential/Parkland area.
Tier 1 guideline values listed if available for the element.
n = 3 for all treatments except Reference where n = 21.
Reference values are a mean of three replicates from each of seven offsite reference locations.
< = most samples below stated average detection limit.
Superscript number = value(s) of sample(s) above detection limit: [1]0.52 [2]0.56 [3]0.49 [4]0.14 [5]0.16 [6]0.13

Table 2.10. Mean plant tissue concentrations of select elements from research plots and references compared to literature values.

Element	Test	Normal†	MTL rodents†	MTL poultry†	MTL cattle†	Cap Depth (cm) or Reference‡					
						Reference	8	15	30	46	91
Cobalt	% ADL					100	100	100	100	100	100
	ppm	0.1 – 0.6	25	25	25	0.15 (0.02)	2.01 (0.79)	1.56 (0.40)	1.13 (0.29)	0.81 (0.12)	0.62 (0.09)
Fluorine	% ADL					19	75	33	75	17	8
	ppm	2 - 20	150	150	40	<3.68[1]	15.12 (7.30)	<3.68[2]	4.16 (0.60)	<3.68[3]	<3.68[4]
Nickel*	% ADL					28	83	67	75	75	67
	ppm	0.5 - 7.8	50	250	100	<1.89[5]	17.20 (3.45)	12.96 (4.27)	19.18 (7.11)	12.56 (2.94)	9.57 (4.01)

MTL = Maximum tolerable limit. % ADL = percent of samples above detection limit.
† Data from United States National Research Council (2005) and Kabata-Pendias (2011).
‡Concentration data are means for samples above detection level with standard error in brackets.
‡n = 12 for all treatments except Reference where n = 30.
< = most samples below stated mean detection limit.
* Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.
Superscript number = value(s) of sample(s) above detection limit: [1]5.80, 13.70, 3.70, 11.90 [2]4.50, 5.10, 3.70, 5.40, [3]3.20, 5.20, [4]2.50 [5]13.67, 14.35, 4.78, 17.09, 6.15, 19.82, 15.72.

Table 2.11. Mean grass tissue concentrations of select elements from research plots and references compared to literature values.

Element	Test	Normal †	MTL rodents †	MTL poultry†	MTL cattle †	Cap Depth (cm) or Reference‡					
						Reference	8	15	30	46	91
Cobalt	% ADL					100.00	100.00	100.00	100.00	100.0	100.0
	ppm	0.1 – 0.6	25	25	25	0.17 (0.02)	1.81 (0.72)	1.39 (0.52)	0.88 (0.33)	0.69 (0.11)	0.67 (0.09)
Fluorine	% ADL					22.00	77.89	33.33	66.67	0.0	0.0
	ppm	2 - 20	150	150	40	<3.68[1]	17.01 (9.35)	<3.68[2]	4.64 (0.67)	<3.68	<3.68
Nickel*	% ADL					33.33	77.67	66.67	66.67	66.7	66.7
	ppm	0.5 - 7.8	50	250	100	<1.89[3]	14.04 (2.00)	10.53 (3.17)	18.27 (6.56)	15.68 (3.33)	8.66 (3.74)

MTL = Maximum tolerable limit. % ADL = percent of samples above detection limit.
† Data from United States National Research Council (2005) and Kabata-Pendias (2011).
‡Concentration data are means for samples above detection level with standard error in brackets.
‡n = 9 for all treatments except Reference where n = 21.
< = most samples below stated mean detection limit.
*Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.
Superscript number = value(s) of sample(s) above detection limit: [1]5.80, 13.70, 11.90 [2]4.50, 5.10, 3.70 [3]13.67, 14.35, 4.78, 6.15, 19.82, 15.72.

Table 2.12. Mean *Medicago sativa* tissue concentrations of select elements from research plots and references compared to literature values.

Element	Test	Normal†	MTL rodents†	MTL poultry†	MTL cattle†	Cap Depth (cm) or Reference‡					
						Reference	8	15	30	46	91
Cobalt	% ADL					100	100	100	100	100.00	100
	ppm	0.1 – 0.6	25	25	25	0.09 (0.01)	2.61 (1.00)	2.08 (0.03)	1.88 (0.15)	1.15 (0.14)	0.44 (0.11)
Fluorine	% ADL					11	67	33	100	67.0	33
	ppm	2 - 20	150	150	40	<3.68[1]	9.45 (1.15)	<3.68[2]	3.20 (0.46)	4.20 (1.00)	<3.68[3]
Nickel*	% ADL					11	100	67	100	100	67
	ppm	0.5 - 7.8	50	250	100	<1.89[4]	23.52 (6.37)	17.83 (6.47)	20.99 (8.21)	6.32 (2.16)	11.38 (4.57)

MTL = Maximum tolerable limit. % ADL = percent of samples above detection limit.
† Data from United States National Research Council (2005) and Kabata-Pendias (2011).
‡Concentration data are means for samples above detection level with standard error in brackets.
‡n = 3 for all treatments except Reference where n = 9.
< = most samples below stated mean detection limit.
*Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.
Superscript number = value(s) of sample(s) above detection limit: [1]3.70 [2]5.40 [3]2.50

3. EFFECT OF SOIL CAP DEPTH, VEGETATION AND SEASON ON WATER CONTENT WITH DEPTH IN PHOSPHOGYPSUM STACKS IN FORT SASKATCHEWAN, ALBERTA

3.1 Introduction

Phosphogypsum (PG) is an industrial by product created during phosphorous fertilizer production when phosphate rock and sulphuric acid are mixed to produce phosphoric acid, the main component of phosphorous fertilizer (Rutherford et al. 1994, Wissa 2003). PG is composed mainly of solid gypsum ($CaSO_4 \cdot 2H_2O$), phosphoric acid, trace elements and small amounts of radionuclides (Rutherford et al. 1994, Thorne 1990). At least 80 countries currently have PG stacks, including Canada and the United States (Florida Institute for Phosphate Research 2010). PG is produced at a ratio of 5 tons of phosphogypsum per ton of phosphorus fertilizer (Rutherford et al. 1994, SENES Consultants Limited 1987). The most common disposal method internationally is wet stacking whereby filtered PG is mixed with water and pumped into settling ponds (Wissa 2003). Water is decanted and solid material is placed in stacks. Stacks can cover areas up to 1 million m^2 and reach tens of meters in height (Rutherford et al. 1995).

PG stacks can pose environmental hazards and must be reclaimed according to local regulations to reduce hazards. Stack closure is regulated by local governments and varies with jurisdiction. A cover is placed over the stack to provide a stable substrate for revegetation, limit erosion and water infiltration and minimize exposure pathways between PG and environmental receptors. The cover is generally a revegetated soil layer but can be high density polyethylene liners (Wissa 2003). Alberta regulations for all industries require reclamation to equivalent predisturbance capability (Alberta Environment 2010). Alberta does not have specific regulations for PG stack reclamation and sites must be assessed individually to develop reclamation plans based on stack characteristics, local climate and landscape. A 1 m soil cap is the default scenario expected by Alberta Environment (2008).

Patel et al. (1996) assessed PG stack hydrology under varying compaction levels in Florida, USA. Increased PG compaction decreased permeability and water infiltration into lower layers. Horizontal permeability of PG was three orders of magnitude higher than its vertical permeability. The low vertical PG permeability lead to long water residence times near the surface which would increase water removal through evapotranspiration. Little water percolated through the stacks as < 1% of rainfall was collected in buried lysimeters.

Fuleihan et al. (2005) assessed various cover systems on side slopes of PG stacks. Bermuda grass sod over leached and limestone amended gypsum performed best of their assessed covers. 15 cm of soil, seeded with grass, over leached gypsum performed well but the soil cover was more susceptible to erosion than the sod cover. These cover systems had positive reclamation outcomes, including lower runoff and infiltration rates and higher evapotranspiration rates, than seeded amended leached gypsum and seeded amended unleached gypsum.

A clay soil cap and vegetating PG stacks decreased or prevented rainwater infiltration into stacks (Wissa 2003). Reducing water infiltration into stacks is important as water can accumulate trace elements from PG and move to ground water. Movement of trace elements to ground water is reduced in weathered PG relative to fresh PG. Local weather conditions significantly affect reclamation in medium to low rainfall areas as cavity creation in stacks is of less concern. Placing drains in and beneath stacks and ditches around stacks is recommended to catch and remove excess runoff and infiltrated rainwater for treatment.

Hallin (2008, 2010) studied Agrium Fort Saskatchewan PG stacks 8 years after reclamation with a 15 cm soil cover and seeding. Water percolation through the cap into PG was low for all magnitudes of storms and quantities of infiltrating water. On the same stacks Jackson (2009, 2011) found that for all cap depths water content 10 cm below the soil-PG interface was generally within plant available range. Water moved below 30 cm in the stacks potentially making it unavailable to plants in early development stages. Volume of leachate collected 30 cm below ground surface from distinct rainfall events was independent of cap depth and precipitation volume. Soil water content fluctuated more in shallow than thick caps. Amount of precipitation and antecedent precipitation index did not substantially influence water content below the interface for all cap depths.

The Operating Approval for Agrium Fort Saskatchewan states that research options for reclamation of the phosphogypsum stacks must continue to be investigated (Alberta Environment 2008). A cover system that limits potential environmental hazards of PG and does not require environmentally damaging stripping of topsoil from surrounding areas is desired. Research must be conducted on suitable cover materials, cover depths and potential hazards of the PG stacks at Agrium in Fort Saskatchewan before a final reclamation plan is developed.

This research will be part of a general environmental risk assessment for Agrium Fort Saskatchewan PG stacks. It will assess effects of soil cap depth and vegetation on water, vegetation and soil and facilitate development of a reclamation plan for inactive PG stacks at Agrium in Fort Saskatchewan and future PG stack reclamation, such as the Redwater, Alberta PG stacks. This chapter focuses on effects of soil cap depth on water quantity with depth in different seasons. Limiting water percolation into PG stacks is a goal of reclamation to reduce sink holes, limit transport of trace elements with water and reduce the quantity of water lost to the stack that cannot be used by plants. Knowing water quantity with depth under different cap depths helps elucidate results for other parameters, including root and above ground plant growth.

3.2 Research Objectives

The research objective is to quantify potential environmental risks posed by the Agrium phosphogypsum stacks in Fort Saskatchewan, Alberta. Specific research objectives for this study are as follows.

- To determine if seeded vegetation species type has an effect on water quantity with depth.
- To determine water content with depth under different soil cap depths.
- To determine water content above and below the soil-PG interface with different cap depths to understand its relationship to root accumulation.

3.3 Materials And Methods

3.3.1 Site Description

Fort Saskatchewan is located approximately 30 km northeast of Edmonton, Alberta (53º 43’ N and 113º 13’ W) in an industrial area with over 40 large companies (Alberta's Industrial Heartland Association 2012, City of Fort Saskatchewan 2012) (Figure 3.1). Residential communities occur on the west side and Fort Saskatchewan's population is approximately 19,000 (Figure 3.2).

The research site is in the Central Parklands Natural Subregion of Alberta within the Aspen Parkland, Ecoregion, between the Dry Mixedwood Natural Subregion to the north and west and Foothills Fescue, Foothills Parkland and Northern Fescue Natural Subregions to the south (Natural Regions Committee 2006). Most of the Subregion is cultivated and inhabited with small sections of native aspen and prairie vegetation. Non native species such as *Bromus inermis* L. (smooth brome) and *Agropyron repens* L. (quack grass) are dominant. Average annual precipitation is 440 mm with 75% falling during the growing season. Frost free days average 109 per year with average temperatures of -14 and 17 °C in January and July, respectively (Environment Canada 2012).

Dominant soils are black chernozems with small proportions of dark gray chernozems and significant areas of solonetzic soils (Natural Regions Committee 2006). Elevation averages 620 m above sea level and major landforms are gently rolling hills and hummocky. Lacustrine and fluvial deposits are common and significant eolian deposits can be found. The Belly River formation, consisting of sandstone, siltstone, mudstone and ironstone beds, forms the bedrock in the Fort Saskatchewan area (Hamilton et al. 2005).

Agrium is located in the industrial district in eastern Fort Saskatchewan. It is bordered by the North Saskatchewan River to the north and agricultural land to the south (Figure 2.2). Dow Chemical Inc., a plastic and chemical products manufacturing facility, is located east of Agrium; Sherritt International, a metal metallurgical services and metal refinery company, is located to the south (Alberta's Industrial Heartland 2012). Agrium specializes in nitrogen, phosphorus, potash and micronutrient fertilizer production (Agrium 2012). Phosphorous fertilizer was produced at their Fort Saskatchewan facilities from 1965-1991 and it currently produces nitrogen fertilizers (Svarich 1999).

Phosphogypsum was stacked on Agrium property for 26 years with approximately 5 million tonnes of dihydrate PG in four stacks on a 35 ha area (Svarich 1999). Stack 1, next to the Fort Saskatchewan River, covers 9.3 ha and was built on a high density polyethylene liner (Figure 3.2). The stack has a settling basin of 4.7 ha. PG stacks were decommissioned in 1991 when phosphate fertilizer production at the Fort Saskatchewan facility ceased. Florida phosphate rock is the source rock for all PG on site (Nichol 2012).

In summer 1998 approximately 15 cm of topsoil was placed on the side slopes of PG Stacks 1 and 2 (Nichol 2012, Hallin 2008). A non native seed mix composed mainly of *Bromus inermis* and *Brassica napus* L. (canola) was seeded on the stack slopes (Nichol 2012). The research plots are located in the basin of Stack 1. The stack settling basins are located on top of the stacks, recessed within the stacks by approximately 10 m, and their surfaces are relatively flat. Where PG is bare and exposed a surface crust has formed.

3.3.2 Experimental Design

Eighteen experimental research plots, established in 2006, were located in the basin of Stack 1 with varying soil cap depth and vegetation treatments (Figure 3.3). Plots are 50 m long by 10 m wide and composed of uncapped plots and capped plots with soil cap depths of 8, 15, 30, 46 and 91 cm (Jackson 2009). Three replicates of each depth occur in a randomized complete block design. The soil for the cap depth plots was acquired from the Petrocan plant east of Fort Saskatchewan. The soil was characterized as a sandy loam to loamy sand with good general soil qualities (low sodium, high calcium, low electrical conductivity, low sodium adsorption ratio) (Jackson 2009).

Plots were divided into five 10 x 10 m subplots. Four subplots were seeded with monocultures of *Agrostis stolonifera* L. (redtop), *Festuca ovina* L. (sheep fescue), *Deschampsia caespitosa* (L.) Beauv. (tufted hair grass) and *Agropyron trachycaulum* (Link) Malte ex H.F. Lewis (slender wheat grass). The fifth was seeded with a mix of these grasses and *Trifolium hybridum* L. (alsike clover). Species were selected for origin, germination, establishment, erosion control, palatability, acidity tolerance, water and nutrient requirements (Jackson 2009).

3.3.3 Meteorological Conditions

A Campbell Scientific meteorological station with a CR10X data logger was installed on stack 1 in 2006 in the centre of basin 1 between two research plots (Jackson 2009). The station records air temperature (°C) and relative humidity (%) with a HMP45C Vaisala relative humidity and temperature probe, total rainfall (mm) with a TE525WS Texas Electronics 20 cm tipping bucket rain gauge and a manual rain gauge, wind speed (m/s) and direction with a 05103-10 RM Young wind monitor and total solar radiation (kW) with a Kipp and Zonen silicon pyranometer. Data are recorded hourly and downloaded regularly. No data are available from late November 2010 to late April 2011 due to technical difficulties. Meteorological data for the years of this study were compared to the Fort Saskatchewan climate normals for 1971-2000 (Environment Canada 2012).

3.3.4 Volumetric Water Content

Cores were taken on PG stack plots to assess effects of soil cap depth on water content with depth in fall 2010 (late October) and spring, summer and fall 2011 (mid-May, late July, late September). In fall 2010 one core was taken in each of three replicates of 8, 15, 30, 46, and 91 cm soil caps seeded with *Agropyron trachycaulum*, for a total of 15 cores. In 2011 one core was taken in each of three replicates of all soil caps (0, 8, 15, 30, 46, 91 cm) in *Agropyron trachycaulum* and *Deschampsia caespitosa* plots to determine if species affected water content with depth. In 2011 36 cores were assessed in each season.

Cores were taken with a Giddings soil corer in fall 2010 and a geoprobe in 2011; both are mechanical direct push machines that take soil cores with little compaction. In fall 2010 and 2011, 4.1 cm cores were taken. In spring and summer 2011, 4.7 cm diameter cores were taken. Different core diameters were used in different seasons because PG wetness in spring and summer caused it to become sticky, which inhibited use of the equipment required for smaller cores. Cores were taken in plastic sheathes. In 2010 cores were taken to a minimum of 20 cm below the soil-PG interface. In 2011 cores were taken to a minimum depth of 120 cm.

Cores were taken in random locations on the selected subplots, then placed horizontally on curved plastic measuring boards, plastic sheaths removed and exact depth of capping soil recorded. Cores were sliced in intervals (Figure 3.4). Within the first 5 cm above and below the soil-PG interface cores were sliced in 1 cm intervals; above and below this interface, cores were sliced in 5 cm intervals. Smaller increments were used around the interface as this is the area of highest interest due to material change and because plant roots accumulated there (See Chapter 2). Samples were placed in labeled, sealed plastic bags and stored in coolers until further examination.

Gravimetric water content was determined in each segment of substrate by weighing it before and after oven drying. Samples were placed in aluminum tins and dried at 40 °C to constant weight. Gravimetric water content was calculated as the mass of water per mass of dry soil or PG. Bulk density of each soil and PG sample was determined by dividing mass of each dry sample by volume of the segment. Average bulk densities for soil and PG were calculated and used to convert gravimetric water content in the samples to volumetric water content. Subsequent statistical analyses were conducted on volumetric water content only. Pictures were taken of all cores to use as a reference because wet and dry areas are visible in the pictures.

3.3.5 Statistical Analyses

Data were compiled and graphed in Excel. The statistical software programs SAS and SPSS were used for analyses. Around the interface, two-way analysis of variance (ANOVA) was conducted to determine if vegetation and soil cap depths had significant effects on water content. Tukey's post hoc multiple comparison tests were conducted with Bonferoni correction (Dytham 2011). Where data did not meet assumptions of normality or homogeneity of variance, the nonparametric Scheirer-Ray-Hare extension of the Kruskal-Wallis test was used with a Tukey's post hoc analysis (Elliott and Hynan 2011).

3.4 Results and Discussion

3.4.1 Meteorological Conditions

The mean air temperate from January to October 2010 on the PG stack was 5.6 °C, which was similar to the Canadian Climate Normals (CCNs) of 5.1 °C for this period (Table 3.1). Total precipitation on the stack from January to October 2010 was 306.1 mm, which was substantially lower than the CCN of 413.5 mm for this period. Low 2010 precipitation was likely a factor in the low water content in the substrate (the soil or PG material assessed) in the fall 2010 analyses. The average relative humidity for January to October 2010 was 70%.

The mean air temperature for May to September 2011 recorded by the PG stack meteorological station was 14.6 °C, which was similar to the CCN of 13.9 °C (Table 3.1). Total precipitation from May to September on the stack was

335.3 mm, which is similar to the CCN for this period of 320.4 mm. The average relative humidity for May to September 2011 was 63%.

3.4.2 Effects of Seeded Species on Water Content

Average soil bulk density was 1.47 Mg/m^3 and average PG bulk density was 1.26 Mg/m^3 and these values were used to convert gravimetric water content values to volumetric water content for all further analyses. Water content with depth was similar in *Agropyron trachycaulum* and *Deschampsia caespitosa* plots. Mean soil and PG water content in cores of the same cap depth from the same season differed by 0.05 cm^3/cm^3 or less between species. In spring 2011 mean soil and PG water content were 0.00 cm^3/cm^3 different between the species (Table 3.2). In summer and fall 2011 mean soil and PG water content were 0.01 cm^3/cm^3 different between the species (Tables 3.3, 3.4).

The standard error for water content in soil and PG was similar for both species; differing by 0.00-0.03 in soil and by 0.00-0.07 in PG depending on the season (Tables 3.2, 3.3, 3.4). Water content around the interface (discussed further in 3.4.5) was only significantly different in 1 of 30 analyses (in summer 2011 the 10-20 cm above the interface was significantly higher in *Deschampsia caespitosa* than in *Agropyron trachycaulum*). Therefore water content from plots of both species were pooled for further analyses.

3.4.3 Effects of Cap Depth on Water Content in the Soil Cap and PG

Volumetric water content (cm^3/cm^3) was higher in soil caps in 8, 15, 30 and 46 cm caps in spring and summer than in 91 cm caps (Figures 3.5, 3.6, 3.7, 3.8, Table 3.5). Water is often a limiting factor for plant growth, thus higher soil water in 8-46 cm caps than in 91 cm caps, could improve plant yield. However, no significant differences were found in 2011 in seeded plant biomass, cover, or health with caps ≥ 15 cm (Chapter 2). Soil water content was similar for all caps in fall, likely due to slightly lower precipitation than in spring and summer. Few roots were found in PG (Chapter 2); therefore water in the soil is more accessible to plants than water in the PG, which likely moves to lower depths in the profile.

Mean water content overall in all PG in cores was similar for 15-46 cm caps (fall 2010 was 0.20-0.23 cm^3/cm^3, spring 2011 0.30-0.32 cm^3/cm^3, summer 2011 0.34-0.35 cm^3/cm^3, fall 2011 0.27-0.32 cm^3/cm^3) (Table 3.5). Mean water content was generally higher in uncapped PG relative to other caps (spring 2011 0.35 cm^3/ cm^3, summer 2011 0.40 cm^3/ cm^3, fall 2011 0.34 cm^3/ cm^3). This is likely due to lack of vegetation in uncapped plots which would use water in the soil cap before it reached the PG (Chapter 2). Water content was frequently higher in PG in 8 cm caps than 15-46 cm caps; again this may be due to less vegetation to take up water (fall 2010 was 0.27 cm^3/ cm^3, spring 2011 0.33 cm^3/ cm^3, summer 2011 0.40 cm^3/ cm^3, fall 2011 0.29 cm^3/ cm^3). Mean water content in PG was slightly lower in 91 cm caps than others in spring and summer 2011 (fall 2010 was 0.21 cm^3/ cm^3, spring, summer and fall 2011 0.27 cm^3/ cm^3). This is likely because cores were only taken to a minimum depth of 120 cm and therefore in 91 cm caps only 30 cm of PG was assessed. Because water content increases in spring and summer 2011 typically occurred 15-60 cm below the interface many were likely below the assessment area in 91 cm caps.

Mean water content was substantially lower in soil than PG for all seasons and all cap depths (Table 3.5). For example in spring 2011 mean soil water content for all caps was 0.20 cm^3/cm^3 whereas mean PG water content was 0.31 cm^3/cm^3. Water content was more variable in PG than in soil in all seasons and caps. In all seasons assessed average standard error was higher in PG than in soil, on average by twice as much. There were typically bulges in water content throughout the PG at variable depths. In spring and summer 2011 these bulges commonly occurred from 15-60 cm below the interface.

Similar to this study Fuleihan et al. (2005) found stacks with a soil cap had lower water infiltration into PG compared to uncapped plots. Jackson found PG water contents 10 cm below the soil-PG interface were similar and within plant available range for cap depths 15-91 cm. Similar to this study the 8 cm cap had substantially different water contents than the other caps; it was lower relative to other cap depths while this study found that it was higher. Jackson found PG water content was slightly lower in the 91 cm cap in summer (similar to this study), however winter water content was higher than other cap depths.

Wissa (2003) indicated that a clay soil cap decreased or prevented infiltration of rainwater into stacks. The soil used in this study was a sandy loam to loamy sand and therefore had higher permeability than clay and it only slightly decreased water infiltration into the stacks. Potentially a finer textured soil would decrease water content in the PG.

3.4.4 General Trends in Water Content with Depth

Water content with depth in all caps in all seasons was lower in soil than PG; it began to increase approximately 5 cm above the interface and increased substantially shortly after reaching the soil-PG interface (Figures 3.5, 3.6, 3.7 and 3.8). This trend was more obvious in some seasons where the increase in water content below the interface was more dramatic. The trend is very obvious in fall 2010, where water content increased 0.14-0.20 cm^3/cm^3 within 10 cm below the interface, then decreased again but generally remained higher than in the soil layer (Figure 3.5). In spring and summer 2011 the same trend occurred but was less obvious (Figures 3.6 and 3.7). Water content increased 10 cm below the interface but the increase was smaller (0.03-0.16 cm^3/cm^3 rise) and sections deeper within PG were often higher in water. In fall 2011 the trend was again obvious, with substantial increases in water content directly below the interface (0.16-0.19 cm^3/cm^3 increases); again sections deeper in the profile often had higher water contents than the area directly below the interface (Figure 3.8). The trend is likely less obvious in spring and summer than fall due to generally higher water contents in cores (from spring run-off and higher precipitation).

Water retention characteristics of PG and soil that Jackson (2009) found affirm these findings. She found water retention in PG was much higher than in soil at low suctions, but was slightly lower at high suctions. This indicates PG would generally have higher water retention than soil and therefore contain higher water contents on average, with the exception of dry periods. Jackson found that soil used for the caps was a sandy loam to loamy sand with a low water holding capacity (approximately 0.10 g/g). The results of this study agree with those of Patel et al. (1996) who found that water in PG had a high residence time due to low vertical hydraulic conductivity.

3.4.5 Interface Water Content and its Relationship to Plant Roots

Plant roots accumulated in the interface area from 8, 15, 30 and 46 cm caps (Chapter 2). Plant roots did not accumulate around the interface in 91 cm caps because they did not reach that deep. Plant roots may have accumulated directly above the interface due to the high water content. In all caps and seasons water content was higher directly above the interface (0-10 cm depths above the interface) than higher (10-20 cm depths above the interface).

A close examination of the interface area indicates that 0-10 and 10-20 cm above the interface, water content was significantly higher in cores from 30 and 46 cm caps than 91 cm caps in spring and higher in summer (significantly higher for 30 cm caps and not 46 cm caps) (Figure 3.10). However, in fall 2010 and 2011 the trend was reversed and water content was significantly higher above the interface in 91 cm caps than 46 and 30 cm caps. Roots reaching the interface in 30 and 46 cm caps, but not 91 cm caps, and water content above the interface being higher in 30 and 46 cm than 91 cm caps in spring and summer, indicates root accumulation around the interface was likely not reducing water content in that zone substantially in spring and summer. However, roots may have been reducing water content just above the interface in fall, since water content was higher in that area in 91 cm caps than 30 and 46 cm caps in fall 2010 and 2011.

In the area below the interface 30 cm caps generally had higher water contents than 46 and 91 cm caps, however, there were no clear trends in water content for caps or seasons (Figure 3.9). The 30 cm cap had significantly higher water content in spring 2011 0-10 cm below the interface area and in summer 2011 10-20 cm below the interface. This may be due to the high variability of water content in PG because all cap depths contained large increases and decreases in water content within PG at varying depths.

3.4.6 Effects of Cap Depth on Deep Profile Water Content

Average volumetric water content (for all cap depths combined) 100-120 cm below the surface was 0.32 cm^3/cm^3 in spring, 0.37.2 cm^3/cm^3 in summer and 0.33 cm^3/cm^3 in fall 2011 (Figures 3.6, 3.7, 3.8, Table 3.6). The higher value in summer was likely due to snow melt waters infiltrating in spring, which took time to reach this deeper zone. Water at these depths will not be taken up by roots and will therefore continue to percolate into the stack. Precipitation was higher in summer 2011 than the Canadian climate normals, and these values therefore represent what occurs in a high precipitation year. High water volumes entering the PG could be a concern because trace elements can then become mobile and move to ground water.

The 91 cm caps in all seasons and 30 cm caps in spring and summer had lower deep profile water contents than other caps, which had similar deep profile water contents in all seasons. This may be because with deeper caps ($\geq$ 30 cm) there is more soil than PG above the deep profile zone (100-120 cm below surface) and because soil has a lower water holding capacity than PG water moved quickly through the soil to even lower depths than assessed here (> 120 cm). Shallow caps (< 30 cm) may have higher deep water contents because PG holds water there due to its high water holding capacity. The high variability of water content in PG may be why 46 cm cores do not exhibit this trend.

3.5 Reclamation Applications

A soil cap depth ≤ 46 cm is recommended for reclamation of PG stacks to obtain elevated soil water in the root zone and potentially decrease water moving deeper in the stack. Soil in the 91 cm cap is significantly drier than in 8-46 cm caps. Water is often the limiting factor for plant growth in the aspen parkland region, therefore high water content could aid in optimum plant growth.

Water content is higher at the soil-PG interface than other profile locations and roots may be accumulating there to access the water. The location of the interface in ≤ 46 cm caps is within the root zone and therefore plants are able to use that water. In 91 cm caps the soil-PG interface is below the root zone and plants are unable to use water accumulating there; thus water may move to locations deeper in the profile before it can be used. Increased water moving to deeper locations is undesirable because trace elements can potentially become mobile with high water content and move to ground water.

3.5 Conclusions

- Seeded plant species did not affect water content with depth, therefore from a water balance perspective, *Deschampsia caespitosa* and *Agropyron trachycaulum* are recommended equally for PG stack reclamation.
- Soil water content was lower in 91 cm than 8-46 cm caps, therefore caps ≤ 46 cm are recommended for reclamation to maintain high soil water content for optimum plant growth.
- PG had higher and more variable water contents than soil under all caps.
- Water content in PG was similar for 15-46 cm caps, comparatively higher for uncapped and 8 cm caps and slightly lower for 91 cm caps. It was likely higher for uncapped and 8 cm caps due to little vegetation growth and slightly

lower for 91 cm caps potentially because sampling was not deep enough below the soil-PG interface or there was more soil above to store water which reduced infiltration to the PG.

- Root removal of water in spring and summer was not a main factor in water content just above the soil-PG interface because water content in that area was higher in 30 and 46 cm caps than 91 cm caps.
- Substantial quantities of water were found below the root zone, indicating it is lost to plants and will end up deeper in the stack. Further research should be conducted on water content deeper in the stacks and stack drainage.
- Water content was higher near the interface than elsewhere in the profile which could be a cause of root accumulations.

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Figure 3.1 Map of location of Fort Saskatchewan in Alberta, Canada (Adapted from GreenField Development Corp. 2009).

Figure 3.2 Aerial view of Agrium facilities and phosphogypsum stacks in Fort Saskatchewan, Alberta (Adapted from Google Inc. 2012).

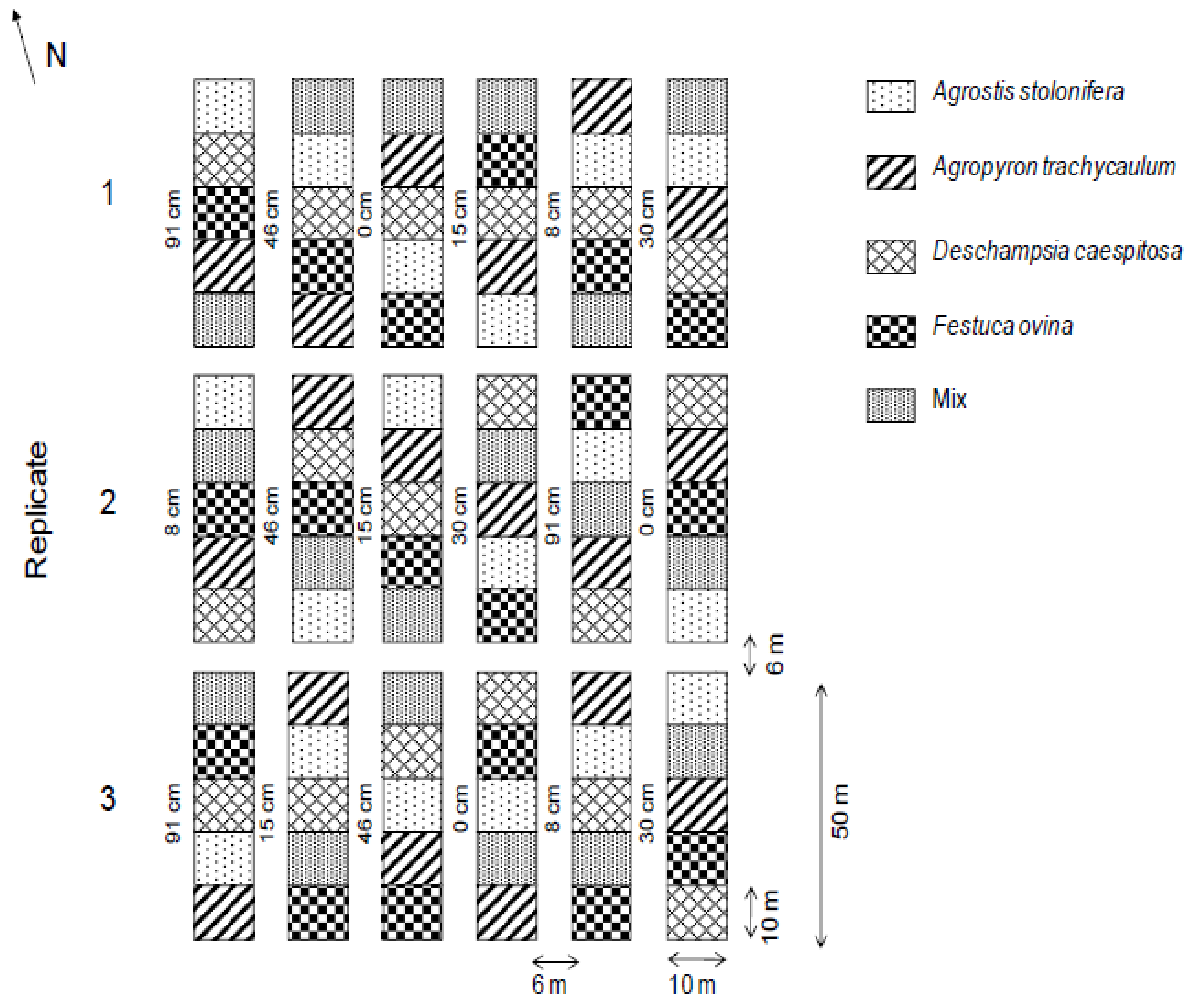

Figure 3.3 Experimental research plots at Agrium, Fort Saskatchewan, Alberta (Jackson 2009).

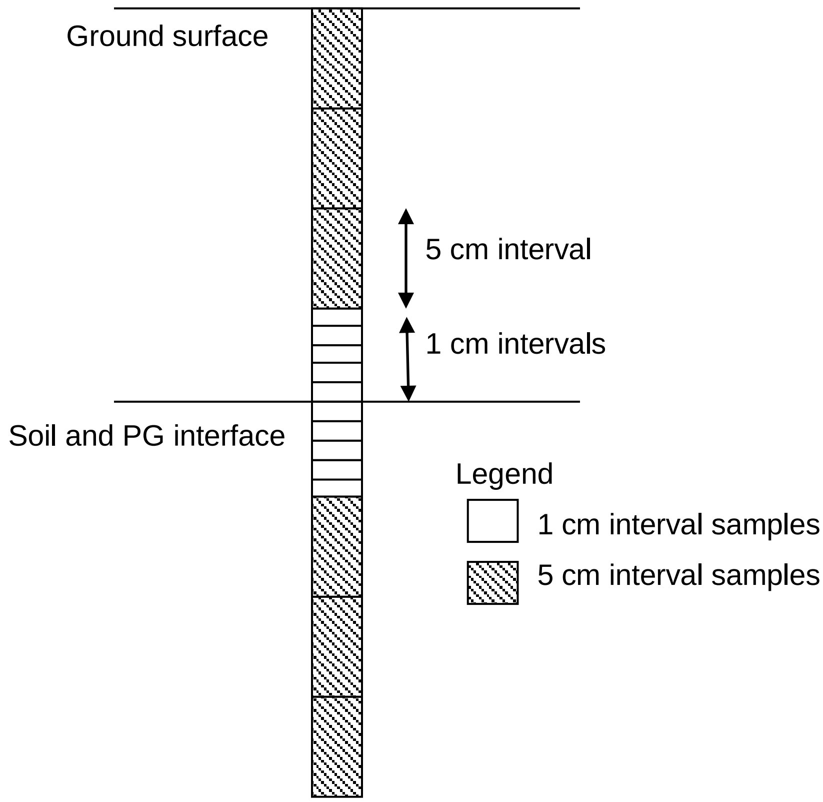

Figure 3.4 Soil and PG sample intervals with depth.

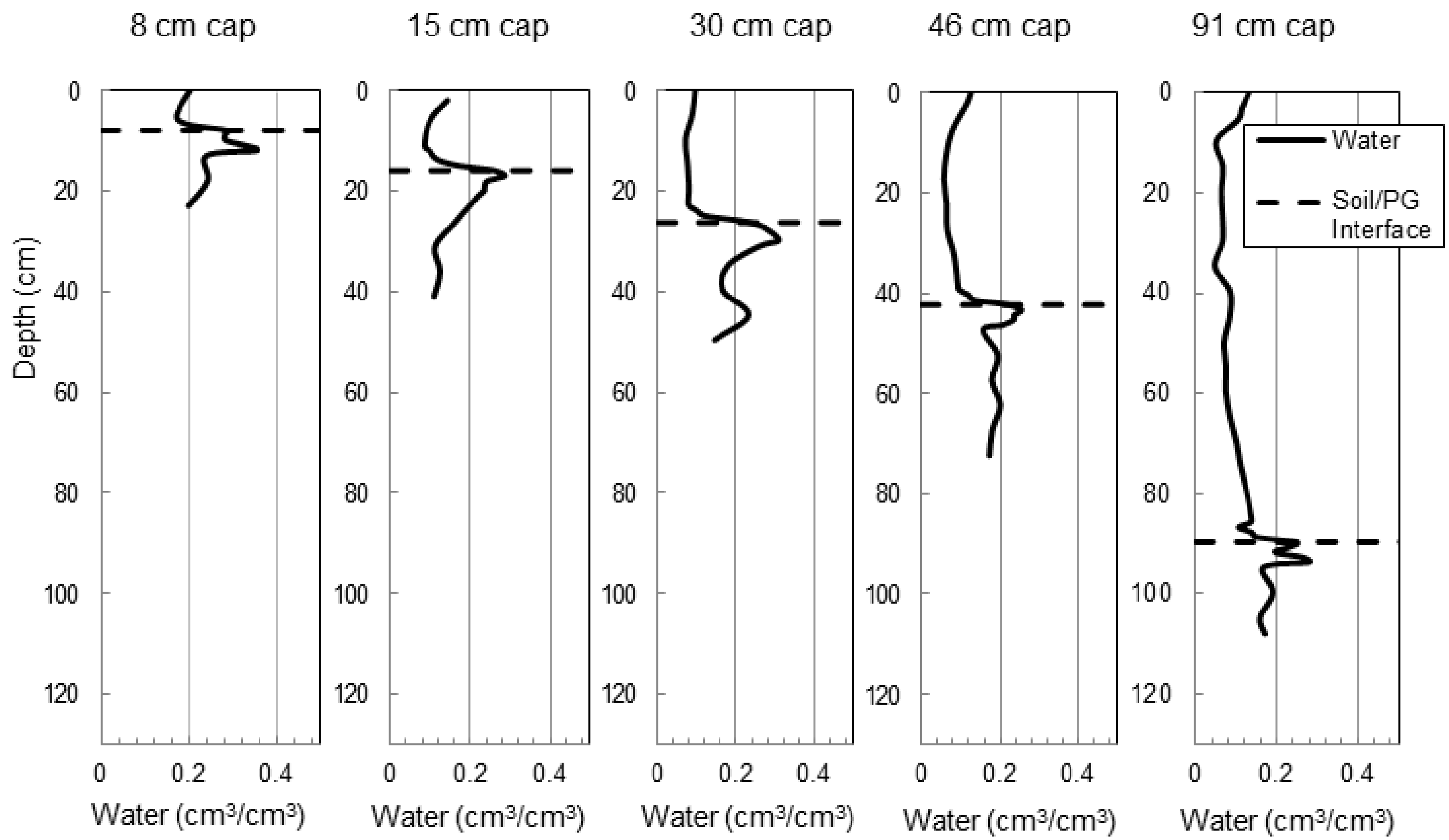

Figure 3.5 Fall 2010 water content with depth below surface as a function of soil cap depth at Agrium in Fort Saskatchewan, Alberta.

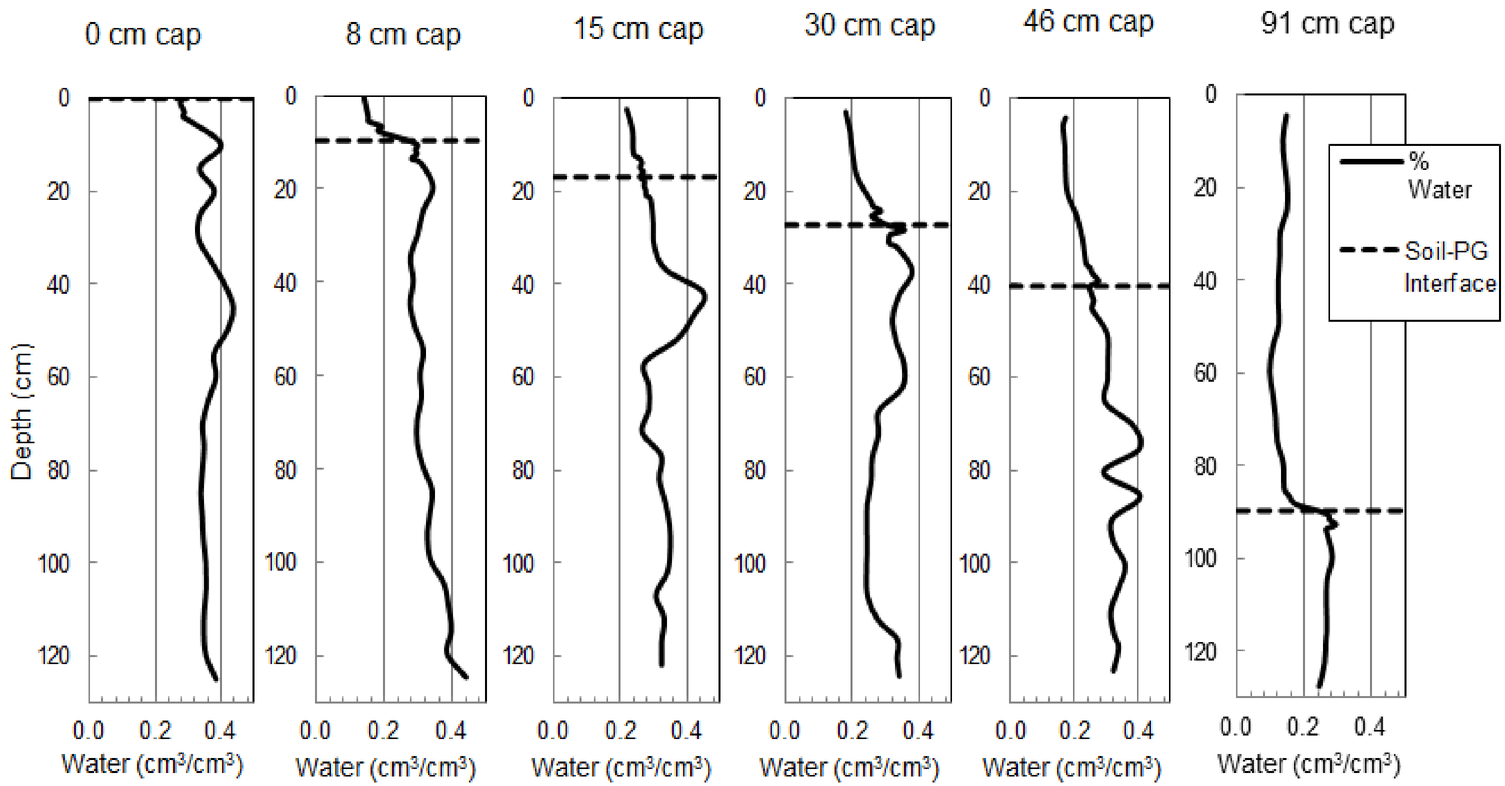

Figure 3.6 Spring 2011 water content with depth below surface as a function of soil cap depth at Agrium in Fort Saskatchewan, Alberta.

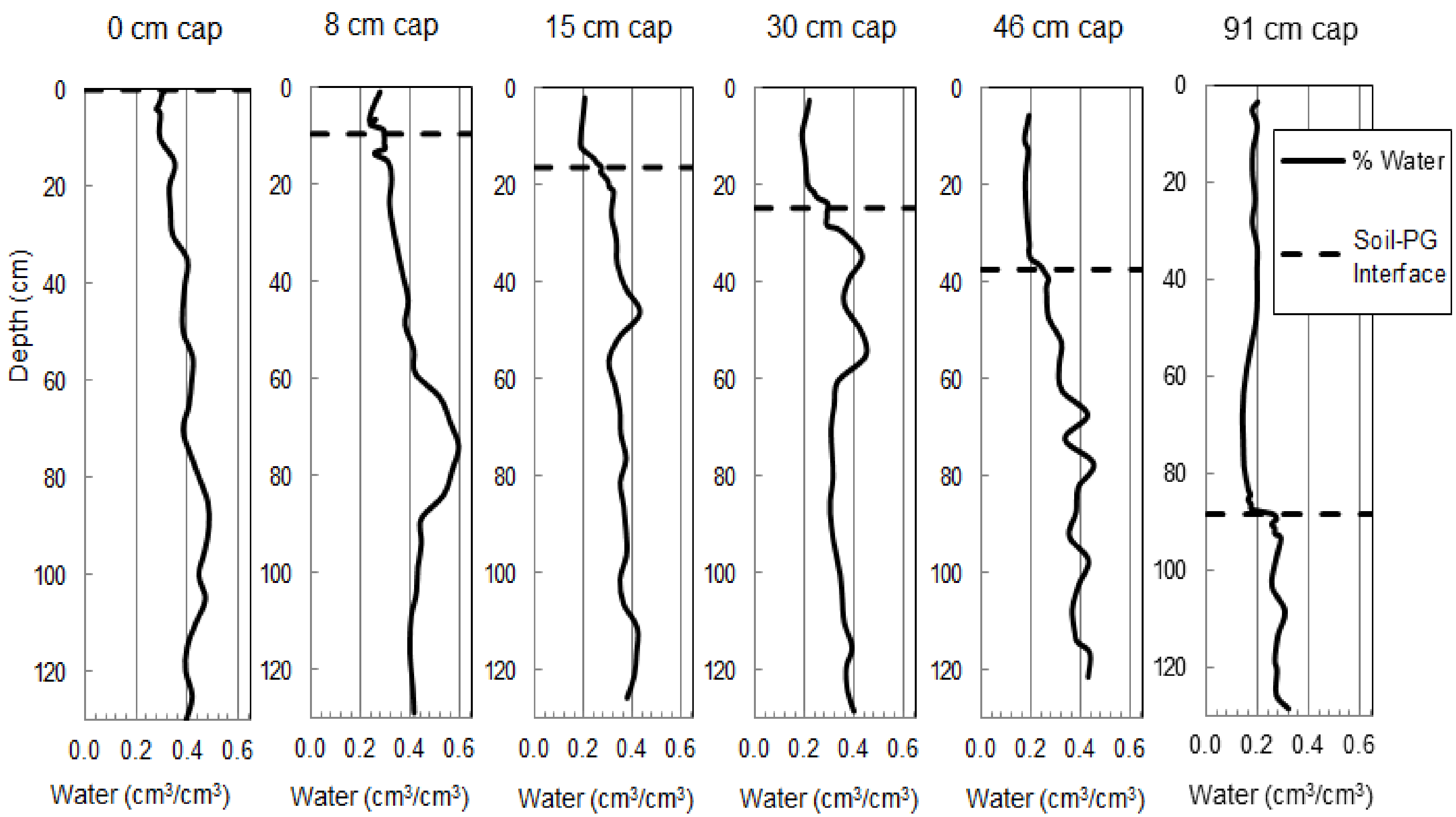

Figure 3.7 Summer 2011 water content with depth below surface as a function of soil cap depth at Agrium in Fort Saskatchewan, Alberta.

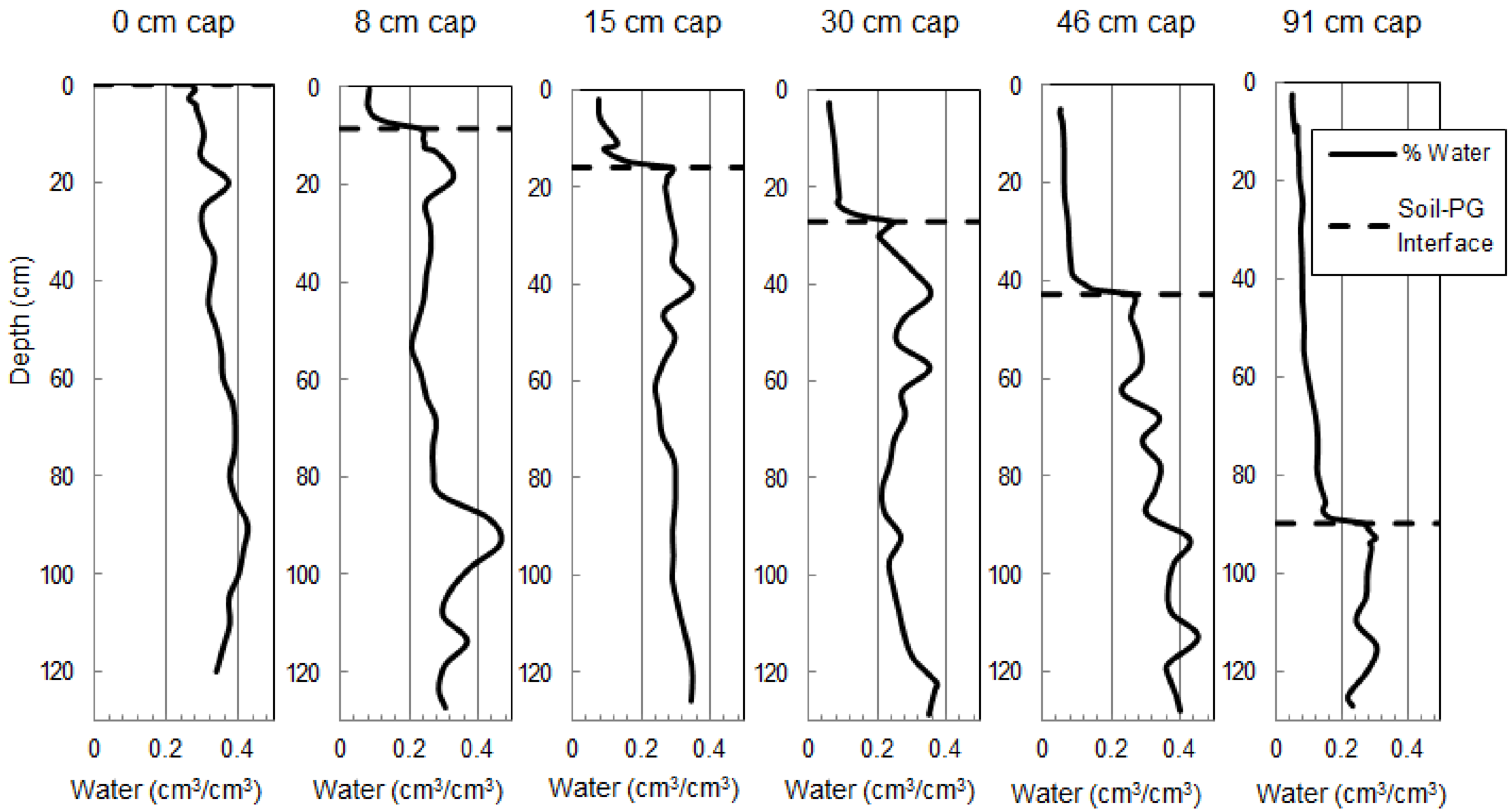

Figure 3.8 Fall 2011 water content with depth below surface as a function of soil cap depth at Agrium in Fort Saskatchewan, Alberta.

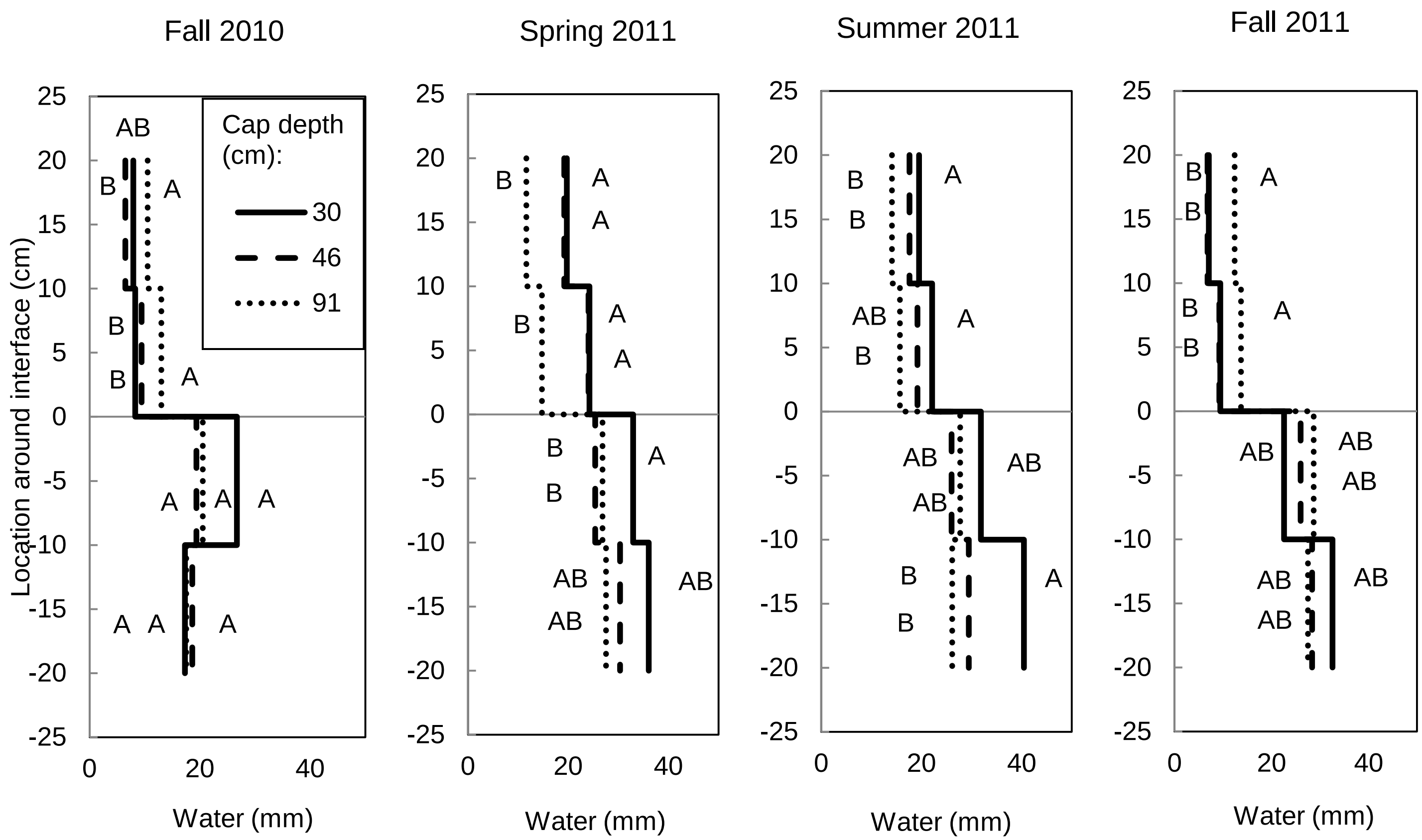

Figure 3.9 Water content in 10 cm intervals with depth around the soil-PG interface on caps in different seasons in 2010 and 2011.

Table 3.1. Meteorological data for 2010 and 2011 study period in Fort Saskatchewan, Alberta.

Year	Month	Mean Air Temperature (°C)		Precipitation (mm)	
		PG stack	CCN	PG stack	CCN
2010	January	-12.6	-13.5	0.8	23.4
	February	-9.4	-10.2	8.9	13.5
	March	-0.6	-3.8	2.5	14.4
	April	6.1	4.8	38.6	24.6
	May	9.1	11.2	82.3	43.8
	June	15.4	14.9	62.2	88.8
	July	17.0	16.7	100.1	83.1
	August	15.6	15.8	9.4	61.7
	September	9.3	10.7	1.3	43.0
	October	5.9	4.7	0.0	17.2
	Average	5.6	5.1		
	Total			306.1	413.50
2011	May	12.6	11.2	17.3	43.8
	June	14.8	14.9	125.0	88.8
	July	16.4	16.7	159.0	83.1
	August	16.3	15.8	24.4	61.7
	September	13.1	10.7	9.7	43.0
	Average	14.6	13.9		
	Total			335.3	320.4

CCN = Canadian climate normal for 1971 – 2000
CCN data obtained from Environment Canada for the Oliver AGDM Station (2012).

Table 3.2. Spring 2011 volumetric water content in soil and PG as a function of soil cap depth and seeded species in research plots.

Cap Depth (cm)	Species or Difference Between Species	Soil Water content (cm^3/cm^3)	PG Water content (cm^3/cm^3)
0	*Deschampsia caespitosa*		0.35 (0.08)
8	*Deschampsia caespitosa*	0.17 (0.05)	0.33 (0.07)
15	*Deschampsia caespitosa*	0.25 (0.02)	0.32 (0.11)
30	*Deschampsia caespitosa*	0.21 (0.03)	0.29 (0.08)
46	*Deschampsia caespitosa*	0.21 (0.05)	0.30 (0.07)
91	*Deschampsia caespitosa*	0.14 (0.03)	0.28 0.03)
Average	*Deschampsia caespitosa*	0.20 (0.03)	0.31 (0.07)
0	*Agropyron trachycaulum*		0.34 (0.07)
8	*Agropyron trachycaulum*	0.17 (0.05)	0.32 (0.09)
15	*Agropyron trachycaulum*	0.24 (0.04)	0.32 (0.11)
30	*Agropyron trachycaulum*	0.26 0.06)	0.32 (0.06)
46	*Agropyron trachycaulum*	0.21 (0.04)	0.32 (0.09)
91	*Agropyron trachycaulum*	0.12 (0.04)	0.26 (0.03)
Average	*Agropyron trachycaulum*	0.20 (0.04)	0.31 0.07)
0	Difference		0.01 (0.01)
8	Difference	0.00 (0.00)	0.01 (0.02)
15	Difference	0.01 (0.02)	0.00 (0.00)
30	Difference	0.05 (0.03)	0.03 (0.02)
46	Difference	0.00 (0.01)	0.02 (0.02)
91	Difference	0.02 (0.01)	0.02 (0.00)
Average	Difference	0.00 (0.01)	0.00 (0.00)

Data are means with standard errors in brackets.
Difference = Absolute difference between *Agropyron trachycaulum* and *Deschampsia caespitosa.*

Table 3.3. Summer 2011 volumetric water content in soil and PG as a function of soil cap depth and seeded species in research plots.

Cap Depth (cm)	Species or Difference Between Species	Soil Water content (cm^3/cm^3)	PG Water content (cm^3/cm^3)
0	*Deschampsia caespitosa*		0.41 (0.10)
8	*Deschampsia caespitosa*	0.21 (0.03)	0.38 (0.09)
15	*Deschampsia caespitosa*	0.23 (0.02)	0.33 (0.09)
30	*Deschampsia caespitosa*	0.24 (0.06)	0.34 (0.09)
46	*Deschampsia caespitosa*	0.18 (0.03)	0.35 (0.10)
91	*Deschampsia caespitosa*	0.18 (0.04)	0.26 (0.02)
Average	*Deschampsia caespitosa*	0.21 (0.04)	0.34 (0.08)
0	*Agropyron trachycaulum*		0.36 (0.08)
8	*Agropyron trachycaulum*	0.31 (0.04)	0.43 (0.16)
15	*Agropyron trachycaulum*	0.20 (0.04)	0.36 (0.09)
30	*Agropyron trachycaulum*	0.22 (0.04)	0.35 (0.07)
46	*Agropyron trachycaulum*	0.20 (0.03)	0.33 (0.09)
91	*Agropyron trachycaulum*	0.17 (0.04)	0.29 (0.05)
Average	*Agropyron trachycaulum*	0.22 (0.04)	0.35 (0.09)
0	Difference		0.05 (0.02)
8	Difference	0.10 (0.01)	0.05 (0.07)
15	Difference	0.03 (0.02)	0.03 (0.00)
30	Difference	0.02 (0.02)	0.01 (0.02)
46	Difference	0.02 (0.00)	0.02 (0.01)
91	Difference	0.01 (0.00)	0.03 (0.03)
Average	Difference	0.01 (0.00)	0.01 (0.00)

Data are means with standard errors in brackets.
Difference = Absolute difference between *Agropyron trachycaulum* and *Deschampsia caespitosa.*

Table 3.4. Fall 2011 volumetric water content in soil and PG as a function of soil cap depth and seeded species in research plots.

Cap Depth (cm)	Species or Difference Between Species	Soil	PG
		Water content (cm^3/cm^3)	Water content (cm^3/cm^3)
0	*Agropyron trachycaulum*		0.36 (0.09)
8	*Agropyron trachycaulum*	0.12 (0.05)	0.30 (0.11)
15	*Agropyron trachycaulum*	0.10 (0.04)	0.29 (0.07)
30	*Agropyron trachycaulum*	0.09 (0.03)	0.26 (0.07)
46	*Agropyron trachycaulum*	0.09 (0.03)	0.32 (0.12)
91	*Agropyron trachycaulum*	0.10 (0.04)	0.28 (0.04)
Average	*Agropyron trachycaulum*	0.10 (0.04)	0.30 (0.08)
0	*Deschampsia caespitosa*		0.32 (0.07)
8	*Deschampsia caespitosa*	0.08 (0.02)	0.27 (0.8)
15	*Deschampsia caespitosa*	0.12 (0.06)	0.30 (0.06)
30	*Deschampsia caespitosa*	0.09 (0.04)	0.27 (0.10)
46	*Deschampsia caespitosa*	0.08 (0.03)	0.33 (0.08)
91	*Deschampsia caespitosa*	0.10 (0.04)	0.26 (0.05)
Average	*Deschampsia caespitosa*	0.09 (0.04)	0.29 (0.07)
0	Difference		0.04 (0.02)
8	Difference	0.04 (0.03)	0.03 (0.03)
15	Difference	0.02 (0.02)	0.01 (0.01)
30	Difference	0.00 (0.01)	0.01 (0.03)
46	Difference	0.01 (0.00)	0.01 (0.04)
91	Difference	0.00 (0.00)	0.02 (0.01)
Average	Difference	0.01 (0.00)	0.01 (0.01)

Data are means with standard errors in brackets.
Difference = Absolute difference between *Agropyron trachycaulum* and *Deschampsia caespitosa.*

Table 3.5. Volumetric water content in soil and PG as a function of soil cap depth and season in research plots at Agrium Fort Saskatchewan, Alberta.

Season	Year	Cap Depth (cm)	Soil Water content (cm^3/cm^3)	PG Water content (cm^3/cm^3)
Fall	2010	8	0.19 (0.02)	0.27 (0.09)
		15	0.13 (0.04)	0.20 (0.08)
		30	0.09 (0.02)	0.23 (0.09)
		46	0.09 (0.03)	0.20 (0.06)
		91	0.10 (0.04)	0.21 (0.06)
		Average	0.12 (0.03)	0.22 (0.08)
Spring	2011	0		0.35 (0.08)
		8	0.17 (0.05)	0.33 (0.08)
		15	0.25 (0.03)	0.32 (0.11)
		30	0.24 (0.05)	0.30 (0.07)
		46	0.21 (0.05)	0.31 (0.08)
		91	0.13 (0.03)	0.27 (0.03)
		Average	0.20 (0.04)	0.31 (0.07)
Summer	2011	0		0.38 (0.09)
		8	0.26 (0.04)	0.40 (0.13)
		15	0.21 (0.03)	0.35 (0.09)
		30	0.23 (0.05)	0.34 (0.08)
		46	0.19 (0.03)	0.34 (0.10)
		91	0.18 (0.04)	0.27 (0.04)
		Average	0.22 (0.04)	0.35 (0.09)
Fall	2011	0		0.34 (0.08)
		8	0.10 (0.03)	0.29 (0.09)
		15	0.11 (0.05)	0.29 (0.07)
		30	0.09 (0.03)	0.27 (0.09)
		46	0.08 (0.03)	0.32 (0.10)
		91	0.10 (0.04)	0.27 (0.05)
		Average	0.10 (0.04)	0.30 (0.08)

Data are means with standard errors in brackets.
n = 3 for 2010 data and n = 6 for 2011 data.
2010 data is *for Agropyron trachycaulum* plots, 2011 data is *Deschampsia caespitosa* and *Agropyron trachycaulum* data combined.

Table 3.6. Deep profile water content (100-120 cm below the surface) as a function of soil cap depth and season.

Season	Soil Cap Depth (cm)	Water Content (cm^3/cm^3)
Spring	0	0.35 (0.00)
	8	0.37 (0.03)
	15	0.33 (0.02)
	30	0.28 (0.04)
	46	0.33 (0.02)
	91	0.27 (0.01)
	Average	0.32 (0.04)
Summer	0	0.44 (0.03)
	8	0.41 (0.02)
	15	0.36 (0.01)
	30	0.36 (0.02)
	46	0.39 (0.03)
	91	0.28 (0.02)
	Average	0.37 (0.06)
Fall	0	0.38 (0.02)
	8	0.34 (0.04)
	15	0.31 (0.02)
	30	0.26 (0.03)
	46	0.39 (0.04)
	91	0.27 (0.03)
	Average	0.33 (0.05)

Data are means with standard errors in brackets.
n = 6.
Data an average of *Deschampsia caespitosa* and *Agropyron trachycaulum* data.

4. SNOW METAL CONTENT ON AGRIUM PROPERTY AND THE NEIGHBOURING METAL REFINERY IN FORT SASKATCHEWAN, ALBERTA

4.1 Introduction

Cumulative effects of heavy metal deposition from industrial sources onto the earth's surface can negatively affect biota; elevated concentrations of heavy metals are toxic to most vegetation (Anderson et al. 1973, Babula et al. 2008). Therefore understanding metal deposition sources and control measures is of environmental significance. Snow is an excellent matrix to study deposition of elements from the atmosphere or nearby locations (Bonham-Carter et al. 2006, Elik 2002). As snow falls it absorbs elements in the atmosphere and contains them above the earth's surface as long as temperatures are low. Particles from nearby surface locations, such as tailings ponds, could be blown onto snow and contained until snow melt, provided the snow does not drift. Snow is present for a known time period, thus assessing concentration of elements in a known volume of snow allows determination of their depositional load at a specific location per unit of time. Increasing knowledge of causes and effects of atmospheric metal deposition has led to increased regulations and control measures.

The Sudbury, Ontario area is a good example of negative environmental consequences of large scale metal mining and smelting (Nkongolo et al. 2008). Nickel and copper have been mined and smelted in the area for over 80 years. Sulphur dioxide emissions and metal particulate deposition from smelters caused soil acidification, persistent erosion, lake acidification, fish death and vegetation denudation for over 260 km^2 (Hutchinson and Whitby 1977, Negusanti 1995). Metal concentration in soils and vegetation decreased exponentially with distance from metal smelters (Hutchinson and Whitby 1977). Sulphur dioxide and metal emissions have decreased substantially in the last 30 years due to control measures and although soil metals are significantly lower than in the 1980s, they are persistent and it will likely take hundreds of years to reach background levels (Nkongolo et al. 2008, Hutchinson and Symington 1997.

In Rouyn-Noranda, Quebec, peat moss, snow, soil, lake water and lake sediments had exponentially increased copper, lead and zinc near a copper smelter relative to background, indicating the smelter was the point source

(Bonham-Carter et al. 2006, Telmer et al. 2004, and Zdanowicz et al. 2006). Smelter metals reached background concentrations 65 km from the smelter; within 5 km they were up to 1000 times higher. Around 60 year old nickel plants in Russia, heavy metals and other elements in snow were 10,000-100,000 times higher than background and contained the fingerprints of ores used in the plants (Gregurek et al. 1998). Nickel in snow near the plant was 1,110-3,830 µg/L. The surrounding ecosystem was severely impacted with no vegetation for hundreds of km^2. Snow metal concentrations around industrial iron and steel mills in Poland decreased exponentially with distance (Zajac and Grodzinska (1982). Wet and dry deposition occurred, with deposition from industrial dust blown onto snow and emissions caught in falling snow. Concentrations were affected by sampling time due to snowfall, temperature, wind direction and velocity. Metal concentrations were higher with long durations and low snow cover.

In northern Alberta bitumen upgraders and oil sands developments were point sources of several elements including lead, mercury, nickel, chromium and copper, which decreased exponentially with distance from those sources (Kelly et al. 2010). In Poland significant quantities of dust with chemical compositions similar to that of open tailings ponds from zinc-lead smelting refineries, but different from the environmental background, were found on pine needles in the surrounding area (Teper 2009). Highest concentrations were found closer to the tailings ponds, indicating material was being deposited in the surrounding areas.

Ceburnis et al. (2002) found the pattern of metal concentration in snow and moss around two electric thermal power stations and a cement factory in Lithuania was similar to a bull's eye, with exponentially higher concentrations near the center. Wind direction affected distribution of emitted elements and concentrations were slightly higher in the direction of the prevailing wind. At distances 20 km from source metals concentrations were similar to background values. They developed a semi-empirical model to describe depositional pattern of metals around point sources of pollution and to estimate amount of metals emitted from them. Values for parameters in their models changed based on specific metal (nickel, chromium, vanadium) and stations. General trends were similar for all metals and stations or factories assessed, however average concentrations and the exact curve shapes differed. They stressed that to use the model to characterize the metal deposition curve around specific stations many samples were needed close to the point source compared further away because major changes occur close to the source.

Agrium in Fort Saskatchewan is located in a highly industrial area adjacent a metal refinery to the south. Based on literature and sampling on the stacks, metal concentrations on the stacks are higher than expected for the PG composition. PG is derived from Florida source rock which typically has lower concentrations of cobalt, copper and nickel (2, 8, 2 mg kg^{-1}, respectively) than PG from other source rocks (May and Sweeney 1984, Rutherford et al. 1994). In samples from PG stacks cobalt, copper and nickel were often substantially higher in the surface than deeper in the profile, indicating metals may be accumulating on stack surfaces (Unpublished data). Metal refinery stack emissions and material blown from the refinery tailings ponds are possible sources of metals on Agrium property. Determining the point source of metals on Agrium property is important in developing control measures to reduce metal contamination and in facilitating development of a reclamation plan for Agrium PG stacks. Sources of metal deposition can be determined by assessing snow metal concentrations and determining if they increase with proximity to the potential source.

4.2 Research Objectives

The research objectives are to determine if cobalt, copper, iron and nickel on Agrium property in Fort Saskatchewan, Alberta originate from outside sources and are being deposited through air, and specifically if they originate from the neighbouring metal refinery.

4.3 Materials and Methods

4.3.1 Research Site Description

Fort Saskatchewan is located approximately 30 km northeast of Edmonton, Alberta (53º 43’ N and 113º 13’ W) in an industrial area with over 40 large companies (Alberta’s Industrial Heartland Association 2012, City of Fort Saskatchewan 2012) (Figure 4.1). Residential communities occur on the west side and Fort Saskatchewan’s population is approximately 19,000 (Figure 4.2).

The research site is in the Central Parklands Natural Subregion of Alberta within the Aspen Parkland, Ecoregion, between the Dry Mixedwood Natural

Subregion to the north and west and Foothills Fescue, Foothills Parkland and Northern Fescue Natural Subregions to the south (Natural Regions Committee 2006). Most of the Subregion is cultivated and inhabited with small sections of native aspen and prairie vegetation. Elevation averages 620 m above sea level and the land form is hummocky with gently rolling hills.

Average annual precipitation is 440 mm including approximately 104.6 cm of snowfall per year, which generally falls from November to March (City of Fort Saskatchewan 2012, Environment Canada 2012, Natural Regions Committee 2006). Frost free days average 109 per year with average temperatures of -14 and 17 °C in January and July, respectively (Environment Canada 2012). The prevailing wind direction varies by season: in spring from the northwest; in summer from the northwest and west; in the fall from the southwest; and in the winter from the southwest (McCullum et al. 2003).

Agrium is located in the industrial district in eastern Fort Saskatchewan. It is bordered by the North Saskatchewan River to the north and agricultural land to the south (Figure 4.2). Dow Chemical Inc., a plastic and chemical products manufacturing facility, is located east of Agrium; Sherritt International, a metallurgical services and metal refinery company, is located to the south (Alberta's Industrial Heartland 2012). Agrium specializes in nitrogen, phosphorus, potash and micronutrient fertilizer production (Agrium 2012). Phosphorous fertilizer was produced at their Fort Saskatchewan facilities from 1965-1991 and it currently produces nitrogen fertilizers (Svarich 1999).

Production of phosphorus fertilizer created phosphogypsum (PG), a by product composed mainly of solid gypsum ($CaSO_4 \cdot 2H_2O$), phosphoric acid, trace elements and small amounts of radionuclides (Rutherford et al. 1994, Thorne 1990). The trace elements it contains are dependent upon the source rock. PG at Agrium in Fort Saskatchewan was stacked on site in 4 wet stacks and one dry stockpile covering approximately 35 ha (Hallin 2008, Svarich 1999) (Figure 4.2). Agrium Fort Saskatchewan currently produces nitrogen fertilizers.

The nitrogen fertilizer production plant is in the south-central part of the Agrium Fort Saskatchewan property (Figure 4.2). A neighboring metal refinery contains a tailings pond east of the Agrium plant; west and north are open fields and treed areas, accessible to the public and fenced off from the rest of Agrium property. Northeast and eastern areas contain PG stacks and cooling ponds.

4.3.2 Meteorological Conditions

Precipitation and maximum wind gust data for Fort Saskatchewan were obtained from Environment Canada (2012) for winter 2009/2010 and 2010/2011, the periods of this study. Meteorological data for the study years for November through March were compared to Environment Canada Canadian climate normals (CCNs) for 1971-2000 if available. Environment Canada does not have prevailing wind direction for gusts < 29 km h^{-1} for Fort Saskatchewan and thus this information was obtained from McCullum et al. (2003) for 1990 – 2002.

4.3.3 Experimental Design

In 2010 six snow sampling transects were run north to south on two PG stacks at Agrium, Fort Saskatchewan to assess if metal concentration increased with proximity to the metal refinery to the south (Figure 4.3). Two transects were on Stack 1, three on Stack 2 and one between Stacks 1 and 2. Five samples were taken at random locations on each transect (total 30 samples). Four control samples were taken at the Ellerslie Farm in an open agricultural field southwest of Edmonton (45 km from Fort Saskatchewan) and one in Sherwood Park in a residential backyard east of Edmonton (30 km from Fort Saskatchewan). Agrium is located on the outskirts of a city and does not receive as much automotive pollution as city centres; control locations were just outside a city for similarity.

In 2011 the sampling area at Agrium was expanded from the 2010 sampling area to determine metal concentrations in snow over a larger area. Eight transects were run from north to south across Agrium property (Figure 4.4). Transects were 300 m apart and from 790 to 1,460 m long. Approximate transect locations were mapped prior to sampling. Five samples were taken at random locations on each transect for a total of 40 samples. If an obstacle was encountered (cooling pond, building), the point nearest to the transect was used. Distance along the transect for each sample location was noted and mapped.

4.3.4 Snow Sampling

Snow was sampled on March 8, 2010 at Agrium and on April 2 at control locations. Sampling was conducted with a plastic snow core of 7.62 cm diameter. Snow from the snow pack to a depth just above the ground surface was collected without soil or sediment. Samples were placed into plastic nalgene bottles, nitric acid preservative added, then stored in the refrigerator until analyses. Samples were analyzed with inductively coupled plasma optical emission spectrometry (ICP-OES) at AGAT Laboratories in Edmonton. A subset of 5 samples was analyzed for nickel, copper and cobalt to determine whether concentrations were substantial and a trend with distance was occurring, to warrant further analyses. The remaining 29 samples were analyzed for nickel, cobalt and iron. Copper was not assessed in these samples since concentrations were not high in the first analysis. Iron was assessed since it is often found in metal refinery tailings ponds and will aid in determining a point source for nickel and cobalt.

Similar sampling occurred on March 13 and 14, 2011. Samples were weighed in the laboratory after melting then analyzed with inductively coupled plasma mass spectrometry (ICP-MS) for concentrations of cobalt, iron and nickel at Exova Laboratories in Edmonton. The total load of assessed metals in each sample was determined by multiplying sample metal concentration by snow core calculated water volume. The snow core sample water volume was assumed equal to the weight of water in each sample.

4.3.5 Statistical Analyses

Sample locations from 2010 and 2011 were plotted on a site map in Google Earth. Distance between sample points and the neighboring metal refinery were calculated with the Google Earth measuring function for use in further analyses. While many areas of the refinery may be point sources of metals, a tailings pond southeast of Agrium property was identified as a potentially dominant source and used as the point from which to calculate distances (Nichol 2012). All sample distances and metal concentrations were entered and graphed in excel. Curve estimation was completed to determine the best fit curves and their r^2 values for the relationship between metals and distance from the tailings pond.

4.4 Results and Discussion

4.4.1 Meteorological Conditions

Fort Saskatchewan winter precipitation (November-March) was 116.3 mm in 2009-2010 and 157.2 mm in 2010-2011 (Table 4.1). Both were higher than the

Canadian climate normal of 97.3 mm. Higher than average precipitation, especially snow, could cause snow metals to be less concentrated than in years with average precipitation and snowfall.

The prevailing maximum wind gust (> 29 km h^{-1}) direction in Fort Saskatchewan in winter 2009-2010 and 2010-2011 was from the north west, however it varied throughout the winter, including southeast and east. Historical winter prevailing wind direction is from the southwest (McCullum et al. 2003). This could cause snow metals to accumulate to the northeast of a metal source due to the prevailing wind direction and southeast due to prevailing maximum wind gust direction. However, because wind direction varies during the winter, snow metals could accumulate all around the source.

4.4.2. Element Concentrations

In 2010 and 2011 there was a clear trend of decreasing concentrations of cobalt, iron and nickel in snow with increasing distance from the tailings pond (Figures 4.5. 4.6, 4.7, 4.8, Tables 4.2, 4.3, 4.4). The shape of the concentration-distance curve varied by metal. There was no clear trend for copper in 2010 and therefore only preliminary analyses were done. The highest sample point for 2011 graphs was substantially higher than other points and therefore other sample points appear clustered at lower values. When the highest sample point is removed from the 2011 graphs, and samples taken 200 m or more away from the pond are graphed, the trend in these points is more apparent because the graph scale changes and the data can be spread out (Figure 4.7).

4.4.2.1. Cobalt

2010 cobalt concentrations in snow exponentially decreased with distance from the tailings pond (Figure 4.5, Tables 4.2, 4.3). The r^2 value was 0.61. In 2011 the best fit curve was inverse and concentrations decreased with distance from the tailings pond with an r^2 value of 0.76 (Figures 4.6, 4.7, Table 4.4). In 2011 the sample closest to the tailings pond had substantially higher cobalt concentrations than other samples (4.730 mg cobalt L^{-1}). The three other samples with highest concentrations were found close to the tailings pond.

The 2010 sample area represents a portion of the 2011 sample area. Beyond 1253 m from the tailings pond, concentrations of ≤ 0.032 mg L^{-1} were found. Snow samples from Agrium had higher concentrations than those from control locations in 2010 and 2011 (Table 4.5).

4.4.2.2 Iron

Snow iron concentrations generally decreased in 2010 with distance from the tailings pond and the relationship was exponential with an r^2 of 0.45 (Figure 4.5, Tables 4.2, 4.3). Three samples had iron concentrations substantially higher than the others (3.7 to 5.5 mg L^{-1}), and these were samples located closer to the tailings pond (470 m to 585 m away). In 2010 the control sample from Sherwood Park had a lower iron concentration than samples taken from Agrium. The 2010 Ellerslie farm control samples had relatively high iron concentrations (1.7 to 3.7 mg L^{-1}) which were not as high as the highest values found at Agrium (5.5 and 4.3 mg L^{-1}) but were higher than the majority of samples taken at Agrium. It is possible that there was a source of iron which affected Ellerslie Farm in 2010.

Snow iron concentrations in 2011 decreased with distance from the tailings pond and the best fit curve was inverse with an r^2 of 0.82. At two points closest to the tailing pond iron concentrations were highest (60.1 and 16.8 mg iron/L) (Figure 4.6 and Table 4.4). On Agrium property snow iron concentrations reached background levels consistently at 746 m from the tailings pond. In 2011 control samples contained iron concentrations of ≤ 0.28 mg L^{-1} which was lower than concentrations found consistently at points ≤ 746 m from the tailings pond at Agrium in 2011 (Table 4.5).

4.4.2.3 Nickel

Snow nickel concentration in 2010 decreased logarithmically with distance from the tailings pond and the r^2 value was 0.64 (Figure 4.5, Tables 4.2, 4.3). Samples with the highest nickel concentrations were the two closest to the tailings pond (1.42 and 1.14 mg nickel L^{-1} at 393 and 427 m from the tailings pond, respectively). Samples with lowest concentrations were further from the tailings pond (0.003 and 0.198 mg nickel L^{-1} at 902 and 966 m, respectively). Snow samples from Agrium all contained nickel concentrations higher than those from the 2010 control locations.

Snow nickel concentrations in 2011 decreased inversely with distance from the tailings pond and the r^2 values was 0.83. Higher concentrations of nickel were found closer to the tailings pond than further away, and the range in concentrations was much greater at locations closer to the tailings pond compared to locations further away (Figures 4.6, 4.7, Tables 4.3, 4.4). The point sampled closest to the tailings pond (99 m away) had a substantially higher nickel concentration than other samples (10.30 mg L^{-1}). In 2011 samples from Agrium property, except one, were above the control sample concentrations (Table 4.4 and Table 4.5).

4.4.2.4 Copper

No clear trends in copper concentration with distance from the tailings pond were found and therefore only 5 preliminary samples were analyzed (Tables 4.2, 4.3). Copper concentrations in snow were all low (5.02-22.50 µg L^{-1}). Since copper concentration did not increase with proximity to the metal refinery the refinery may not be a source of copper onsite or copper may not have moved substantially from the tailings pond to snow in winters 2010 and 2011.

Others studies found similar metal concentration decreases with distance from metal refineries (Bonham-Carter et al. 2006, Ceburnis et al. 2002, Gregurek et al. 1998). Many samples should be taken at locations where concentrations change substantially to characterize the shape of the relationship curve. If further research is done on this study more samples should be taken at locations under 300 m from the tailings pond. Background metal concentrations are often found several km from a refinery. Background concentrations of nickel and cobalt were not found onsite in this study, thus elevated concentrations are likely further away. This study found elevated snow metal concentrations for winters 2010 and 2011; if similar amounts are deposited in future, with time cumulative metal volumes could, and may have already, caused negative ecological effects.

4.5 Conclusions

- Significant amounts of cobalt, iron and nickel were present in snow on Agrium property in the winter months of 2009-2010 and 2010-2011.
- Cobalt, iron and nickel at Agrium likely originated from the neighboring metal refinery and associated tailings pond.
- Copper at Agrium likely did not originate from the metal refinery and

associated tailings pond.

- Concentrations of cobalt, iron and nickel on Agrium property declined with distance from the tailings pond.
- Copper concentrations did not decrease with distance from the tailings pond.
- At locations very close to the tailing pond (< 200 m) concentrations of copper, iron and nickel were exponentially higher than at locations further away.
- Nickel and cobalt concentrations did not consistently reach background values within the sampled area (1580 m from the tailings pond).
- Iron concentrations reached background levels consistently at approximately 746 m from the tailings pond.
- Of the assessed metals, iron concentrations were highest, followed by nickel then cobalt.

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Figure 4.1. Map of location of Fort Saskatchewan in Alberta, Canada (Adapted from GreenField Development Corp. 2009).

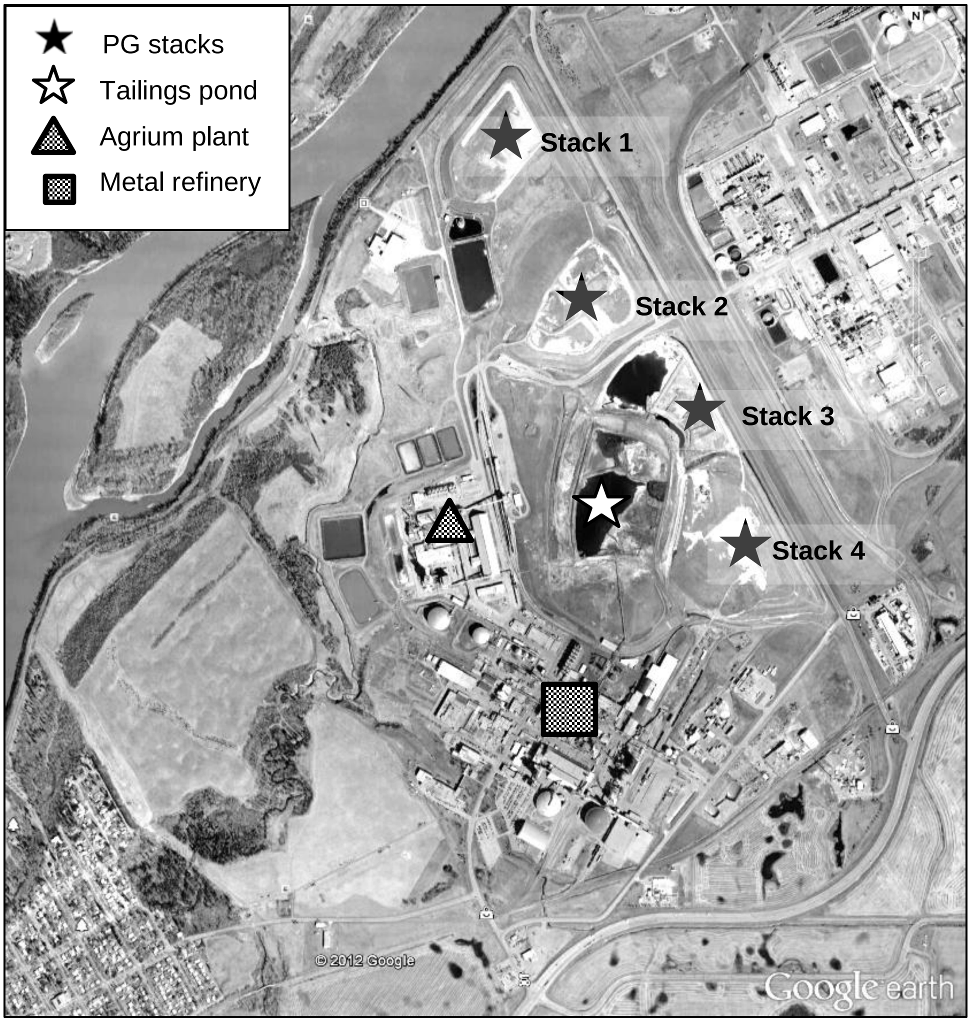

Figure 4.2. Aerial view of Agrium facilities and phosphogypsum stacks in Fort Saskatchewan, Alberta (Adapted from Google Inc. 2012).

Figure 4.3. Map of snow sample transect locations on phosphogypsum stacks at Agrium, Fort Saskatchewan in 2010 (Adapted from Google Inc. 2012).

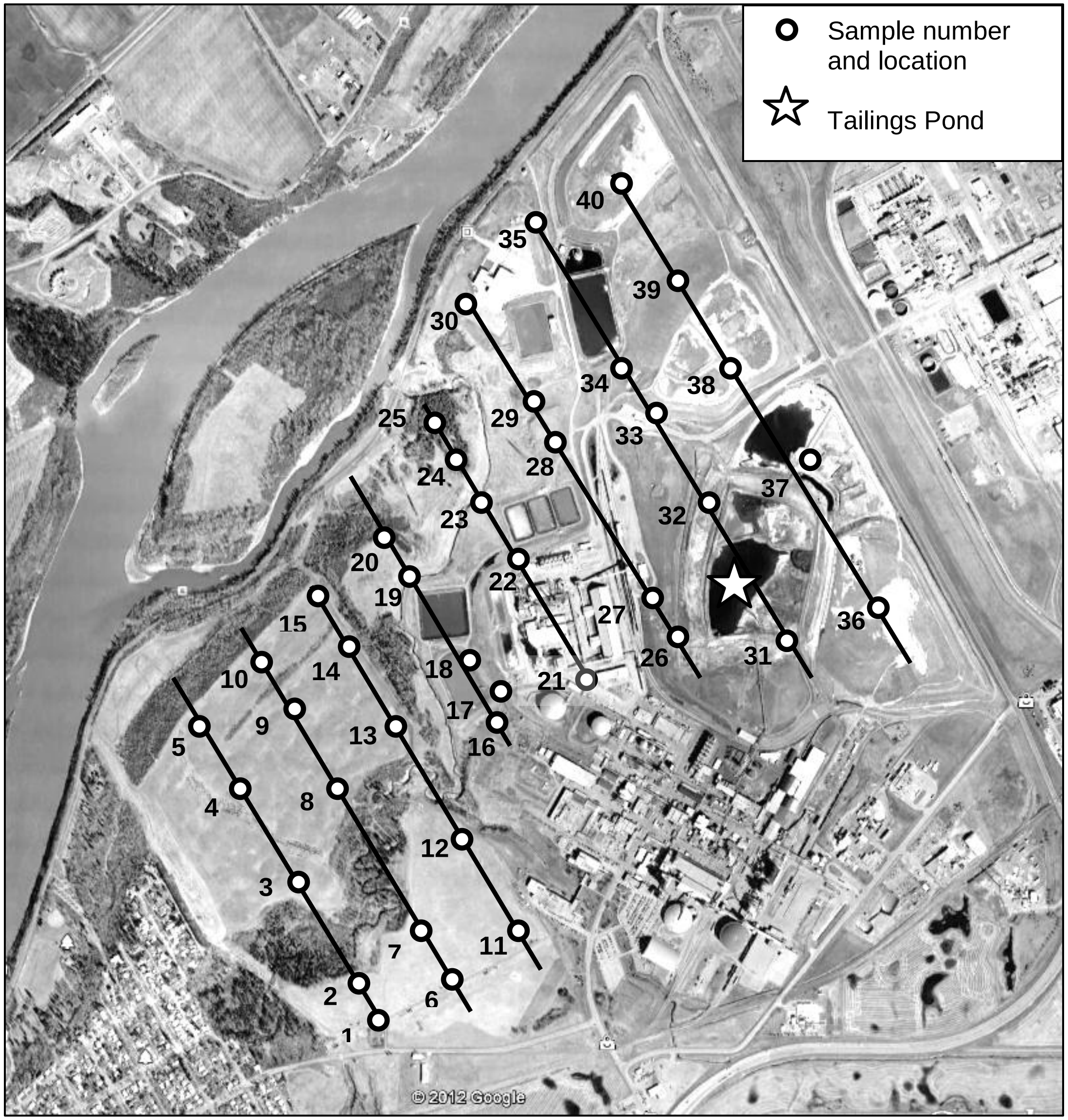

Figure 4.4. Map of snow sample transects at Agrium Fort Saskatchewan in 2011 (Adapted from Google Inc. 2012).

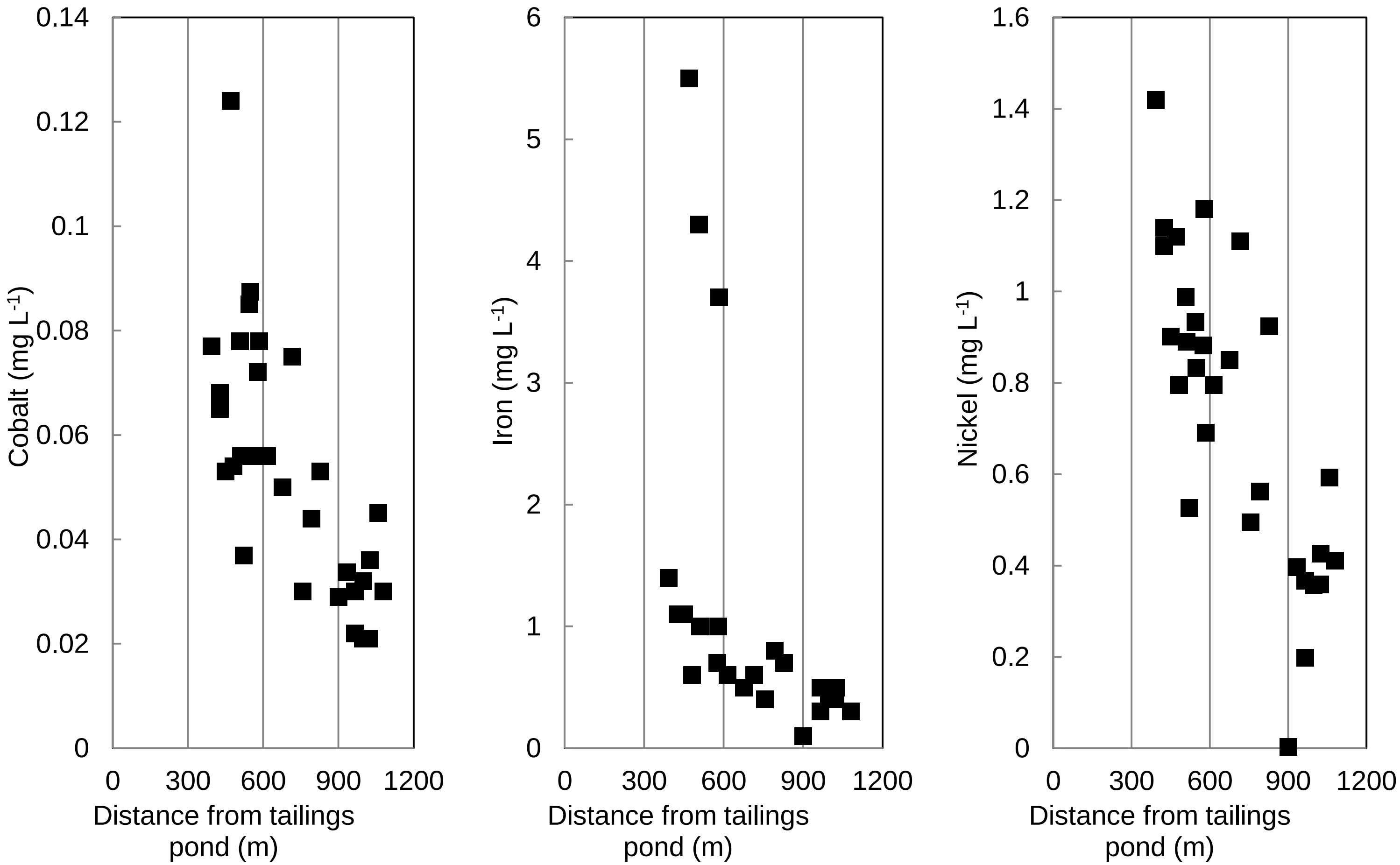

Figure 4.5. Snow cobalt, iron and nickel concentrations with distance from a tailings pond at Agrium in Fort Saskatchewan, Alberta in 2010.

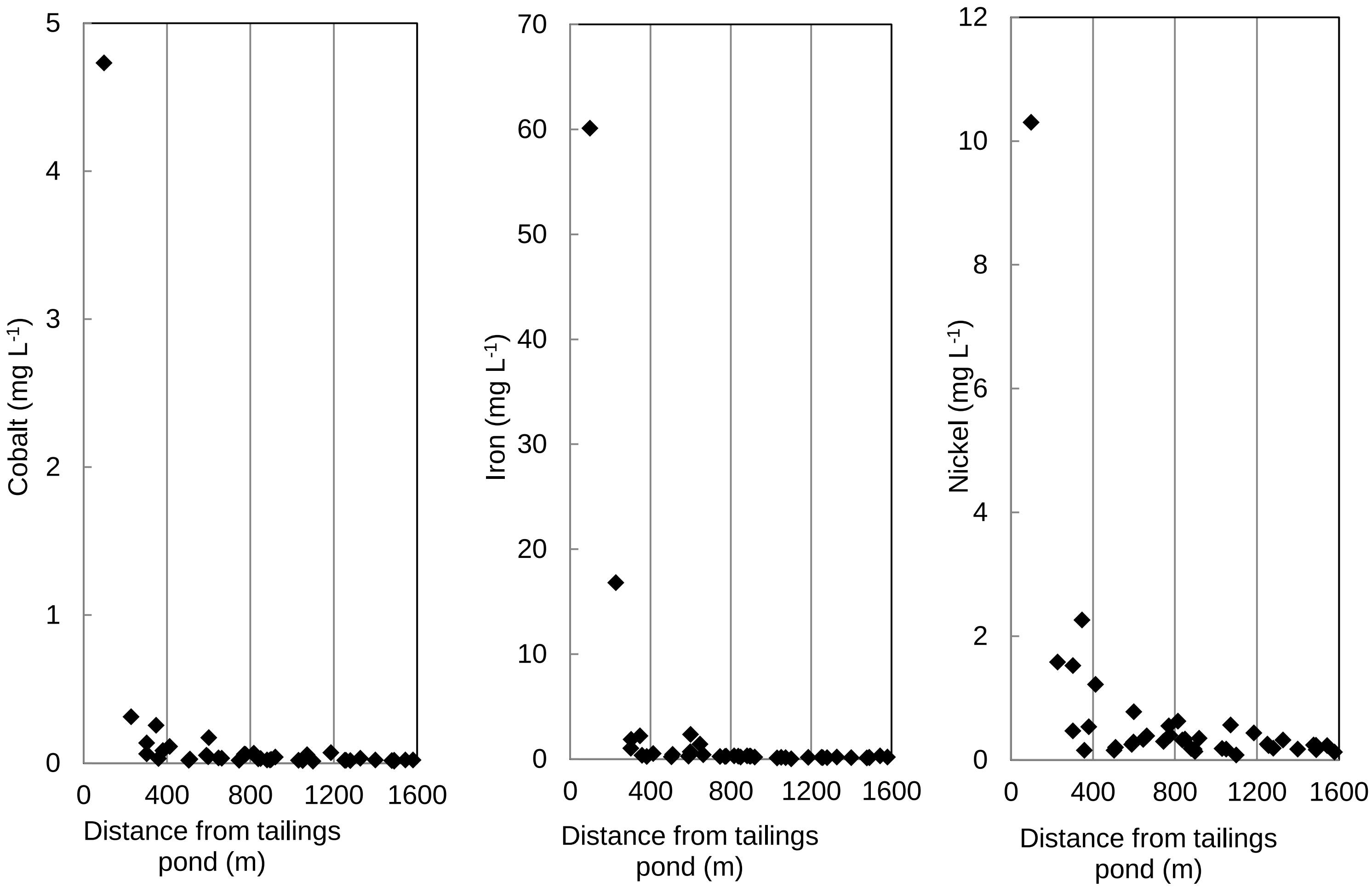

Figure 4.6. Snow cobalt, iron and nickel concentrations with distance from a tailings pond at Agrium in Fort Saskatchewan, Alberta in 2011.

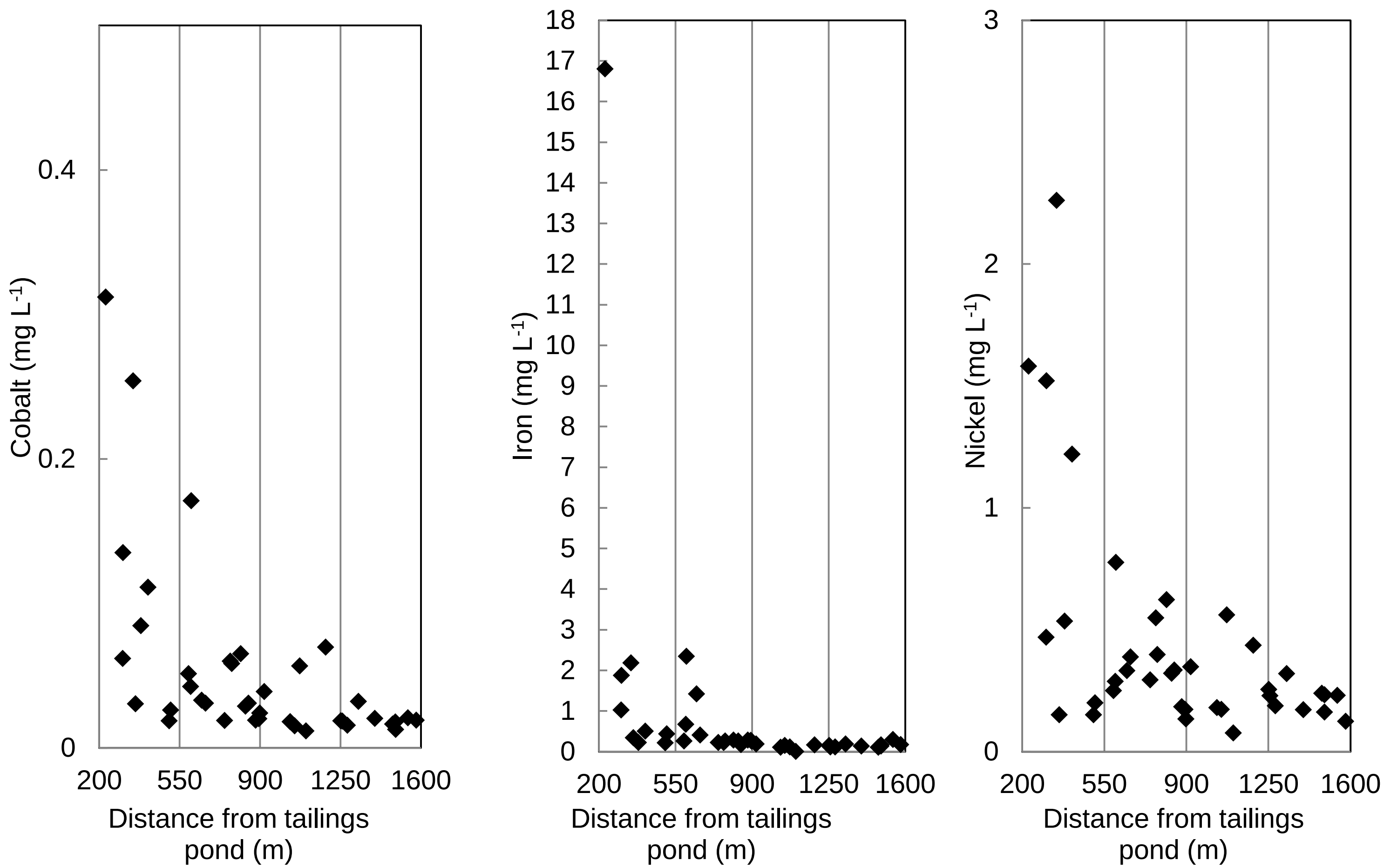

Figure 4.7. Snow cobalt, iron and nickel concentrations with distances over 200 meters from a tailings pond in 2011.

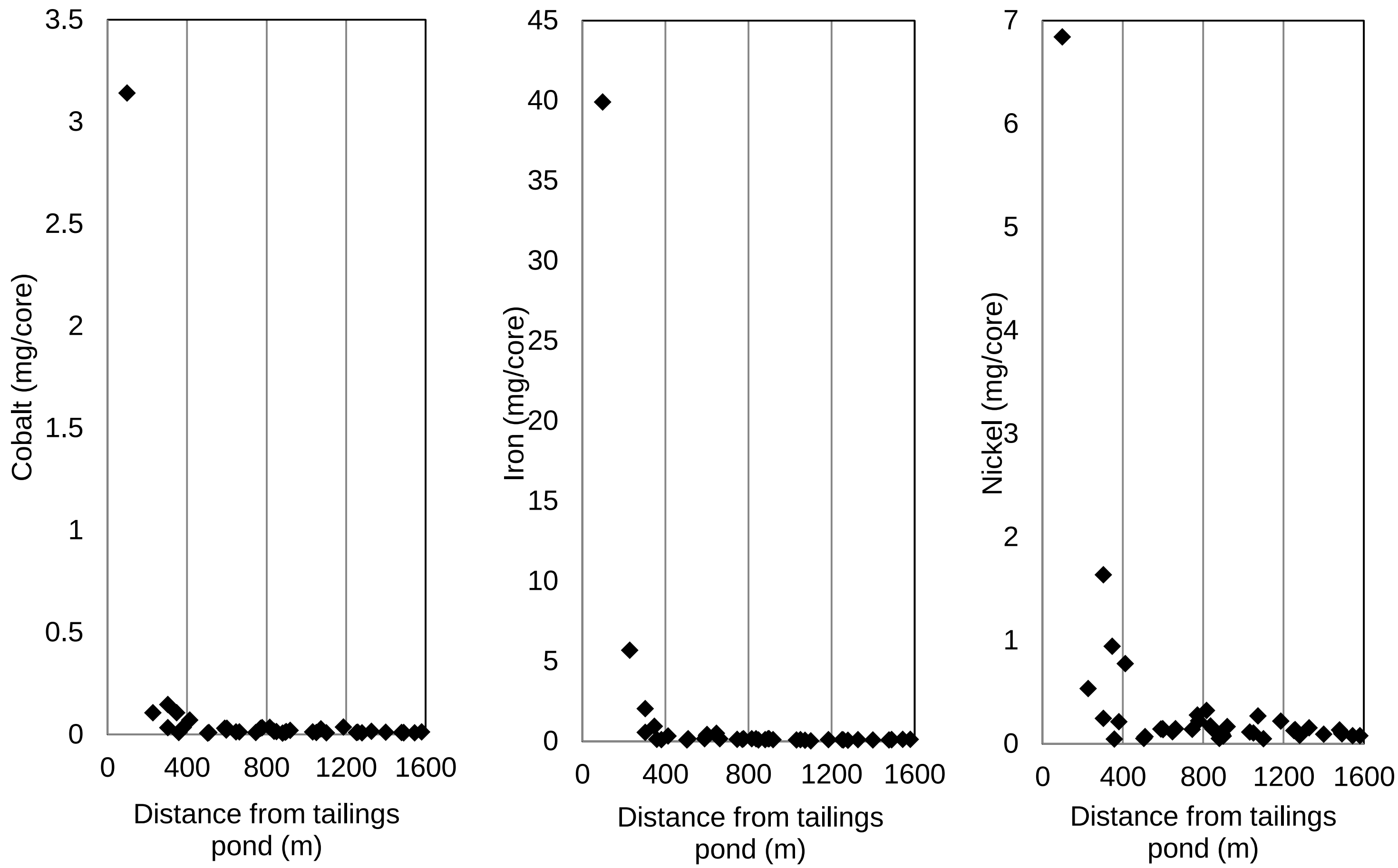

Figure 4. 8. Total load of cobalt, iron and nickel per core in snow with distance from a tailings pond at Agrium in Fort Saskatchewan, Alberta in 2011.

Table 4.1. Winter meteorological data for Fort Saskatchewan, Alberta.

Month	Precipitation (mm)			Wind		
				Maximum Gust Direction		Prevailing Direction
	2009/2010*	2010/2011*	CCN*	2009/2010*	2010/2011*	Average**
November	19.5	34.1	22.7	NW	N	SW
December	78.4	28.4	23.3	NW	NW	SW
January	14.1	59.3	23.4	-	NW	SW
February	2.2	27.4	13.5	S	NW	SW
March	2.1	8	14.4	NW	SE	SW
Sum	116.3	157.2	97.3			
Prevailing				NW	NW	SW

*Data from Environment Canada.
**Data from McCullum et al. (average for 1990 – 2002).
Maximum wind gust direction recorded when gust is > 29 km / hour.
CCN = Canadian Climate Normal (average based on 1971 – 2000).
N = north, S = south, E = east, W = west.
- = insufficient data.

Table 4.2. Snow cobalt, iron, nickel and copper concentrations with distance from a tailings pond at Agrium in Fort Saskatchewan, Alberta and in control locations in 2010.

Distance from tailings pond (m)	Sample Number or Control Sample Location	Concentration			
		Cobalt (mg L^{-1})	Iron (mg L^{-1})	Nickel (mg L^{-1})	Copper (µg L^{-1})
393	20	0.077	1.4	1.42	
427	19	0.065	1.1	1.14	
427	21	0.068	1.1	1.1	
451	18	0.053	1.1	0.901	
470	22	0.124	5.5	1.12	
482	17	0.054	0.6	0.795	
508	23	0.078	4.3	0.988	
512	29	0.056	1.0	0.89	
523	16	0.0369		0.526	5.48
546	24	0.085		0.933	10.4
549	28	0.0874		0.833	22.5
577	25	0.056	0.7	0.882	
580	30	0.072	1	1.18	
585	27	0.078	3.7	0.691	
616	26	0.056	0.6	0.795	
677	15	0.05	0.5	0.85	
717	14	0.075	0.6	1.11	
758	13	0.03	0.4	0.495	
793	12	0.044	0.8	0.562	
828	11	0.053	0.7	0.924	
902	1	0.029	0.1	0.003	
935	2	0.0337		0.397	5.02
966	3	0.022	0.5	0.198	
966	6	0.03	0.3	0.367	
998	4	0.021	0.4	0.358	
1000	7	0.032	0.4	0.357	
1023	5	0.021	0.4	0.358	
1026	8	0.036	0.5	0.426	
1059	9	0.045		0.593	5.37
1081	10	0.03	0.3	0.411	
N/A	Ellerslie Farm	0.001	2.1	0.017	
N/A	Ellerslie Farm	0.001	1.7	0.008	
N/A	Ellerslie Farm	0.001	3.7	0.011	
N/A	Sherwood Park	0.001	0.1	0.004	

Table 4.3. Relationship curves between snow metal concentrations and distance from a tailings pond at Agrium in Fort Saskatchewan, Alberta.

Metal	Year	Model Summary			
		Best Fit Curve	R^2	Equation	P value
Cobalt	2010	Exponential	0.608	In(Y) = In(0.153) + (-0.002*X)	0.000
	2011	Inverse	0.762	Y = -0.505 + (400.04/X)	0.000
Copper	2010	No trend	N/A	N/A	N/A
Iron	2010	Exponential	0.447	In(Y)= In(4.786) + (-0.003*X)	0.000
	2011	Inverse	0.816	Y = -6.831 + (5429.084/X)	0.000
Nickel	2010	Logarithmic	0.641	Y = 6.246 + (-0.848*In(X))	0.000
	2011	Inverse	0.831	Y = -0.859 + (913.83/X)	0.000

Table 4.4. Snow cobalt, iron, and nickel concentration and total load with distance from the tailings pond at Agrium in Fort Saskatchewan, Alberta in 2011.

Distance from Tailings Pond (m)	Sample Number	Sample Weight (g)	Concentration (mg L^{-1})			Total Load (mg/core)		
			Cobalt	Iron	Nickel	Cobalt	Iron	Nickel
99	32	664	4.73	60.1	10.3	3.141	39.91	6.84
228	37	337.29	0.312	16.8	1.58	0.105	5.67	0.53
303	27	519.85	0.062	1.02	0.47	0.032	0.53	0.24
304	31	1075.39	0.135	1.87	1.52	0.145	2.01	1.63
348	26	416.92	0.254	2.18	2.26	0.106	0.91	0.94
359	33	276.71	0.03	0.34	0.15	0.008	0.09	0.04
381	38	395.24	0.084	0.22	0.54	0.033	0.09	0.21
413	36	633.18	0.111	0.5	1.22	0.07	0.32	0.77
505	34	334.66	0.019	0.21	0.15	0.006	0.07	0.05
511	28	333.25	0.026	0.43	0.2	0.009	0.14	0.07
590	39	566.87	0.051	0.26	0.25	0.029	0.15	0.14
599	22	497.82	0.042	0.67	0.29	0.021	0.33	0.14
601	21	174.97	0.171	2.34	0.78	0.03	0.41	0.14
647	29	342.48	0.033	1.42	0.33	0.011	0.49	0.11
663	23	371.82	0.031	0.4	0.39	0.011	0.15	0.14
746	24	465.72	0.019	0.22	0.29	0.009	0.1	0.14
771	18	500.87	0.06	0.22	0.55	0.03	0.11	0.27
778	17	554.23	0.058	0.26	0.4	0.032	0.14	0.22
817	16	512.88	0.065	0.28	0.62	0.033	0.14	0.32
838	25	526.38	0.029	0.26	0.32	0.015	0.14	0.17
850	19	421.09	0.031	0.17	0.33	0.013	0.07	0.14
881	40	270.58	0.019	0.28	0.18	0.005	0.08	0.05
895	30	533.25	0.02	0.27	0.17	0.011	0.14	0.09
900	35	549.08	0.024	0.25	0.13	0.013	0.14	0.07
919	20	471.68	0.039	0.18	0.35	0.018	0.08	0.16
1032	13	608.42	0.018	0.1	0.18	0.011	0.06	0.11
1051	14	597.05	0.015	0.15	0.17	0.009	0.09	0.1
1073	12	476.46	0.057	0.11	0.56	0.027	0.05	0.27
1101	15	622.12	0.012	<0.05	0.08	0.007	<0.03	0.05
1186	11	498.41	0.07	0.16	0.44	0.035	0.08	0.22
1253	8	496.45	0.019	0.15	0.26	0.009	0.07	0.13
1258	9	581.44	0.019	0.11	0.23	0.011	0.06	0.13
1281	10	419.28	0.016	0.11	0.19	0.007	0.05	0.08
1328	7	474.76	0.032	0.18	0.32	0.015	0.09	0.15
1400	6	533.58	0.02	0.13	0.17	0.011	0.07	0.09
1479	4	552.5	0.016	0.1	0.24	0.009	0.06	0.13
1490	3	455.4	0.018	0.16	0.23	0.008	0.07	0.11
1491	5	568.42	0.013	0.13	0.16	0.007	0.07	0.09
1545	2	328.29	0.021	0.29	0.23	0.007	0.1	0.08
1580	1	598.18	0.019	0.17	0.12	0.011	0.1	0.07

Table 4.5. Snow cobalt, iron and nickel concentrations and total load at control sample locations in Alberta in 2011.

Sample Location	Sample Weight (g)	Concentration (mg L^{-1})			Total Load (mg/core)		
		Cobalt	Iron	Nickel	Cobalt	Iron	Nickel
North East Fort Saskatchewan River Valley	320.86	0.009	0.26	0.11	0.003	0.08	0.04
North East Fort Saskatchewan River Valley	501.66	0.008	0.28	0.10	0.004	0.14	0.05
North East Fort Saskatchewan River Valley	523.65	0.008	0.18	0.09	0.004	0.09	0.05
South West Fort Saskatchewan River Valley	494.81	0.009	0.14	0.08	0.005	0.07	0.04
South West Fort Saskatchewan River Valley	614.03	0.006	0.17	0.08	0.004	0.10	0.05
South West Fort Saskatchewan River Valley	499.01	0.006	0.11	0.07	0.003	0.05	0.03
Ellerslie Farm	577.18	0.000	0.07	0.00	0.000	0.04	0.00
Ellerslie Farm	587.09	0.001	0.24	0.00	0.001	0.14	0.00
Ellerslie Farm	588.96	0.000	0.26	0.00	0.000	0.15	0.00
Sherwood Park	662.60	0.003	0.07	0.01	0.002	0.05	0.00
Sherwood Park	673.80	0.000	0.08	0.00	0.000	0.05	0.00
Sherwood Park	552.32	0.000	0.08	0.00	0.000	0.04	0.00

5. VEGETATION ON PHOSPHOGYPSUM STACK SLOPES AND A BASIN 12 YEARS AFTER SOIL PLACEMENT IN FORT SASKATCHEWAN, ALBERTA

5.1 Introduction

Phosphogypsum (PG) is a by product created during production of phosphorous fertilizer by mixing phosphate rock with sulphuric acid to produce phosphoric acid, the main component of phosphorous fertilizer (Rutherford et al. 1994, Wissa 2003). PG is composed mainly of solid gypsum ($CaSO_4 \cdot 2H_2O$), phosphoric acid, trace elements and small amounts of radionuclides (Rutherford et al. 1994, Thorne 1990). At least 80 countries currently have PG stacks, including Canada and the United States (Florida Institute for Phosphate Research 2010). PG is produced at a ratio of 5 tons PG per ton of phosphorus fertilizer (Rutherford et al. 1994, SENES 1987). The most common disposal method internationally is wet stacking whereby filtered PG is mixed with water and pumped into settling ponds (Wissa 2003). The water is decanted and solid material is placed in stacks. Stacks can cover areas up to 1 million m^2 and reach tens of meters in height (Rutherford et al. 1995).

PG stacks can pose environmental hazards, which can be substantially reduced through reclamation. Potential environmental hazards include ground water contamination, radon gas and gamma radiation, and atmospheric contamination by fluoride (Rutherford et al. 1994, Tayibi et al. 2009, Wissa 2003). For example SENES (1987) found that while active stacks caused increases in ambient and foliage fluoride concentrations nearby, this did not occur when the production plant and stacks became inactive.

Stack closure is regulated by local governments, varying with jurisdiction. It involves covering the stack to provide a stable substrate for revegetation, limit erosion and water infiltration and minimize exposure pathways between PG and environmental receptors. The cover is generally a revegetated soil layer but can be a high density polyethylene liner (Wissa 2003). Alberta regulations require all industries to reclaim to predisturbance equivalent capability (Alberta Environment 2010). Alberta does not have specific regulations for PG stack reclamation and sites must be assessed individually to develop reclamation plans based on stack characteristics, local climate and landscape (Alberta Environment 2010).

PG stack reclamation has been studied in various locations. Plants on bare PG on a tailings pond in Medicine Hat, Alberta accumulated elements elevated in PG including selenium, fluorine and cadmium in potentially toxic concentrations for wildlife (Thorne 1990). Most factors limiting plant growth, except selenium hyper accumulation by vegetation, were overcome by adding amendments. In a greenhouse study in Romania, mixing dolomite, kaolin and sewage sludge with PG and capping with 15 cm of soil increased micronutrients, pH, water holding capacity and organic matter creating a suitable substrate for revegetation (Komnitsas et al. 1999).

At Fort Saskatchewan, Alberta, PG stacks covered with 15 cm of soil and revegetated were assessed after 8 years (Hallin et al. 2008, 2010). Plant cover was high and relatively consistent throughout the stacks and comprised mainly of grasses and ruderal species. Plant tissue contained elevated concentrations of nickel and fluorine relative to a reference sample. Fluorine concentrations in the soil cover consistently exceeded Alberta soil quality criteria guidelines, while guidelines were exceeded for nickel in one third of the samples and cobalt in one fifth of samples. On the same sites Jackson et al. (2009, 2011) found vegetation cover, biovolume, health and height were higher on capped plots than uncapped plots, and were not significantly different in plots from cap depths 8 cm or over.

Reclamation may occur naturally, but over long periods of time. In Belarus, Gusev (2006) studied 0-15, 15-30 and > 30 year old PG stacks. Without reclamation or amendments succession was slow but steady. Plant species diversity was low relative to undisturbed sites. Succession was substantially quicker at the bottom of stack slopes than at mid and upper locations, likely because litter, soil and seeds from nearby locations were more easily deposited and accumulated. In the first 15 years stacks generally had some young trees and a herbaceous cover of 1.1-4.5% on lower and mid slopes, but no vegetation on upper slopes. By 30 years herbaceous cover was 20-60%, with young trees and litter layers over 0.5 cm thick on lower, mid and upper slopes.

The Operating Approval for Agrium Fort Saskatchewan states that research options for reclamation of the phosphogypsum stacks must continue to be investigated (Alberta Environment 2008). A cover system limiting potential environmental hazards of PG which does not require environmentally damaging stripping of topsoil from surrounding areas is desired. This research will be part of a general environmental risk assessment for the Agrium Fort Saskatchewan PG stacks. It will help to develop a reclamation plan for the inactive PG stacks at Agrium in Fort Saskatchewan and for future PG stack reclamation in other jurisdictions.

5.2 Research Objectives

The research objective was to determine vegetation species composition and ground cover characteristics on Agrium phosphogypsum stacks in Fort Saskatchewan, Alberta 12 years after soil cap placement and seeding. Which plant species were adapted to phosphogypsum stacks and what required time frames are for adequate ground cover on different areas of the stacks were key focuses to help create phosphogypsum stack reclamation plans.

5.3 Materials and Methods

5.3.1 Research Site Description

Fort Saskatchewan is located approximately 30 km northeast of Edmonton, Alberta (53º 43’ N and 113º 13’ W) in an industrial area with over 40 large companies (Alberta’s Industrial Heartland Association 2012, City of Fort Saskatchewan 2012) (Figure 5.1). Residential communities occur on the west side and Fort Saskatchewan’s population is approximately 19,000 (Figure 5.2).

The research site is in the Central Parklands Natural Subregion of Alberta within the Aspen Parkland, Ecoregion, between the Dry Mixedwood Natural Subregion to the north and west and Foothills Fescue, Foothills Parkland and Northern Fescue Natural Subregions to the south (Natural Regions Committee 2006). Most of the Subregion is cultivated and inhabited with small sections of native aspen and prairie vegetation. Non native species such as *Bromus inermis* L. (smooth brome) and *Agropyron repens* L. (quack grass) are dominant. Average annual precipitation is 440 mm with 75% falling during the growing season. Frost free days average 109 per year with average temperatures of -14 and 17 °C in January and July, respectively (Environment Canada 2012).

Dominant soils are black chernozems with small areas of dark gray chernozems and solonetzic soils (Natural Regions Committee 2006). Elevation averages 620 m above sea level and the major landforms are gently rolling hills and hummocks. Lacustrine and fluvial deposits are common with significant eolian deposits. The Belly River formation, composed of sandstone, siltstone, mudstone and ironstone beds, forms bedrock around Fort Saskatchewan (Hamilton et al. 2005).

Agrium is located in the industrial district in eastern Fort Saskatchewan. It is bordered by the North Saskatchewan River to the north and agricultural land to the south (Figure 5.2). Dow Chemical Inc., a plastic and chemical products manufacturing facility, is located east of Agrium; Sherritt International, a metallurgical services and metal refinery company, is located to the south (Alberta's Industrial Heartland 2012). Agrium specializes in nitrogen, phosphorus, potash and micronutrient fertilizer production (Agrium 2012). Phosphorous fertilizer was produced at their Fort Saskatchewan facilities from 1965-1991 and it currently produces nitrogen fertilizers (Svarich 1999).

Phosphogypsum was stacked on Agrium property for 26 years with approximately 5 million tonnes of dihydrate PG in four stacks on a 35 ha area (Svarich 1999). Stack 1, next to the Fort Saskatchewan River, covers 9.3 ha and was built on a high density polyethylene liner (Figure 5.2). Stack 2, south of stack 1 covers 8.5 ha and was built on a clay liner. Both stacks have settling basins of 4.7 ha. Stacks 1 and 2 were decommissioned in 1991 when phosphate fertilizer production at the Fort Saskatchewan facility ceased. Florida phosphate rock is the source rock for all PG on site (Nichol 2012).

In summer 1998 approximately 15 cm of topsoil was placed on the side slopes of PG stacks 1 and 2 (Nichol 2012, Hallin 2008). A non native seed mix composed mainly of *Bromus inermis* and *Brassica napus* L. (canola) was seeded on the stack slopes (Nichol 2012). Further information about the contents of the seed mix is unavailable. The stack settling basins are located on top of the stacks, recessed within the stacks by approximately 10 m, and their surfaces are relatively flat. Where PG is bare and exposed a surface crust has formed.

5.3.2 Experimental Design

Transects were used for systematic sampling of the slopes of Stacks 1 and 2 and the basin of Stack 2 (Figure 5.2). On Stacks 1 and 2 transects were placed from the bottom to the top of the stack slopes and three transects were used at each of the cardinal and ordinal directions. In the basin of Stack 2 three transects were placed from east to west. Three quadrats were placed on each transect to assess vegetation and ground cover. On stack slopes quadrats were placed on bottom, mid and lower slope positions and in the basin they were randomly located on each transect.

5.3.3 Vegetation and Ground Cover Assessment

Vegetation was assessed to determine species composition and relative abundance and to provide information on surviving seeded species and naturally encroaching species. Vegetation and above ground cover was assessed from June 24 to July 5, 2010. Three 0.5 m^2 quadrats were assessed on each transect and a species area curve, created at the time of sampling, was used to determine sample number. Within each quadrat all plant species were identified and their percent ground cover (2 cm above the ground) and percent canopy cover (total cover occupied of the plant) were estimated. Within each quadrat the percent area occupied by live vegetation, bare ground, rocks, litter, moss and wood was estimated. A walk through of the stacks was conducted after quadrat assessments and any species not previously identified were listed.

5.3.4 Statistical Analyses

Data were compiled in Excel and organized into cardinal and ordinal direction and slope position categories for each stack. For each direction and slope position, averages were calculated for all criteria assessed and used for further analyses. Determination of status for each species as native, introduced, or weed was based on data from the USDA Plants Database (2012) and the Alberta Invasive Plants Council (2012).

5.4 Results and Discussion

5.4.1 Ground Cover

The two stacks had substantive live vegetation and litter cover (Tables 5.1, 5.2). Total canopy cover on slopes ranged from 10.0-52.3% on Stack 1 and 11.3-43.0% on Stack 2. Litter on slopes ranged from 46.7-93.3% on Stack 1 and 23.0-92.0% on Stack 2. Bare ground was low on Stack 1 (0.0-3.7%) and higher on Stack 2 (0.3-64.7%). Rocks, moss and wood covered a relatively small percentage of the ground on both stacks.

Ground cover was affected by slope position. The lower slope had greatest cover and the upper slope least (Tables 5.1, 5.2). The basin of stack 2 had greater canopy cover than the slopes. Due to differences in cover for slope position, data were kept separate for each slope position. The lower slopes likely had greater cover and lower bare ground due to reduced erosion and higher soil water content.

5.4.2 Plant Species Composition

A total of 35 species were found on the two PG stacks; 10 grasses, 24 forbs and 1 tree (Tables 5.3, 5.4, 5.5). A mix of native, introduced, ruderal and weedy invasive species were found on the stacks. Ruderals and grass species comprised the majority of canopy cover. *Bromus inermis* Leyss. (smooth brome) was the most abundant species with a mean cover of 12%. *Bromus inermis* was in the original seed mix planted on the stacks in summer 1998 and has thrived since then. It is an introduced grass species that can be weedy and invasive in certain areas, including Alberta.

Other species with high cover were the ruderal nuisance weed *Agropyron repens* (L.) Gould (quack grass) (3% cover) and the native species *Bromus pumpellianus* Scribn (2.3%) (Pumpelly's brome). The ruderal nuisance weed *Thalapsi arvense* L. (stink weed) had the highest occurrence of the forbs (16%). The seed mix contained *Brassica napus* L. (canola) which was not found on the stacks since it is an annual and has long disappeared from the plant community. The rest of the seed mix used in 1998 was unknown.

Species not seeded on the stacks potentially encroached from the nearby river valley which contains a mix of native, introduced, ruderal and weedy species. Ruderal species are typically the first to colonize a disturbed area and other native species move in and replace them with time. Potentially the stacks still contain many ruderals 12 years after capping because the site still has disturbance characteristics. Hallin (2010) found that 8 years after soil capping the stack slope cap had mixed with some PG and contained elevated fluoride and nickel relative to soil quality guidelines. Cap depth varied substantially throughout the stacks (Stack 1 ranged from 8-27 cm with a 16 cm mean) and substantial mixing of the cap and underlying PG had occurred indicating plant roots would be in contact with PG. Phosphogypsum has low nutrient status (Jackson 2009, Komnitsas et al. 1999). Due to these factors many areas of the stack slopes, especially where soil cover is lower than average and substantial mixing has occurred, are still disturbed environments and this is potentially why many ruderal species persist.

5.5 Conclusions

- 12 years after soil capping and seeding the PG stacks supported a plant community of mainly grasses.
- Vegetation canopy cover and litter were the two main ground cover components on the two stacks.
- Vegetation canopy cover was greatest in lower slope positions and least in upper positions.
- Bare ground was highest in upper slope positions and least in mid and lower slope positions.
- A total of 35 species were identified on the two PG stacks; 10 grasses, 24 forbs, and 1 tree.
- The majority of species on the stacks were introduced ruderals.
- *Bromus inermis* persisted and thrived since seeding.
- *Bromus inermis* was the most abundant species on the stacks; other abundant species were *Agropyron repens*, *Thlaspi arvense* and *Bromus pumpellianus*.

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Figure 5.1. Map of location of Fort Saskatchewan in Alberta, Canada (Adapted from GreenField Development Corp. 2009).

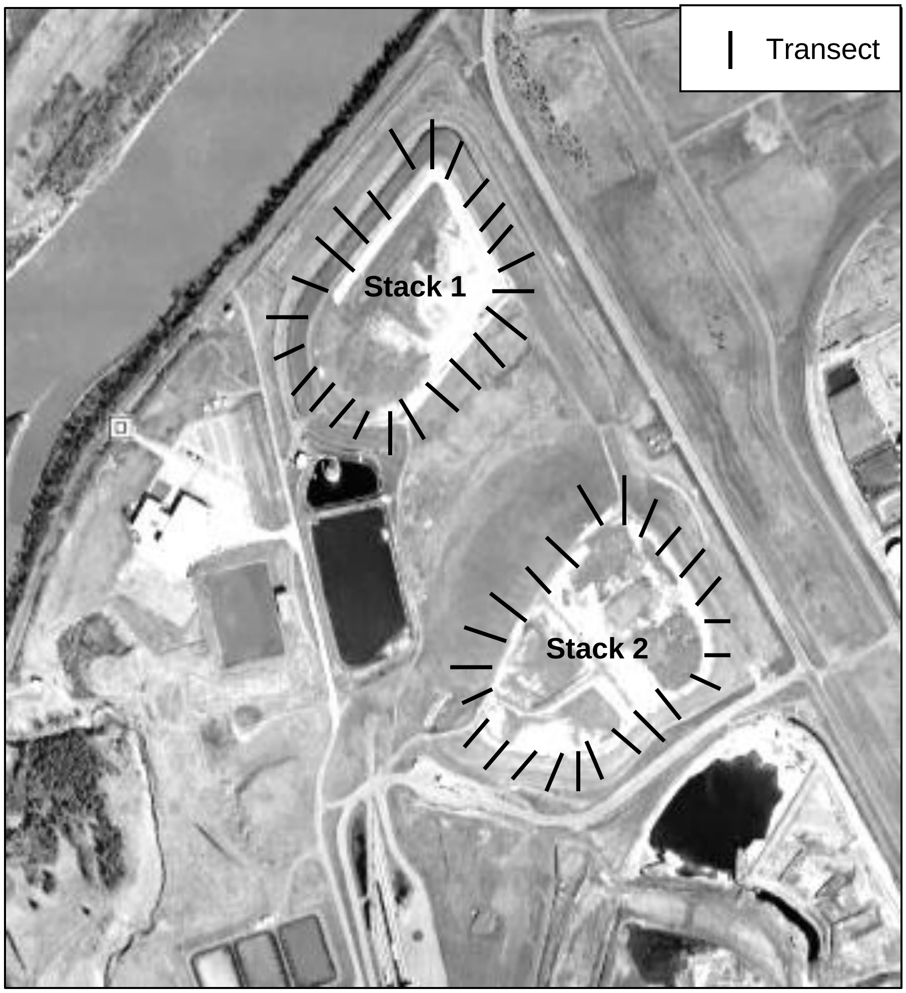

Figure 5.2. Map of vegetation assessment transect locations on phosphogypsum stack slopes at Agrium, Fort Saskatchewan in 2010 (Adapted from Google Inc. 2012).

Table 5.1. Ground cover on phosphogypsum Stack 1.

Aspect	Slope Position	Ground Cover (%) Live Cover	Canopy Cover	Rocks	Moss	Bare Ground	Litter
North-west	Lower	12.0 (3.0)	43.3 (5.8)	0.0 (0.0)	0.3 (0.3)	0.5 (0.5)	87.3 (3.1)
	Mid	6.7 (0.6)	20.7 (0.6)	0.0 (0.0)	2.3 (0.6)	0.7 (0.6)	90.3 (0.6)
	Upper	9.0 (5.3)	29.7 (17.8)	0.3 (0.6)	5.3 (1.5)	2.0 (2.0)	83.3 (7.4)
North	Lower	19.0 (3.6)	48.0 (23.1)	0.0 (0.0)	0.7 (1.2)	0.3 (0.6)	76.7 (4.7)
	Mid	9.3 (2.3)	28.0 (12.0)	0.0 (0.0)	0.3 (0.6)	0.0 (0.0)	90.3 (2.1)
	Upper	5.7 (1.2)	15.3 (7.0)	1.3 (1.5)	2.5 (3.9)	0.0 (0.0)	90.7 (4.0)
North-east	Lower	25.7 (14.0)	81.7 (7.6)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	74.3 (14.0)
	Mid	5.7 (2.1)	14.7 (9.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	94.3 (2.1)
	Upper	4.0 (1.0)	8.7 (2.9)	1.7 (2.9)	1.0 (1.7)	0.3 (0.6)	93.0 (2.6)
East	Lower	13.0 (2.6)	49.7 (38.5)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	87.0 (2.6)
	Mid	9.0 (1.7)	20.3 (9.0)	0.0 (0.0)	0.7 (1.2)	0.0 (0.0)	90.3 (1.5)
	Upper	13.0 (2.6)	29.0 (7.9)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	82.3 (8.3)
South-east	Lower	8.7 (1.5)	33.0 (28.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	91.3 (1.5)
	Mid	6.0 (0.0)	22.0 (10.0)	0.0 (0.0)	0.0 (0.0)	1.3 (1.5)	92.7 (1.5)
	Upper	5.0 (2.0)	22.0 (10.6)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	92.7 (2.5)
South	Lower	8.3 (2.3)	32.0 (11.5)	0.0 (0.0)	0.0 (0.0)	1.0 (1.7)	79.3 (21.1)
	Mid	7.3 (2.1)	22.3 (13.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	84.7 (14.6)
	Upper	5.3 (0.6)	17.7 (8.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	89.0 (10.4)
South-west	Lower	7.0 (1.0)	20.3 (5.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	86.7 (10.1)
	Mid	4.3 (0.6)	10.0 (2.6)	0.0 (0.0)	0.0 (0.0)	1.0 (1.0)	93.7 (2.1)
	Upper	5.3 (1.2)	12.7 (4.9)	0.0 (0.0)	0.0 (0.0)	0.3 (0.6)	93.3 (0.6)
West	Lower	8.0 (4.0)	52.3 (44.5)	0.0 (0.0)	0.0 (0.0)	1.0 (1.0)	46.7 (44.1)
	Mid	6.7 (5.0)	20.0 (16.5)	0.0 (0.0)	1.3 (2.3)	1.7 (2.9)	90.0 (6.2)
	Upper	5.3 (5.3)	17.7 (17.7)	2.0 (2.0)	0.2 (0.2)	3.7 (3.7)	86.0 (86.0)

Data are means with standard deviation in brackets.

Table 5.2. Ground cover on phosphogypsum Stack 2.

		Ground Cover (%)					
Aspect	Slope Position	Live Cover	Canopy Cover	Rocks	Moss	Bare Ground	Litter
North	Lower	8.7 (5.1)	43.0 (35.6)	0.0 (0.0)	1.0 (1.7)	2.0 (3.5)	65.0 (39.0)
	Mid	3.3 (1.5)	15.3 (7.0)	0.0 (0.0)	11.3 (16.3)	2.0 (3.5)	77.7 (17.8)
	Upper	4.7 (2.1)	18.0 (7.5)	1.0 (1.7)	13.3 (21.4)	1.0 (1.7)	73.7 (17.5)
North-east	Lower	11.7 (3.5)	50.0 (8.7)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	65.0 (17.3)
	Mid	4.3 (3.2)	14.0 (8.0)	0.7 (1.2)	5.0 (8.7)	16.7 (28.9)	72.0 (36.4)
	Upper	3.7 (0.6)	15.7 (4.5)	2.0 (1.0)	8.5 (9.2)	21.3 (30.9)	62.3 (36.8)
East	Lower	4.3 (0.6)	19.3 (6.0)	0.0 (0.0)	0.3 (0.6)	0.0 (0.0)	83.3 (11.2)
	Mid	3.7 (0.6)	30.0 (20.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	72.0 (23.1)
	Upper	4.3 (1.2)	15.3 (7.5)	0.0 (0.0)	1.0 (1.0)	0.0 (0.0)	86.0 (9.0)
South-east	Lower	2.7 (1.5)	11.3 (8.1)	1.0 (1.7)	0.7 (1.2)	3.3 (5.8)	92.0 (8.7)
	Mid	4.7 (0.6)	15.0 (5.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	90.0 (8.7)
	Upper	7.7 (6.4)	26.0 (21.6)	0.7 (1.2)	0.3 (0.6)	21.7 (22.5)	58.7 (47.9)
South	Lower	4.7 (1.2)	15.7 (1.2)	0.3 (0.6)	0.0 (0.0)	18.0 (27.7)	75.3 (23.5)
	Mid	8.7 (5.7)	29.3 (17.9)	0.5 (0.7)	1.7 (2.9)	7.3 (11.0)	70.3 (35.4)
	Upper	6.3 (2.9)	24.0 (6.6)	5.3 (4.2)	0.0 (0.0)	64.7 (15.0)	18.0 (19.3)
South-west	Lower	6.0 (1.0)	33.0 (10.4)	2.3 (2.1)	0.0 (0.0)	15.0 (21.8)	56.3 (27.0)
	Mid	4.3 (2.1)	27.3 (11.7)	0.0 (0.0)	0.0 (0.0)	5.0 (8.7)	71.7 (20.2)
	Upper	6.3 (1.5)	36.3 (27.7)	2.7 (2.1)	0.0 (0.0)	45.0 (31.8)	34.3 (42.4)
West	Lower	3.7 (2.1)	17.3 (13.3)	0.7 (1.2)	0.3 (0.6)	13.3 (22.2)	73.3 (17.4)
	Mid	5.3 (2.5)	30.7 (1.2)	0.0 (0.0)	3.3 (5.8)	0.0 (0.0)	73.3 (17.2)
	Upper	5.0 (1.7)	28.3 (14.4)	3.0 (2.6)	0.0 (0.0)	50.3 (43.7)	23.0 (27.9)
North-west	Lower	4.0 (1.0)	20.7 (8.1)	1.0 (1.0)	2.7 (3.8)	0.3 (0.6)	85.0 (11.5)
	Mid	3.7 (1.2)	21.7 (3.2)	0.7 (1.2)	6.0 (9.5)	0.3 (0.6)	89.3 (9.9)
	Upper	5.0 (4.4)	22.0 (11.8)	0.3 (0.6)	13.3 (15.3)	22.7 (31.0)	62.0 (30.2)
Basin	Lower	25.0 (10.0)	88.7 (7.8)	0.0 (0.0)	0.0 (0.0)	13.3 (18.9)	61.7 (27.5)
	Mid	35.7 (48.8)	71.7 (30.1)	0.0 (0.0)	0.0 (0.0)	2.3 (3.2)	62.0 (52.0)
	Upper	7.0 (9.5)	34.3 (27.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	93.0 (9.5)

Data are means with standard deviation in brackets.

Table 5.3. List of plant species and their mean % canopy cover and occurrence on two phosphogypsum stacks in Fort Saskatchewan, Alberta.

Scientific Name	Common Name	Status	Canopy Cover (%)	Occurrence (%)
Agropyron dasystachyum (Hook.) Scribn. & J.G. Sm.	Northern wheat grass	Native	T (1)	4
Agropyron repens(L.) Gould	Quack grass	Nuisance weed	3.0 (5.4)	41
Agropyron smithii Rydb.	Western wheat grass	Native	T (T)	1
Agropyron trachycaulum(Link) Gould ex Shinners	Slender wheat grass	Native	T (1)	1
Bromus inermis Leyss.	Smooth brome	Introduced	11.9 (9.1)	83
Bromus pumpellianus Scribn.	Pumpelly's brome	Native/Introduced	2.3 (3.9)	29
Festuca rubra L.	Creeping red fescue	Native	T (0.8)	10
Hordeum jubatum L.	Foxtail barley	Native/Introduced	T (T)	2
Phalaris arundinacea L.	Reed canary grass	Native	T (T)	T
Poa pratensis L.	Kentucky blue grass	Native/Introduced	T (0.9)	13
Axyris amaranthoidesL.	Russian pigweed	Native/Introduced	0.5 (1.3)	11
Achillea millefolium	Yarrow	Native	T (T)	1
Androsace septentrionalis L.	Northern fairy candelabra	Native	T (T)	1
Brassica kaber (DC.) L.C. Wheeler	Wild mustard	Introduced	0.9 (5.0)	4
Chenopodium album L.	Lamb's quarters	Introduced	T (T)	4
Cirsium arvense L.	Canada thistle	Noxious weed	0.6 (2.5)	6
Crepis Tectorum Hill.	Narrow leaved hawk's beard	Nuisance weed	T (T)	T
Descurainia sophia (L.) Webb.	Flixweed	Nuisance weed	0.7 (2.3)	8
Dracocephalum parviflorum Nutt.	American dragonhead	Native	T (T)	2
Epilobium angustifolium L.	Fireweed	Native	T (1.1)	6
Erysimum cheiranthoides L.	Wormseed mustard	Nuisance weed	T (2.0)	6
Kochia scoparia (L.) *Schrad.*	Mexican fireweed	Nuisance weed	T (1.2)	6
Linaria vulgaris Hill.	Toadflax	Noxious weed	T (1.7)	6
Linum perenne L.	Blue flax	Introduced	T (0.6)	3
Matricaria perforata Merat.	Scentless chamomile	Noxious weed	T (T)	T
Medicago sativa L.	Alfalfa	Introduced	T (T)	1

Data are means with standard deviation in brackets.
T = trace and indicates values < 0.5 %.

Table 5.3. List of plant species and their mean % canopy cover and occurrence on two phosphogypsum stacks in Fort Saskatchewan, Alberta (continued).

Scientific Name	Common Name	Status	Canopy Cover (%)	Occurrence (%)
Melilotus alba Desr.	White sweet clover	Introduced	T (T)	13
Polygonum aviculare L.	Prostrate knotweed	Nuisance weed	T (T)	1
Polygonum convolvulus L.	Wild buckwheat	Nuisance weed	T (T)	8
Sonchus arvensis L.	Perennial sow thistle	Noxious weed	T (T)	4
Taraxacum officinale Weber	Dandelion	Nuisance weed	T (0.6)	7
Thlaspi arvense L.	Stinkweed	Nuisance weed	1.2 (3.2)	16
Trifolium hybridum L.	Alsike clover	Native/Introduced	T (T)	0
Vicia americana Muhl. Ex Willd	Wild vetch	Native	T (T)	1
Populus tremuloides Michx.	Trembling aspen	Native	T (T)	T

Data are means with standard deviation in brackets.
T = trace and indicates values < 0.5 %.

Table 5.4. Vegetation species composition on PG Stack 1.

Aspect	Plot	Plant Species Present	Cover (%)	Occurrence (%)
Northwest	Lower	*Bromus inermis*	41.3 (7.6)	100
		Agropyron repens	1.0 (1.7)	33
		Agropyron dasystachyum	0.3 (0.6)	33
		Poa pratensis	0.7 (1.2)	33
	Mid	*Bromus inermis*	17.0 (1.0)	100
		Circisum arvense	1.0 (1.7)	33
		Agropyron repens	1.7 (1.2)	100
		Poa pratensis	0.7 (0.6)	67
		Festuca rubra	0.3 (0.0)	33
	Upper	*Bromus inermis*	24.3 (14.0)	100
		Medicago sativa	0.7 (1.2)	33
		Festuca rubra	3.7 (3.8)	100
		Polygonum convolvulus	0.3 (0.6)	33
		Agropyron repens	0.7 (1.2)	33
North	Lower	*Bromus inermis*	21.3 (37.0)	33
		Festuca rubra	1.0 (1.7)	33
		Thlaspi arvense	15.0 (15.1)	100
		Agropyron repens	1.3 (1.5)	67
		Brassica kaber	6.7 (5.8)	67
		Melilotus alba	0.3 (0.6)	33
		Chenopodium album	0.7 (1.2)	33
		Bromus pumpellianus	1.7 (2.9)	33
		Cirsium arvense	0.2 (0.3)	33
	Mid	*Bromus inermis*	19.2 (4.9)	100
		Festuca rubra	4.0 (5.3)	67
		Poa pratensis	4.0 (4.2)	67
		Agropyron repens	1.0 (1.0)	67
		Melilotus alba	0.2 (0.3)	33
		Polygonum convolvulus	0.2 (0.3)	33
	Upper	*Bromus inermis*	12.0 (9.2)	100
		Agropyron repens	1.3 (0.6)	100
		Festuca rubra	0.3 (0.6)	33
		Melilotus alba	0.2 (0.3)	33
		Bromus pumpellianus	1.7 (2.9)	33
Northeast	Lower	*Bromus pumpellianus*	20.0 (34.6)	33
		Bromus inermis	6.0 (7.2)	67
		Linum perenne	0.3 (0.6)	33
		Thlaspi arvense	12.7 (14.2)	67
		Brassica kaber	34.3 (36.7)	67
		Agropyron repens	10.0 (17.3)	33
		Polygonum convolvulus	0.7 (1.2)	33
		Melilotus alba	0.7 (1.2)	33
		Chenopodium album	0.3 (0.6)	33

Data are means with standard deviation in brackets.

Table 5.4. Vegetation species composition on PG Stack 1 (continued).

Aspect	Plot	Plant Species Present	Cover (%)	Occurrence (%)
Northeast	Mid	*Melilotus alba*	0.5 (0.0)	67
		Bromus pumpellianus	8.0 (6.1)	100
		Agropyron repens	0.7 (0.6)	67
		Bromus inermis	5.8 (2.8)	100
	Upper	*Melilotus alba*	0.5 (0.0)	100
		Poa pratensis	0.2 (0.3)	33
		Polygonum convolvulus	0.2 (0.3)	33
		Bromus inermis	3.8 (1.9)	100
		Bromus pumpellianus	4.2 (1.8)	100
		Agropyron repens	0.5 (0.5)	67
		Agropyron smithii	0.2 (0.3)	33
		Festuca rubra	0.3 (0.6)	33
		Thlaspi arvense	0.2 (0.3)	33
East	Lower	*Bromus pumpellianus*	15.3 (17.2)	67
		Poa pratensis	2.0 (2.0)	67
		Festuca rubra	1.3 (1.2)	67
		Bromus inermis	5.0 (6.2)	67
		Taraxacum officinale	1.7 (2.9)	33
		Cirsium arvense	2.0 (3.5)	33
		Agropyron repens	2.3 (4.0)	33
	Mid	*Poa pratensis*	2.7 (3.1)	67
		Festuca rubra	1.7 (1.5)	67
		Bromus pumpellianus	3.3 (3.5)	67
		Bromus inermis	3.3 (8.9)	100
		Agropyron repens	2.7 (2.5)	67
	Upper	*Bromus pumpellianus*	10.3 (9.3)	67
		Agropyron repens	8.5 (14.3)	67
		Bromus inermis	10.3 (4.6)	100
Southeast	Lower	*Epilobium angustifolium*	3.7 (3.2)	67
		Bromus inermis	17.0 (24.4)	67
		Agropyron repens	7.0 (8.2)	67
		Poa pratensis	0.2 (0.3)	33
		Brassica kaber	0.2 (0.3)	33
	Mid	*Bromus pumpellianus*	4.7 (8.1)	33
		Agropyron repens	17.7 (13.7)	100
		Melilotus alba	0.2 (0.3)	33
		Epilobium angustifolium	0.3 (0.6)	33
		Axyris amaranthoides	1.2 (0.8)	33
		Thlaspi arvense	0.2 (0.3)	33
		Poa pratensis	0.7 (1.2)	33
		Bromus inermis	2.0 (3.5)	33

Data are means with standard deviation in brackets.

Table 5.4. Vegetation species composition on PG Stack 1 (continued).

Aspect	Plot	Plant Species Present	Cover (%)	Occurrence (%)
Southeast	Upper	*Agropyron repens*	5.7 (7.4)	67
		Epilobium angustifolium	6.3 (6.0)	67
		Bromus pumpellianus	1.0 (1.7)	33
		Festuca rubra	0.2 (0.3)	33
		Bromus inermis	5.7 (8.5)	67
South	Lower	*Epilobium angustifolium*	2.3 (4.0)	33
		Bromus inermis	10.3 (9.0)	67
		Trifolium hybridum	0.2 (0.3)	33
		Melilotus alba	0.2 (0.3)	33
		Agropyron repens	1.7 (1.5)	67
		Bromus pumpellianus	1.0 (1.0)	67
		Polygonum convolvulus	0.7 (1.2)	33
		Descurainia sophia	8.0 (13.9)	33
	Mid	*Bromus inermis*	15.7 (12.5)	100
		Bromus pumpellianus	2.0 (2.0)	67
		Vicia americana	0.3 (0.6)	33
		Epilobium angustifolium	2.3 (4.0)	33
		Taraxacum officinale	2.0 (3.5)	33
		Festuca rubra	0.2 (0.3)	33
	Upper	*Bromus inermis*	17.3 (8.1)	100
		Agropyron repens	0.3 (0.6)	33
		Descurainia sophia	0.2 (0.3)	33
Southwest	Lower	*Agropyron repens*	6.7 (2.9)	100
		Bromus inermis	5.7 (4.0)	100
		Axyris amaranthoides	6.7 (5.8)	67
		Thlaspi arvense	0.7 (1.2)	33
		Polygonum convolvulus	0.7 (1.2)	33
	Mid	*Polygonum convolvulus*	0.3 (0.6)	33
		Bromus inermis	7.0 (2.6)	100
		Bromus pumpellianus	1.7 (2.9)	33
		Agropyron repens	0.2 (0.3)	33
	Upper	*Bromus inermis*	12.3 (5.7)	100
		Agropyron repens	0.3 (0.6)	67

Data are means with standard deviation in brackets.

Table 5.4. Vegetation species composition on Stack 1 (continued).

Aspect	Plot	Plant Species Present	Cover (%)	Occurrence (%)
West	Lower	*Thlaspi arvense*	11.7 (20.2)	33
		Polygonum convolvulus	1.3 (2.3)	33
		Agropyron repens	29.3 (49.9)	67
		Axyris amaranthoides	3.5 (5.6)	67
		Bromus inermis	3.0 (5.2)	33
		Descurainia sophia	3.3 (5.8)	33
		Chenopodium album	0.3 (0.6)	33
	Mid	*Bromus inermis*	1.3 (1.2)	67
		Agropyron repens	1.7 (2.1)	67
		Hordeum jubatum	0.3 (0.6)	33
		Sonchus arvensis	1.7 (2.9)	33
		Linum perenne	0.7 (1.2)	33
		Bromus pumpellianus	2.0 (3.5)	33
		Dracocephalum parviflorum	1.3 (2.3)	33
		Descurainia sophia	5.0 (8.7)	33
		Polygonum convolvulus	2.3 (4.0)	33
		Thlaspi arvense	1.0 (1.7)	33
		Axyris amaranthoides	2.7 (4.6)	33
	Upper	*Bromus inermis*	3.0 (1.2)	100
		Taraxacum officinale	1.0 (1.7)	33
		Linum perenne	3.9 (8.5)	67
		Sonchus arvensis	1.3 (2.3)	33
		Agropyron repens	0.5 (0.5)	67
		Bromus pumpellianus	7.0 (11.3)	67

Data are means with standard deviation in brackets.

Table 5.5. Vegetation species composition on PG Stack 2.

Aspect	Slope Position	Plant Species	Cover (%)	Occurrence (%)
North	Lower	*Agropyron repens*	11.0 (19.1)	33
		Bromus pumpellianus	2.0 (3.5)	33
		Bromus inermis	27.7 (45.3)	67
		Cirsium arvense	2.3 (4.0)	33
		Melilotus alba	0.2 (0.3)	33
	Mid	*Epilobium angustifolium*	0.7 (1.2)	33
		Melilotus alba	0.3 (0.6)	33
		Bromus inermis	9.7 (10.8)	100
		Bromus pumpellianus	2.0 (1.7)	67
		Achillea millefolium	1.0 (1.7)	33
		Poa pratensis	1.7 (2.9)	33
		Trifolium hybridum	1.0 (1.7)	33
	Upper	*Axyris amaranthoides*	0.3 (0.6)	33
		Bromus pumpellianus	2.3 (2.5)	67
		Bromus inermis	11.7 (11.5)	100
		Melilotus alba	1.3 (2.3)	33
		Poa pratensis	1.3 (1.5)	67
		Hordeum jubatum	0.2 (0.3)	33
Northeast	Lower	*Bromus inermis*	44.7 (15.0)	100
		Bromus pumpellianus	5.0 (8.7)	33
	Mid	*Thlaspi arvense*	0.3 (0.6)	33
		Hordeum jubatum	0.7 (1.2)	33
		Bromus inermis	11.0 (7.9)	100
		Bromus pumpellianus	2.0 (2.6)	67
		Sonchus arvensis	0.3 (0.6)	33
		Agropyron repens	0.3 (0.6)	33
	Upper	*thlaspi arvense*	0.2 (0.3)	33
		Bromus inermis	11.3 (6.7)	100
		Sonchus arvensis	1.3 (2.3)	33
		Melilotus alba	0.2 (0.3)	33
		Bromus pumpellianus	2.7 (4.6)	33
East	Lower	*Bromus inermis*	16.7 (10.4)	100
		Linaria vulgaris	1.0 (1.7)	33
	Mid	*Bromus pumpellianus*	1.7 (1.7)	33
		Bromus inermis	13.3 (15.3)	67
		Descurainia sophia	0.7 (1.2)	33
		Cirsium arvense	14.0 (24.2)	33
		Agropyron dasystachyum	1.0 (1.7)	33
		Agropyron repens	0.7 (1.2)	33
		Sonchus arvensis	0.3 (0.6)	33
	Upper	*Bromus inermis*	9.3 (10.1)	67
		Bromus pumpellianus	2.0 (1.7)	67
		Taraxacum officinale	1.0 (1.7)	33
		Agropyron dasystachyum	2.0 (3.5)	33
		Agropyron repens	2.0 (3.5)	33
		Thlaspi arvense	0.2 (0.3)	33

Data are means with standard deviation in brackets.

Table 5.5. Vegetation species composition on PG Stack 2 (continued).

Aspect	Slope Position	Plant Species	Cover (%)	Occurrence (%)
Southeast	Lower	*Bromus pumpellianus*	5.0 (5.0)	67
		Bromus inermis	6.3 (5.1)	100
		Agropyron repens	0.2 (0.3)	33
	Mid	*Bromus inermis*	15.0 (5.0)	100
	Upper	*Bromus inermis*	8.3 (8.5)	67
		Thlaspi arvense	0.7 (1.2)	33
		Polygonum convolvulus	0.3 (0.6)	33
		Agropyron trachycaulum	7.3 (12.7)	33
		Chenopodium album	1.0 (1.7)	33
		Kochia scoparia aria	6.8 (11.4)	67
		Polygonum aviculare	0.7 (1.2)	33
		Axyris amaranthoides	1.0 (1.7)	33
South	Lower	*Agropyron dasystachyum*	2.7 (4.6)	33
		Axyris amaranthoides	1.7 (2.9)	33
		Kochia scoparia	1.7 (2.9)	33
		Thlaspi arvense	0.3 (0.6)	33
		Descurainia sophia	1.0 (1.7)	33
		Bromus pumpellianus	1.0 (1.7)	33
		Bromus inermis	8.3 (6.5)	100
		Erysimum cheiranthoides	0.7 (1.2)	33
	Mid	*Bromus inermis*	9.3 (9.0)	67
		Linaria vulgaris	2.0 (0.8)	33
		Taraxacum officinale	1.3 (2.3)	33
		Axyris amaranthoides	1.0 (1.7)	33
		Descurainia sophia	0.3 (0.6)	33
		Agropyron repens	1.7 (2.9)	33
		Kochia scoparia	1.7 (2.9)	33
	Upper	*Thlaspi arvense*	1.0 (1.7)	33
		Descurainia sophia	0.7 (1.2)	33
		Taraxacum officinale	1.0 (1.7)	33
		Kochia scoparia	0.3 (0.6)	33
		Agropyron repens	2.0 (3.5)	33
		Linaria vulgaris	1.7 (0.3)	33
		Axyris amaranthoides	1.7 (2.9)	33
		Bromus inermis	7.7 (6.4)	100
SouthWest	Lower	*Linaria vulgaris*	1.3 (1.5)	33
		Bromus inermis	8.7 (1.2)	100
		Kochia scoparia	3.3 (5.8)	33
		Chenopodium album	1.3 (2.3)	33
	Mid	*Linaria vulgaris*	2.7 (4.6)	33
		Bromus inermis	5.7 (9.8)	33
		Erysimum cheiranthoides	12.7 (21.9)	33
		Kochia scoparia	0.7 (1.2)	33
		Thlaspi arvense	0.7 (1.2)	33
		Agropyron repens	5.0 (8.7)	33

Data are means with standard deviation in brackets.

Table 5.5. Vegetation species composition on PG Stack 2 (continued).

Aspect	Slope Position	Plant Species	Cover (%)	Occurrence (%)
SouthWest	Upper	*Descurainia sophia*	13.3 (23.1)	33
		Thlaspi arvense	3.3 (5.8)	33
		Cirsium arvense	1.7 (2.9)	33
		Erysimum cheiranthoides	7.0 (7.2)	100
		Axyris amaranthoides	1.3 (1.2)	67
		Bromus inermis	3.7 (3.5)	67
		Kochia scoparia	3.3 (5.8)	33
		Agropyron repens	2.7 (4.6)	33
West	Lower	*Axyris amaranthoides*	3.7 (4.7)	67
		Dracocephalum parviflorum	1.0 (1.7)	33
		Bromus inermis	7.7 (6.0)	100
		Erysimum cheiranthoides	0.7 (1.2)	100
		Linaria vulgaris	3.0 (5.2)	33
		Polygonum convolvulus	0.3 (0.6)	33
		Thlaspi arvense	0.3 (0.6)	33
		Agropyron repens	0.7 (1.2)	33
	Mid	*Cirsium arvense*	10.0 (10.0)	67
		Thlaspi arvense	4.7 (6.4)	67
		Descurainia sophia	2.3 (2.1)	67
		Agropyron dasystachyum	1.7 (2.9)	33
		Agropyron repens	11.7 (16.9)	67
		Epilobium angustifolium	0.3 (0.6)	33
	Upper	*Descurainia sophia*	0.7 (1.2)	33
		Thlaspi arvense	2.3 (4.0)	33
		Axyris amaranthoides	0.7 (1.2)	33
		Bromus inermis	26.7 (16.1)	100
Northwest	Lower	*Linaria vulgaris*	7.0 (9.6)	67
		Bromus inermis	10.3 (4.5)	100
		Taraxacum officinale	0.5 (0.5)	33
		Vicia americana	2.7 (2.5)	67
		Poa pratensis	0.3 (0.6)	33
		Androsace septentrionalis	0.2 (0.3)	33
		Melilotus alba	0.2 (0.3)	33
	Mid	*Taraxacum officinale*	2.0 (2.6)	67
		Poa pratensis	3.3 (3.1)	67
		Bromus inermis	13.7 (4.0)	67
		Bromus pumpellianus	1.7 (2.9)	33
		Agropyron repens	0.3 (0.6)	33
		Melilotus alba	0.2 (0.3)	33
		Androsace septentrionalis	0.7 (1.2)	33

Data are means with standard deviation in brackets.

Table 5. Vegetation species composition on PG Stack 2 (continued).

Aspect	Slope Position	Plant Species	Cover (%)	Occurrence (%)
Northwest	Upper	*Bromus pumpellianus*	0.7 (1.2)	33
		Melilotus alba	0.7 (1.2)	33
		Bromus inermis	17.0 (15.7)	100
		Agropyron repens	0.8 (1.0)	67
		Thlaspi arvense	0.2 (0.3)	33
		Dracocephalum parviflorum	0.3 (0.6)	33
		Taraxacum officinale	2.7 (4.6)	33
Basin	West	*Agropyron repens*	23.3 (40.4)	33
		Brassica kaber	1.3 (1.5)	67
		Descurainia sophia	1.8 (2.8)	67
		Thlaspi arvense	1.3 (2.3)	33
		Kochia scoparia	31.5 (49.8)	100
		Cirsium arvense	1.3 (2.3)	33
		Hordeum jubatum	1.7 (2.9)	33
		Matricaria perforata	0.2 (0.3)	33
	Mid	*Bromus inermis*	26.3 (45.6)	33
		Kochia scoparia	23.3 (40.4)	33
		Sonchus arvensis	7.0 (12.1)	33
		matricaria perforata	2.3 (4.0)	33
		Crepis Tectorum	0.2 (0.4)	33
		Descurainia sophia	1.1 (1.9)	33
		Bromus inermis	5.6 (9.6)	33
		Hordeum jubatum	0.3 (0.6)	33
		Agropyron repens	5.8 (8.2)	67
		Thlaspi arvense	1.7 (2.9)	33
		Linaria vulgaris	0.7 (1.2)	33
	East	*Phalaris arundinacea*	3.3 (5.8)	33
		Bromus inermis	16.7 (28.9)	33
		Kochia scoparia	1.0 (1.7)	33
		Descurainia sophia	11.7 (20.2)	33
		Cirsium arvense	5.0 (8.7)	33

Data are means with standard deviation in brackets.

6. SUMMARY AND FUTURE RESEARCH

6.1 Research Summary

On reclaimed phosphogypsum stacks, revegetation was the most successful on cap depths ≥ 15 cm. Vegetation on ≥ 15 cm caps had similar health, height, cover and biomass. Little vegetation grew on uncapped plots; on 8 cm caps plants were of intermediate health, height, cover and biomass. Of the seeded species, *Agropyron trachycaulum* (Link) Malte ex H.F. Lewis (slender wheat grass), *Festuca ovina* L. (sheep fescue) and *Agrostis stolonifera* L. (redtop) were growing well on the stack; *Deschampsia caespitosa* (L.) Beauv. (tufted hair grass) and *Trifolium hybridum* L. (alsike clover) were not. Few plant roots were found in PG. Root mass accumulations at the soil-PG interface were common, possibly due to higher water content at that location or because they are unable to move deeper due to PG characteristics such as compaction, acidity, or low nutrient concentration.

Fluorine, cobalt and nickel were elevated in some plants from the research plots however their concentrations were substantially lower than the maximum tolerable limits for rodents, poultry and cattle (United States National Research Council 2005, Kabata-Pendias 2011). Elevated nickel and cobalt in the plants may be due to metals accumulating on the stacks from outside sources. Cap depths ≥ 15 cm contained tissue fluorine concentrations similar to references and within the normal plant range. Tissue cobalt decreased with increasing cap depth and was within the normal plant range in the 91 cm cap depth and slightly elevated in cap depths of 30 to 46 cm.

Water content was substantially higher at the soil-PG interface than at other profile locations. High water content at the interface may be one of the reasons roots are accumulating there. Soil water content was lower in 91 cm caps than 8 and 46 cm caps; therefore cap depths ≤ 46 cm may be preferable caps to maintain high soil water content for optimum plant growth. Water content in PG was similar for 15-46 cm caps, higher for 0 and 8 cm caps and slightly lower for 91 cm caps. It was likely higher for 0 and 8 cm caps due to little vegetation to take up and transpire water, and lower for 91 cm caps because sampling was not deep enough below the soil-PG interface. Substantial quantities of water were found below the root zone, indicating it is lost to plants, will not be transpired and will end up deeper in the stack.

Snow metal concentrations were assessed with distance from the neighbouring metal refinery and associated tailings pond. Cobalt, iron and nickel at Agrium likely originated from the refinery because their snow concentrations increase with proximity to the refinery. At locations very close to the tailings pond concentrations of copper, iron and nickel were exponentially higher than at locations further away. Copper concentrations at Agrium likely do not originate from the refinery because there is no discernible pattern of copper concentration in snow with distance to the refinery.

Vegetation 12 years after soil capping and seeding consisted of 35 species of mainly grasses and ruderals. Stack slopes were covered mainly by vegetation and litter. More vegetation and less bare ground was found on lower slope positions than upper slope positions, with mid slope positions intermediate in vegetation cover.

6.2 Reclamation Applications

Results from this research indicate soil caps ≥ 15 cm are adequate for plant growth and development with acceptable health, cover and biomass. Caps ≥ 8 cm sustain plants with trace element concentrations that are safe for consumption to herbivores based on values from the United States National Research Council (2005). Caps ≤ 46 cm may be preferable to deeper caps due to higher root zone water which allow plants to access water rather than have it percolate to deeper layers. Nickel, copper and iron are likely originating from the nearby metal refinery and therefore these metals are not an inherent aspect of PG stack reclamation in Fort Saskatchewan; this should be considered in reclamation plans. Based on these studies a cap depth of 15 to 46 cm is recommended for reclamation, however further research must be conducted on other parameters to make final recommendations.

6.3 Future Research

Future research could be conducted to assess longer term effects of capping depths on previously and non-previously assessed parameters to determine an optimal cover system for PG stacks. Further research could be conducted to further characterize the relationship of snow metals onsite to the neighboring metal refinery. Specific areas for further studies could include the following.

- Response of seeding plant species, including trees and shrubs, not previously seeded on the stacks to determine optimal seed mixes for PG stack reclamation.
- Effect of compacting the PG surface before capping on water and vegetation to determine the ideal level of compaction for PG stack reclamation.
- Effect of creating a layer of mixed soil and PG above the PG and below a soil cap on vegetation and water to determine if this will improve reclamation.
- Ecotoxicology studies to determine effects of PG, and various combinations of PG and soil, on biological organisms such as earthworms to assess capping depth necessary to protect burrowing organisms.
- Assessment of actual evapotranspiration of stack vegetation as a component of a water balance assessment.

6. 4 References

Kabata-Pendias, A. 2011. Trace elements in soils and plants. 4th Edition. Taylor & Francis Group. Boca Raton FL. 520 pp.

United States National Research Council. 2005. Mineral tolerance of animals. 2nd Edition. Subcommittee on Mineral Toxicity in Animals. National Academic Press. Washington DC. 510 pp.

APPENDIX

Table A.2.1. Trace element concentrations in substrate from research plots at Agrium Fort Saskatchewan, Alberta and references.

Element	Test	Cap Depth (cm) or Reference						
		Reference	0	8	15	30	46	91
Antimony	% ADL	100	100	100	100	100	100	100
	ppm	0.58 (0.0)	0.28 (0.0)	0.27 (0.0)	0.29 (0.0)	0.30 (0.0)	0.31 (0.0)	0.30 (0.0)
Arsenic	% ADL	100	100	100	100	100	100	100
	ppm	6.63 (0.4)	2.22 (1.0)	2.26 (0.3)	3.40 (0.6)	3.68 (0.2)	3.94 (0.0)	3.88 (0.1)
Barium	% ADL	100	100	100	100	100	100	100
	ppm	639.36 (19.5)	75.76 (18.8)	259.98 (37.7)	467.39 (48.3)	476.64 (3.5)	480.69 (4.4)	477.37 (5.5)
Bromine	% ADL	100	100	100	100	100	100	100
	ppm	4.39 (0.6)	0.68 (0.2)	1.75 (0.4)	3.69 (0.3)	4.20 (0.3)	2.49 (0.2)	3.84 (0.1)
Cadmium	% ADL	0	0	0	0	0	0	0
	ppm	<0.89	<0.89	<0.89	<0.89	<0.89	<0.89	<0.89
Cerium	% ADL	100	100	100	100	100	100	100
	ppm	43.69 (3.1)	80.66 (15.4)	44.30 (3.6)	22.42 (1.1)	24.30 (3.3)	22.93 (0.2)	22.29 (0.7)
Caesium	% ADL	100	67	100	100	100	100	100
	ppm	2.70 (0.2)	0.17 (0.1)	0.54 (0.1)	0.87 (0.1)	1.04 (0.0)	0.98 (0.0)	0.90 (0.1)
Chromium	% ADL	100	100	100	100	100	100	100
	ppm	48.76 (3.4)	33.03 (9.8)	57.15 (15.4)	63.02 (43.1)	23.24 (1.1)	62.03 (33.4)	62.38 (34.8)
Cobalt	% ADL	100	100	100	100	100	100	100
	ppm	5.96 (0.4)	27.20 (4.5)	14.03 (4.0)	6.64 (1.9)	3.33 (0.6)	4.14 (0.5)	5.03 (0.3)
Europium	% ADL	86	100	100	33	67	33	33
	ppm	0.79 (0.1)	2.61 (0.7)	1.21 (0.1)	<0.45	0.45 (0.0)	<0.45	<0.45
Fluorine	% ADL	100	100	100	100	100	100	100
	ppm	270.48 (17.0)	8310.00 (871.7)	4593.33 (308.5)	995.00 (754.1)	196.67 (52.4)	210.67 (10.7)	177.00 (39.6)
Gold	% ADL	0	100	100	33	33	67	100
	ppb	-	4.24 (1.2)	2.21 (0.7)	<0.85	<0.85	1.58 (0.7)	1.34 (0.4)

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments except Reference where n = 21.
Reference values are a mean of three replicates from seven offsite reference locations which all had similar trace elements concentrations.

Table A.2.1. Trace element concentrations in substrate from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference						
		Reference	0	8	15	30	46	91
Hafnium	% ADL	100	67	100	100	100	100	100
	ppm	4.04 (0.3)	1.90 (0.6)	2.59 (0.6)	2.27 (0.3)	2.4 (0.3)	2.53 (0.1)	2.40 (0.1)
Iridium	% ADL	0	0	0	0	0	0	0
	ppb	<5.99	<5.99	<5.99	<5.99	<5.99	<5.99	<5.99
Iron	% ADL	100	100	100	100	100	100	100
	%	2.30 (0.2)	0.21 (0.0)	0.65 (0.1)	0.90 (0.2)	1.07 (0.1)	1.03 (0.0)	1.04 (0.0)
Lanthanum	% ADL	100	100	100	100	100	100	100
	ppm	20.37 (1.2)	70.99 (20.3)	31.91 (3.6)	13.99 (0.6)	11.73 (0.3)	13.60 (0.6)	13.20 (0.2)
Lutetium	% ADL	86	67	67	33	67	33	33
	ppm	0.11 (0.0)	0.55 (0.0)	0.43 (0.0)	<0.03	0.05 (0.0)	<0.03	<0.03
Mercury	% ADL	0	0	0	0	0	0	0
	ppm	<2.74	<2.74	<2.74	<2.74	<2.74	<2.74	<2.74
Molybdenum	% ADL	0	0	0	0	0	0	0
	ppm	<0.71	<0.71	<0.71	<0.71	<0.71	<0.71	<0.71
Nickel	% ADL	100	100	100	100	100	100	67
	ppm	25.03 (2.2)	73.27 (11.9)	40.63 (15.6)	27.12 (11.8)	13.26 (1.7)	12.03 (1.9)	13.77 (3.2)
Potassium	% ADL	100	33	67	100	67	100	67
	%	2.13 (0.2)	*	0.66 (0.0)	0.78 (0.1)	1.15 (0.2)	0.73 (0.1)	0.89 (0.0)
Rubidium	% ADL	100	33	100	100	100	100	100
	ppm	71.78 (4.0)	*	19.29 (4.2)	34.11 (3.5)	38.76 (3.1)	38.05 (3.6)	38.50 (4.9)
Samarium	% ADL	100	100	100	100	100	100	100
	ppm	3.54 (0.2)	8.73 (0.9)	5.09 (0.4)	2.46 (0.4)	2.00 (0.1)	2.29 (0.1)	2.19 (0.0)
Scandium	% ADL	100	100	100	100	100	100	100
	ppm	7.67 (0.6)	1.05 (0.2)	2.08 (0.3)	2.75 (0.5)	3.20 (0.1)	3.28 (0.1)	3.18 (0.2)

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments except Reference where n = 21.
Reference values are a mean of three replicates from seven offsite reference locations which all had similar trace elements concentrations.
-Data below detection limit; *Incomplete data set available for calculation of mean because most data below detection limit.

Table A.2.1. Trace element concentrations in substrate from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference						
		Reference	0	8	15	30	46	91
Selenium	% ADL	0	0	0	0	0	0	0
	ppm	<1.03	<1.03	<1.03	<1.03	<1.03	<1.03	<1.03
Silver	% ADL	0	67	0	0	0	0	0
	ppm	<0.56	3.40 (2.7)	<0.56	<0.56	<0.56	<0.56	<0.56
Sodium	% ADL	100	100	100	100	100	100	100
	%	0.72 (0.0)	0.08 (0.0)	0.35 (0.0)	0.49 (0.1)	0.59 (0.0)	0.57 (0.0)	0.56 (0.0)
Tantalum	% ADL	100	100	100	100	100	100	100
	ppm	0.41 (0.0)	0.30 (0.1)	0.23 (0.0)	0.30 (0.1)	0.20 (0.0)	0.55 (0.3)	0.22 (0.1)
Tellurium	% ADL	0	0	0	0	0	0	0
	ppm	<1.87	<1.87	<1.87	<1.87	<1.87	<1.87	<1.87
Terbium	% ADL	100	100	100	100	100	100	100
	ppm	0.39 (0.0)	1.44 (0.3)	0.66 (0.1)	0.31 (0.0)	0.22 (0.0)	0.28 (0.0)	0.26 (0.1)
Thorium	% ADL	100	100	100	100	100	100	100
	ppm	7.81 (0.4)	1.81 (0.2)	2.92 (0.3)	3.77 (0.4)	4.22 (0.2)	4.16 (0.2)	4.52 (0.4)
Tin	% ADL	0	0	0	0	0	0	0
	ppm	<46.37	<46.37	<46.37	<46.37	<46.37	<46.37	<46.37
Tungsten	% ADL	81	0	33	67	67	100	100
	ppm	0.81 (0.1)	<0.32	<0.32	0.33 (0.0)	0.41 (0.1)	0.41 (0.1)	0.32 (0.0)
Uranium	% ADL	100	100	100	100	100	100	100
	ppm	1.76 (0.1)	3.50 (0.2)	2.07 (0.4)	1.19 (0.2)	0.89 (0.0)	1.05 (0.1)	1.02 (0.1)
Ytterbium	% ADL	100	100	100	100	100	100	100
	ppm	1.68 (0.1)	3.70 (1.0)	1.83 (0.1)	0.85 (0.2)	0.82 (0.0)	0.96 (0.1)	0.91 (0.1)
Zinc	% ADL	90	33	67	33	67	33	33
	ppm	76.15 (4.6)	<43.01	41.00 (4.0)	<43.01	37.03 (5.3)	<43.01	<43.01
Zirconium	% ADL	76	33	33	33	67	33	0
	ppm	198.50 (13.6)	<118.93	<118.93	<118.93	121.00 (5.0)	<118.93	<118.93

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit. n = 3 for all treatments except Reference where n = 21.
Reference values are a mean of three replicates from seven offsite reference locations which all had similar trace elements concentrations.
-Data below detection limit; *Incomplete data set available for calculation of mean because most data below detection limit.

Table A.2.2. Mean plant tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references.

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Antimony	% ADL	65	25	0	17	33	25
	ppm	0.02 (0.00)	<0.02	<0.02	<0.02	<0.02	<0.02
Arsenic†	% ADL	0	33	0	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Barium	% ADL	100	75	75	75	75	75
	ppm	34.52 (4.69)	24.74 (6.62)	20.65 (5.18)	33.38 (5.99)	29.38 (4.46)	29.27 (3.90)
Bromine	% ADL	100	100	100	100	100	100
	ppm	3.35 (1.26)	250.38 (166.22)	240.40 (14.78)	154.44 (136.80)	267.69 (42.83)	260.51 (37.61)
Cadmium†	% ADL	0	0.00	0.00	8.25	0.00	0.00
	ppm	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
Cerium	% ADL	97	25.00	33.50	33.25	0.0	0.0
	ppm	0.26 (0.04)	<0.14	<0.14	<0.14	<0.14	<0.14
Caesium	% ADL	57	25.00	33.25	24.75	8.3	16.8
	ppm	0.02 (0.03)	<0.03	<0.03	<0.03	<0.03	<0.03
Chromium	% ADL	89	50.00	25.00	66.50	33.5	33.3
	ppm	0.40 (0.08)	0.41 (0.08)	<0.31	0.41 (0.07)	<0.31	<0.31
Cobalt	% ADL	100	100	100	100	100	100
	ppm	0.15 (0.02)	2.01 (0.79)	1.56 (0.40)	1.13 (0.29)	0.81 (0.12)	0.62 (0.09)
Europium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fluorine	% ADL	19	75	33	75	17	8
	ppm	<3.68	15.12 (7.30)	<3.68	4.16 (0.60)	<3.68	<3.68
Gold	% ADL	78	83	92	92	92	83
	ppb	4.78 (1.03)	2.82 (0.79)	3.52 (1.25)	2.46 (0.66)	3.38 (1.27)	3.72 (0.71)

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 12 for all treatments except Reference where n = 21.
Reference values are a mean of three replicates from seven offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.2. Mean plant tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references.

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Hafnium	% ADL	47	8	0	0	0	0
	ppm	0.02 (0.00)	<0.02	<0.02	<0.02	<0.02	<0.02
Iridium	% ADL	0	0	0	0	0	0
	ppb	<0.39	<0.39	<0.39	<0.39	<0.39	<0.39
Iron	% ADL	100	92	75	83	75	75
	%	0.013 (0.002)	0.01 (0.00)	0.006 (0.001)	0.007 (0.001)	0.007 (0.000)	0.007 (0.001)
Lanthanum	% ADL	25	8	0	0	0	0
	ppm	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Lutetium	% ADL	70	59	50	42	50	25
	ppm	0.003 (0.000)	0.002 (0.000)	0.007 (0.001)	<0.002	0.002 (0.000)	<0.002
Mercury	% ADL	0	0	0	8	0	0
	ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Molybdenum	% ADL	0	0	0	0	0	0
	ppm	<0.96	<0.96	<0.96	<0.96	<0.96	<0.96
Nickel†	% ADL	28	83	67	75	75	67
	ppm	*	17.20 (3.45)	12.96 (4.27)	19.18 (7.11)	12.56 (2.94)	9.57 (4.01)
Potassium	% ADL	100	92	100	92	92	92
	%	1.67 (0.14)	1.15 (0.13)	1.45 (0.21)	1.29 (0.14)	7.59 (0.21)	1.41 (0.42)
Rubidium	% ADL	100	83	83	92	83	75
	ppm	4.03 (0.82)	7.63 (3.34)	7.67 (2.80)	6.16 (1.35)	6.51 (0.92)	7.24 (1.75)
Samarium	% ADL	88	42	25	59	17	17
	ppm	0.03 (0.01)	<0.01	<0.01	0.02 (0.00)	<0.01	<0.01
Scandium	% ADL	72	8	17	8	0	17
	ppm	0.03 (0.01)	<0.01	<0.01	<0.01	<0.01	<0.01

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 12 for all treatments except Reference where n = 21.
Reference values are a mean of three replicates from seven offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.2. Mean plant tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references.

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Selenium	% ADL	7	0	0	0	0	0
	ppm	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
Silver	% ADL	19	0	0	0	0	0
	ppm	*<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sodium	% ADL	100	83	75	92	75	75
	%	0.006 (0.001)	0.005 (0.001)	0.005 (0.003)	0.007 (0.001)	0.010 (0.005)	0.019 (0.007)
Tantalum	% ADL	0	0	0	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tellurium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Terbium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Thorium	% ADL	54	8	8	0	0	0
	ppm	0.06 (0.01)	<0.03	<0.03	<0.03	<0.03	<0.03
Tin	% ADL	0	0	0	0	0	0
	ppm	<4.83	<4.83	<4.83	<4.83	<4.83	<4.83
Tungsten†	% ADL	47	8	17	25	25	33
	ppm	3.43 (2.92)	<0.10	<0.10	<0.10	<0.10	<0.10
Uranium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Ytterbium	% ADL	0	0	0	0	0	0
	ppm	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Zinc	% ADL	100	100	100	100	100	100
	ppm	21.07 (2.05)	18.33 (2.75)	22.99 (1.60)	24.91 (2.36)	25.99 (3.26)	26.67 (3.68)
Zirconium	% ADL	0	0	0	0	0	0
	ppm	<5.93	<5.93	<5.93	<5.93	<5.93	<5.93

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit. n = 12 for all treatments except Reference where n = 21.
Reference values are a mean of three replicates from seven offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.3. *Agropyron trachycaulum* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references.

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Antimony	% ADL	50	33	0	33	33	0
	ppm	0.02 (0.01)	<0.02	<0.02	<0.02	<0.02	<0.02
Arsenic†	% ADL	0	0	0	0	0	0
	ppm	<13.39	<13.39	<13.39	<13.39	<13.39	<13.39
Barium	% ADL	100	0	0	0	0	0
	ppm	43.39 (6.90)	<19.38	<19.38	<19.38	<19.38	<19.38
Bromine	% ADL	100	100	100	100	100	100
	ppm	5.31 (2.85)	991.24 (662.55)	952.25 (57.44)	607.94 (544.52)	1064.09 (170.03)	1031.32 (146.39)
Cadmium†	% ADL	0	0	0	0	0	0
	ppm	<2.98	<2.98	<2.98	<2.98	<2.98	<2.98
Cerium	% ADL	100	0	0	0	0	0
	ppm	0.13 (0.03)	<0.14	<0.14	<0.14	<0.14	<0.14
Caesium	% ADL	17	0	0	33	0	0
	ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Chromium	% ADL	100	33	0	33	0	0
	ppm	0.16 (0.01)	<0.31	<0.31	<0.31	<0.31	<0.31
Cobalt	% ADL	100	100	100	100	100	100
	ppm	0.03 (0.01)	1.70 (1.03)	1.63 (0.26)	1.02 (0.64)	1.27 (0.12)	1.08 (0.13)
Europium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fluorine	% ADL	0	67	33	100	0	0
	ppm	<3.68	25.40 (18.76)	<3.68	4.43 (0.39)	<3.68	<3.68
Gold	% ADL	100	33	67	67	67	33
	ppb	2.13 (0.43)	<2.25	5.04 (1.55)	3.49 (0.88)	4.33 (1.24)	<2.25

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments except Reference where n = 6.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits are a mean from *Agropyron trachycaulum* samples.

Table A.2.3. *Agropyron trachycaulum* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Hafnium	% ADL	0	0	0	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Iridium	% ADL	0	0	0	0	0	0
	ppb	<0.39	<0.39	<0.39	<0.39	<0.39	<0.39
Iron	% ADL	100	67	0	33	0	0
	%	0.007 (0.001)	0.006 (0.003)	<0.014	<0.014	<0.014	<0.014
Lanthanum	% ADL	0	0	0	0	0	0
	ppm	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Lutetium	% ADL	67	0	67	33	33	33
	ppm	0.003 (0.000)	<0.002	0.011 (0.001)	<0.002	<0.002	<0.002
Mercury	% ADL	0	0	0	33	0	0
	ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Molybdenum	% ADL	0	0	0	0	0	0
	ppm	<0.96	<0.96	<0.96	<0.96	<0.96	<0.96
Nickel†	% ADL	0	33	0	0	33	33
	ppm	<10.65	<10.65	<10.65	<10.65	<10.65	<10.65
Potassium	% ADL	100	67	100	67	67	67
	%	2.03 (0.29)	1.03 (0.03)	1.39 (0.19)	1.03 (0.04)	1.47 (0.13)	1.77 (1.11)
Rubidium	% ADL	100	33	33	67	33	0
	ppm	6 (2)	<1.83	<1.83	3.86 (1.01)	<1.83	<1.83
Samarium	% ADL	83	33	33	67	33	0
	ppm	0.02 (0.00)	<0.01	<0.01	0.02 (0.00)	<0.01	<0.01
Scandium	% ADL	33	33	67	33	0	67
	ppm	0.02 (0.00)	<0.01	0.01 (0.00)	<0.01	<0.01	0.01 (0.00)

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments except Reference where n = 6.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits are a mean from *Agropyron trachycaulum* samples.

Table A.2.3. *Agropyron trachycaulum* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Selenium	% ADL	17	0	0	0	0	0
	ppm	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
Silver	% ADL	33	0	0	0	0	0
	ppm	0.02 (0.00)	<0.05	<0.05	<0.05	<0.05	<0.05
Sodium	% ADL	100	33	0	67	0	0
	%	0.002 (0.000)	<0.01	<0.01	0.001 (0.000)	<0.01	<0.01
Tantalum	% ADL	0	0	33	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tellurium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Terbium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Thorium	% ADL	17	0	0	0	0	0
	ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Tin	% ADL	0	0	0	0	0	0
	ppm	<4.83	<4.83	<4.83	<4.83	<4.83	<4.83
Tungsten†	% ADL	0	0	33	0	33	33
	ppm	<4.38	<4.38	<4.38	<4.38	<4.38	<4.38
Uranium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Ytterbium	% ADL	0	0	0	0	0	0
	ppm	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Zinc	% ADL	100	100	100	100	100	100
	ppm	20.60 (4.31)	12.29 (0.88)	14.95 (0.58)	16.3 (1.2)	18.61 (2.18)	16.61 (2.72)
Zirconium	% ADL	0	0	0	0	0	0
	ppm	<5.93	<5.93	<5.93	<5.93	<5.93	<5.93

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments except Reference where n = 6.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits are a mean from *Agropyron trachycaulum* samples.

Table A.2.4. *Agrostis stolonifera* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references.

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Antimony	% ADL	100	33	0	0	0	0
	ppm	0.01 (0.00)	<0.02[1]	<0.02[1]	<0.02[1]	<0.02[1]	<0.02[1]
Arsenic	% ADL	0	100	100	0	0	0
	ppm	<0.02	0.17 (0.03)	0.13 (0.01)	<0.02	<0.02	<0.02
Barium	% ADL	100	100	100	100	100	100
	ppm	26.70 (2.13)	13.35 (3.58)	22.76 (3.45)	30.65 (2.19)	40.24 (6.48)	33.92 (5.03)
Bromine	% ADL	100	100	100	100	100	100
	ppm	1.77 (0.45)	5.26 (1.33)	3.94 (0.23)	5.39 (1.96)	2.95 (0.56)	2.33 (0.41)
Cadmium†	% ADL	0	0	0	0	0	0
	ppm	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
Cerium	% ADL	100	67	67	100	0	0
	ppm	0.25 (0.07)	0.25 (0.06)	0.16 (0.01)	0.20 (0.03)	<0.14[5]	<0.14[5]
Caesium	% ADL	67	33	100	0	0	0
	ppm	0.02 (0.01)	<0.03	0.02 (0.01)	<0.03	<0.03	<0.03
Chromium	% ADL	100	33	0	100	67	33
	ppm	0.33 (0.12)	<0.31	<0.31	0.30 (0.02)	0.45 (0.00)	<0.31
Cobalt	% ADL	100	100	100	100	100	100
	ppm	0.05 (0.01)	2.12 (0.71)	1.61 (0.85)	0.57 (0.12)	0.21 (0.04)	0.13 (0.01)
Europium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fluorine	% ADL	33	67	67	33	0	0
	ppm	<3.68	19.20 (7.82)	4.40 (0.70)	<3.68	<3.68	<3.68
Gold	% ADL	100	100	100	100	100	100
	ppb	7.09 (1.37)	3.59 (0.40)	4.69 (1.89)	2.43 (0.75)	4.75 (1.42)	6.42 (1.05)

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.4. *Agrostis stolonifera* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Hafnium	% ADL	67	33	0	0	0	0
	ppm	0.02 (0.00)	<0.02	<0.02	<0.02	<0.02	<0.02
Iridium	% ADL	0	0	0	0	0	0
	ppb	<0.39	<0.39	<0.39	<0.39	<0.39	<0.39
Iron	% ADL	100	100	100	100	100	100
	%	0.01 (0.00)	0.005 (0.001)	0.005 (0.000)	0.005 (0.001)	0.006 (0.000)	0.004 (0.000)
Lanthanum	% ADL	0	33	0	0	0	0
	ppm	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Lutetium	% ADL	67	100	0	33	67	0
	ppm	0.00 (0.00)	0.003 (0.000)	<0.002	<0.002	0.001 (0.000)	<0.002
Mercury	% ADL	0	0	0	0	0	0
	ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Molybdenum	% ADL	0	0	0	0	0	0
	ppm	<0.96	<0.96	<0.96	<0.96	<0.96	<0.96
Nickel†	% ADL	0	100	100	100	67	67
	ppm	<1.89	13.67 (3.23)	10.94 (3.77)	26.43 (11.05)	25.04 (5.33)	6.45 (4.19)
Potassium	% ADL	100	100	100	100	100	100
	%	1.58 (0.15)	1.10 (0.16)	1.39 (0.24)	1.49 (0.19)	26.04 (0.21)	1.35 (0.26)
Rubidium	% ADL	100	100	100	100	100	100
	ppm	3.17 (0.44)	7.94 (4.38)	8.08 (4.29)	5.89 (1.96)	6.81 (0.28)	7.95 (1.69)
Samarium	% ADL	100	67	0	100	0	0
	ppm	0.03 (0.01)	0.03 (0.01)	<0.01	0.02 (0.00)	<0.01	<0.01
Scandium	% ADL	100	0	0	0	0	0
	ppm	0.04 (0.01)	<0.01	<0.01	<0.01	<0.01	<0.01

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.4. *Agrostis stolonifera* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Selenium	% ADL	0	0	0	0	0	0
	ppm	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
Silver	% ADL	33	0	0	0	0	0
	ppm	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sodium	% ADL	100	100	100	100	100	100
	%	0.01 (0.00)	0.003 (0.001)	0.005 (0.003)	0.003 (0.001)	0.003 (0.001)	0.002 (0.000)
Tantalum	% ADL	0	0	0	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tellurium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Terbium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Thorium	% ADL	67	33	33	0	0	0
	ppm	0.05 (0.02)	<0.03	<0.03	<0.03	<0.03	<0.03
Tin	% ADL	0	0	0	0	0	0
	ppm	<4.83	<4.83	<4.83	<4.83	<4.83	<4.83
Tungsten†	% ADL	67	0	0	67	67	33
	ppm	0.07 (0.00)	<0.10	<0.10	22.89 (1.95)	14.90 (3.70)	<0.10
Uranium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Ytterbium	% ADL	0	0	0	0	0	0
	ppm	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Zinc	% ADL	100	100	100	100	100	100
	ppm	24.92 (2.00)	12.96 (1.00)	23.26 (2.40)	27.58 (2.18)	29.24 (4.20)	28.23 (4.04)
Zirconium	% ADL	0	0	0	0	0	0
	ppm	<5.93	<5.93	<5.93	<5.93	<5.93	<5.93

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.5. *Festuca ovina* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references.

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Antimony	% ADL	100	33	0	33	100	100
	ppm	0.03 (0.01)	<0.02	<0.02	<0.02	0.01 (0.00)	0.01 (0.00)
Arsenic†	% ADL	0	33	0	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Barium	% ADL	100	100	100	100	100	100
	ppm	28.52 (3.78)	20.29 (0.67)	32.26 (3.93)	30.26 (5.69)	29.60 (2.73)	32.26 (3.71)
Bromine	% ADL	100	100	100	100	100	100
	ppm	2.86 (0.51)	3.11 (0.49)	2.96 (0.50)	2.29 (0.20)	1.93 (0.35)	2.73 (0.27)
Cadmium†	% ADL	0	0	0	33	0	0
	ppm	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
Cerium	% ADL	100	0	0	0	0	0
	ppm	0.46 (0.05)	<0.14	<0.14	<0.14	<0.14	<0.14
Caesium	% ADL	100	0	33	33	0	0
	ppm	0.02 (0.00)	<0.03	<0.03	<0.03	<0.03	<0.03
Chromium	% ADL	100	67	67	100	67	100
	ppm	0.91 (0.13)	0.49 (0.11)	0.34 (0.04)	0.53 (0.11)	0.53 (0.00)	0.63 (0.14)
Cobalt	% ADL	100	100	100	100	100	100
	ppm	0.42 (0.04)	1.63 (0.41)	0.93 (0.45)	1.04 (0.24)	0.60 (0.17)	0.81 (0.12)
Europium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fluorine	% ADL	33	100	0	67	0	0
	ppm	<3.68	6.43 (1.47)	<3.68	4.85 (0.95)	<3.68	<3.68
Gold	% ADL	100	100	100	100	100	100
	ppb	5.11 (1.30)	3.44 (1.08)	2.53 (0.71)	2.03 (0.51)	3.06 (1.96)	3.74 (0.61)

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.5. *Festuca ovina* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Hafnium	% ADL	100	0	0	0	0	0
	ppm	0.03 (0.01)	<0.02	<0.02	<0.02	<0.02	<0.02
Iridium	% ADL	0	0	0	0	0	0
	ppb	<0.39	<0.39	<0.39	<0.39	<0.39	<0.39
Iron	% ADL	100	100	100	100	100	100
	%	0.022 (0.003)	0.007 (0.002)	0.007 (0.001)	0.007 (0.000)	0.008 (0.001)	0.009 (0.001)
Lanthanum	% ADL	100	0	0	0	0	0
	ppm	0.27 (0.02)	<0.10	<0.10	<0.10	<0.10	<0.10
Lutetium	% ADL	100	67	33	33	67	33
	ppm	0.005 (0.000)	0.002 (0.000)	<0.002	<0.002	0.002 (0.000)	<0.002
Mercury	% ADL	0	0	0	0	0	0
	ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Molybdenum	% ADL	0	0	0	0	0	0
	ppm	<0.96	<0.96	<0.96	<0.96	<0.96	<0.96
Nickel†	% ADL	100	100	100	100	100	100
	ppm	13.90 (4.97)	14.42 (0.76)	10.12 (2.57)	10.12 (2.07)	6.32 (1.34)	10.87 (3.29)
Potassium	% ADL	100	100	100	100	100	100
	%	1.35 (0.06)	1.14 (0.14)	1.26 (0.10)	1.40 (0.19)	1.55 (0.15)	1.65 (0.16)
Rubidium	% ADL	100	100	100	100	100	100
	ppm	1.55 (0.04)	6.84 (3.26)	8.46 (2.31)	6.74 (2.02)	4.62 (0.90)	6.16 (1.97)
Samarium	% ADL	100	33	33	67	33	67
	ppm	0.05 (0.01)	<0.01	<0.01	0.02 (0.00)	*	0.02 (0.00)
Scandium	% ADL	100	0	0	0	0	0
	ppm	0.06 (0.01)	<0.01	<0.01	<0.01	<0.01	<0.01

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.5. *Festuca ovina* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Selenium	% ADL	0	0	0	0	0	0
	ppm	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
Silver	% ADL	0	0	0	0	0	0
	ppm	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sodium	% ADL	100	100	100	100	100	100
	%	0.007 (0.001)	0.001 (0.000)	0.001 (0.000)	0.002 (0.000)	0.002 (0.000)	0.003 (0.000)
Tantalum	% ADL	0	0	0	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tellurium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Terbium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Thorium	% ADL	100	0	0	0	0	0
	ppm	0.08 (0.01)	<0.03	<0.03	<0.03	<0.03	<0.03
Tin	% ADL	0	0	0	0	0	0
	ppm	<4.83	<4.83	<4.83	<4.83	<4.83	<4.83
Tungsten†	% ADL	100	0	0	0	0	33
	ppm	4.33 (2.94)	<0.10	<0.10	<0.10	<0.10	<0.10
Uranium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Ytterbium	% ADL	0	0	0	0	0	0
	ppm	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Zinc	% ADL	100	100	100	100	100	100
	ppm	18.94 (0.71)	17.81 (3.21)	25.20 (1.54)	26.55 (3.51)	25.20 (3.24)	30.25 (3.82)
Zirconium	% ADL	0	0	0	0	0	0
	ppm	<5.93	<5.93	<5.93	<5.93	<5.93	<5.93

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.6. *Medicago sativa* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references.

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Antimony	% ADL	11	0	0	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Arsenic†	% ADL	0	0	33	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Barium	% ADL	100	100	100	100	100	100
	ppm	39.45 (5.95)	40.57 (15.61)	27.60 (8.16)	39.24 (10.09)	18.29 (4.17)	21.62 (2.96)
Bromine	% ADL	100	100	100	100	100.0	100
	ppm	3.46 (1.22)	1.93 (0.52)	2.43 (0.96)	2.15 (0.51)	1.80 (0.39)	5.67 (3.39)
Cadmium†	% ADL	0	0	0	0	0	0
	ppm	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
Cerium	% ADL	89	33	67	33	0.0	0.0
	ppm	0.18 (0.03)	<0.14[5]	0.25 (0.05)	<0.14[5]	<0.14[5]	<0.14[5]
Caesium	% ADL	44	67	0	33	33.00	67
	ppm	0.02 (0.07)	0.05 (0.00)	<0.03	<0.03	<0.03	0.05 (0.00)
Chromium	% ADL	56	67	33	33	0	0
	ppm	0.21 (0.05)	0.34 (0.04)	<0.31	<0.31	<0.31	<0.31
Cobalt	% ADL	100	100	100	100	100.00	100
	ppm	0.09 (0.01)	2.61 (1.00)	2.08 (0.03)	1.88 (0.15)	1.15 (0.14)	0.44 (0.11)
Europium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fluorine	% ADL	11	67	33	100	67.0	33
	ppm	<3.68	9.45 (1.15)	<3.68	3.20 (0.46)	4.20 (1.00)	<3.68
Gold	% ADL	11	100	100	100	100.0	100
	ppb	<2.55	1.42 (0.90)	1.83 (0.85)	1.90 (0.52)	1.40 (0.46)	1.00 (0.47)

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments except Reference where n = 9.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.6. *Medicago sativa* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Hafnium	% ADL	22	0	0	0	0	0
	ppm	0.02 (0.00)	<0.02	<0.02	<0.02	<0.02	<0.02
Iridium	% ADL	0	0	0	0	0	0
	ppb	<0.39	<0.39	<0.39	<0.39	<0.39	<0.39
Iron	% ADL	100	100	100	100	100.000	100
	%	0.008 (0.001)	0.008 (0.000)	0.007 (0.001)	0.007 (0.001)	0.007 (0.001)	0.008 (0.001)
Lanthanum	% ADL	0	0	0	0	0	0
	ppm	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Lutetium	% ADL	44	67	100	67	33.000	33
	ppm	0.002 (0.000)	0.002 (0.000)	0.002 (0.000)	0.002 (0.000)	<0.002	<0.002
Mercury	% ADL	0	0	0	0	0	0
	ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Molybdenum	% ADL	0	0	0	0	0	0
	ppm	<0.96	<0.96	<0.96	<0.96	<0.96	<0.96
Nickel†	% ADL	11	100	67	100	100	67
	ppm	<1.89	23.52 (6.37)	17.83 (6.47)	20.99 (8.21)	6.32 (2.16)	11.38 (4.57)
Potassium	% ADL	100	100	100	100	100	100
	%	1.71 (0.07)	1.32 (0.20)	1.75 (0.30)	1.23 (0.14)	1.29 (0.36)	0.87 (0.13)
Rubidium	% ADL	100	100	100	100	100	100
	ppm	5.89 (1.10)	8.10 (2.37)	6.49 (1.79)	8.13 (0.40)	8.10 (1.57)	7.60 (1.58)
Samarium	% ADL	67	33	33	0	0	0
	ppm	0.02 (0.00)	<0.01	<0.01	<0.01	<0.01	<0.01
Scandium	% ADL	56	0	0	0	0	0
	ppm	0.02 (0.00)	<0.01	<0.01	<0.01	<0.01	<0.01

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments except Reference where n = 9.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.

Table A.2.6. *Medicago sativa* tissue trace element concentrations from research plots at Agrium Fort Saskatchewan, Alberta and references (continued).

Element	Test	Cap Depth (cm) or Reference					
		Reference	8	15	30	46	91
Selenium	% ADL	11	0	0	0	0	0
	ppm	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
Silver	% ADL	11	0	0	0	0	0
	ppm	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sodium	% ADL	100	100	100	100	100.000	100
	%	0.009 (0.002)	0.012 (0.002)	0.008 (0.004)	0.024 (0.005)	0.025 (0.015	0.054 (0.021)
Tantalum	% ADL	0	0	0	0	0	0
	ppm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tellurium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Terbium	% ADL	0	0	0	0	0	0
	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Thorium	% ADL	33	0	0	0	0	0
	ppm	0.03 (0.01)	<0.03	<0.03	<0.03	<0.03	<0.03
Tin	% ADL	0	0	0	0	0	0
	ppm	<4.83	<4.83	<4.83	<4.83	<4.83	<4.83
Tungsten†	% ADL	22	33	33	33	0	33
	ppm	5.88 (5.82)	<0.10	<0.10	<0.10	<0.10	<0.10
Uranium	% ADL	0	0	0	0	0	0
	ppm	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Ytterbium	% ADL	0	0	0	0	0	0
	ppm	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Zinc	% ADL	100	100	100	100	100	100
	ppm	19.82 (1.20)	30.25 (5.91)	28.57 (1.87)	29.24 (2.54)	30.92 (3.41)	31.59 (4.13)
Zirconium	% ADL	0	0	0	0	0	0
	ppm	<5.93	<5.93	<5.93	<5.93	<5.93	<5.93

Concentration data are means for all samples above detection level. Standard error is in brackets.
% ADL = Percent of samples above detection limit.
n = 3 for all treatments except Reference where n = 9.
Reference values are a mean of three replicates from two offsite reference locations.
< = most samples below stated mean detection limit.
†Detection limits from *Agropyron trachycaulum* samples not included in mean detection limit because artificially raised due to bromine additions.