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Assessment of Soil Capping for Phosphogypsum Stack Reclamation at Fort Saskatchewan, Alberta

by

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ABSTRACT

Phosphogypsum (PG), an acidic byproduct of phosphoric acid production during phosphate fertilizer manufacturing, is commonly stacked on the facilities and capped with soil at decommissioning. The research evaluated soil capping depth (0, 8, 15, 30, 46, 91 cm) effects on response of five seeded grasses, water movement across the soil / PG interface, leaching, radon gas, gamma radiation and hydrogen fluoride emissions. Vegetation response was not affected by cap depth and plant rooting into PG had no detected adverse effects. Soil water fluctuated more at shallow (0, 8, 15) than thick (30, 46, 91) caps, and water quality on caps $\leq$ 30 cm was not affected by cap depth. Increased cap depth was associated with decreased gamma radiation, while radon gas and hydrogen fluoride emissions had variable responses. Implementation of these findings into a reclamation program in Alberta will be useful for designing a suitable and cost effective cover system.

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1. PHOSPHOGYPSUM PRODUCTION, DISPOSAL AND RECLAMATION

1.0 Background

Phosphogypsum (PG) is an acidic solid by product generated from the production of phosphoric acid (Richardson et al. 1995, Rutherford et al. 1994). The fertilizer industry generates approximately five tonnes of PG per tonne of phosphoric acid, the latter being required for phosphorus fertilizer production (Richardson et al. 1995, Rutherford et al. 1995a, Rutherford et al. 1994, Ferguson 1988). Large quantities of PG are produced annually in at least 80 countries around the world (Florida Institute of Phosphate Research 2006), including Canada and the United States. As of January 2006, Florida had at least 20 PG stacks, the most of any state. Canada has stacks in British Columbia, Alberta, Ontario, Quebec and New Brunswick with the majority and largest of the stacks in Alberta (Thorne 1990). Ferguson (1988) predicted worldwide PG production would reach between 220 and 280 million tonnes by the year 2000. Parreira et al. (2003) indicated that PG production was approximately 180 million tonnes per year in 2003. Abril et al. (2009) estimated annual PG production at 170 million tonnes in 2006. As a result of the large land bases PG stacks occupy, stack reclamation is necessary to contain hazards associated with stacks and achieve an aesthetically pleasing landscape.

1.1 Phosphogypsum Production, Disposal and Reuse

1.1.1 Phosphogypsum production

1.1.1.1 Source rock

Phosphate rock used in phosphoric acid production is commonly of sedimentary origin and is easily open pit and underground mined (Becker 1989). These sedimentary deposits were formed 70 million years ago from plant and animal decay. Phosphate deposits are found in metamorphic and igneous geological formations although their use in phosphoric acid production is only 15 %.

Apatite is the most common mineral in phosphate rock (McClellan and Lehr 1969, Gulbrandsen 1966). The sedimentary phosphate rock used commercially is an apatite structure and contains phosphate, fluorine and calcium ($Ca_{10}(PO_4)_6F_2$) (Becker 1989, McClellan and Lehr 1969). Phosphate rock normally contains 10 to 15 % impurities and approximately 16 heavy metals and rare earth elements (Becker 1989). Mined phosphate rock typically contains 23 to 40 % P_2O_5, the form of phosphorus found in phosphate rock. Ore can also include calcium oxide (CaO), silicon dioxide (SiO_2), fluoride (F), carbon dioxide (CO_2), sulphur trioxide (SO_3), aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3), magnesium oxide (MgO) and sodium oxide (Na_2O) (Rutherford et al. 1994).

Relative to shale, a common marine and surficial sediment, cadmium (Cd), uranium (U), silver (Ag), yttrium (Y), selenium (Se), ytterbium (Yb), molybdenum (Mo), lanthanum (La), strontium (Sr), lead (Pb), zinc (Zn) and all rare earth elements except cerium (Ce) are elevated in sedimentary phosphate rock (Altschuler 1980). Thorium (Th) is present in phosphate rock due to substitution for calcium (Ca) in apatite structure as a result of similar ionic radii (Rutherford et al. 1994, Gulbrandsen 1966).

Demand for high grade phosphate rock, with a P_2O_5 composition between 33 and 39 %, has resulted in depletion of worldwide reserves and in turn, forced mining of lower quality deposits with variable compositions (Becker 1989). All phosphate rock ores behave differently and contribute to the unique composition and nature of produced phosphoric acid.

1.1.1.2 Phosphoric acid production

Phosphate rock must be upgraded to concentrate P_2O_5 and impurities removed prior to selling on the international market for phosphoric acid production (Becker 1989). Common practice for upgrading rock is to crush and screen or grind ore followed by pneumatic particle size selection, washing and desliming.

Phosphoric acid is produced from phosphate rock by wet or electric furnace processes (Becker 1989). Over 90 % is produced by wet process with sulphuric acid attack. Reaction of phosphate rock, sulphuric acid and water produce 27 to

30 % P_2O_5 phosphoric acid (Becker 1989, Schroeder and Gorecki 1980), gypsum and hydrofluoric acid by the reaction: $Ca_{10}(PO_4)_6F_2 + 10H_2SO_4 + 20H_2O \rightarrow 10CaSO_4 \bullet 2H_2O + 6H_3PO_4 + 2HF$ (Rutherford et al. 1994). Four main steps occur in phosphoric acid production in dihydrate systems, which produce a dihydrated calcium suphate (Becker 1989). Between 60 and 70 % of the ore must be ground to particle sizes < 150 µm using ball or rod mills. In a reactor tank, phosphate rock, sulphuric acid and recycled acid must be continuously fed into the system to maintain proper reaction conditions. The third step involves phosphoric acid reaction and gypsum crystal precipitation. Generally, the phosphate rock source determines the PG volume created. For every tonne of phosphoric acid produced, approximately 5 tonnes of PG are created (Richardson et al. 1995, Rutherford et al. 1995a, Rutherford et al. 1994, Ferguson 1988). In the final step, phosphoric acid is separated from gypsum by filtration (Becker 1989).

Phosphoric acid is used in phosphorus fertilizer production and hydrofluoric acid is recycled in acidic process waters (Rutherford et al. 1994). The gypsum precipitate is either pumped into moving water bodies, reused or stacked (Becker 1989). Gypsum is termed phosphogypsum due to the nature of its production.

1.1.2 Phosphogypsum disposal

1.1.2.1 Wet stacking

PG is commonly wet stacked on land adjacent to fertilizer production facilities (Luther and Dudas 1993) where it can span hundreds of hectares and tens of meters in height (Rutherford et al. 1995b). Some of the largest PG stacks in Florida are visible in LANDSAT imagery (Hull and Burnett 1996). The Agrium Redwater stack is the largest and only active stack in Canada (Nichol 2007). It is estimated to cover 300 ha and be 40 m in height at closure around 2035. Stacks are built to specific dimensions based on shape and slope of deposit, PG specific gravity, production rate, expected storage time and soil properties (Becker 1989).

PG stack design and construction requires intensive planning and engineering. The stack must have a sturdy base to support the weight of PG and an effective water management system to prevent ground or surface water contamination

(Agrium 2008a). In Florida, composite liners are required below PG stacks which must meet specific criteria (FDEP 1994). Liners must be able to resist physical, chemical and mechanical stresses imposed by PG and encompass all land which could potentially come into contact with PG, leachate or process wastewater. Liner systems in Florida consist of a 1.5 mm or thicker geomembrane liner plus 46 cm layer of compacted soil below the synthetic liner or a 1.5 mm or thicker geomembrane liner plus a layer at least 61 cm thick of mechanically compacted PG above the synthetic liner.

Two PG stacks at Agrium near Fort Saskatchewan, Alberta were constructed on a natural clay bed, one on a clay liner and one on a high density polyethylene (HDPE) synthetic liner (Svarich 1999). Most of the PG stack at Agrium near Redwater, Alberta is unlined. The recent expansion of the existing stack has been outfitted with a 1.6 mm HDPE liner system (Unruh 2008).

After filtration of PG from phosphoric acid in the plant, water and PG are slurried and pumped to the top of the stack (Wissa 2002). To prevent build up of PG in pipes, a constant slurry flow rate is used (Becker 1989). At Agrium Redwater, PG is produced continuously and piped at 4 m/s (Unruh 2008). Slurry material is piped into large settling ponds at the top of the stack where PG settles out of solution (Wissa 2002, Rutherford et al. 1994, Becker 1989). Excess water is decanted and reused. Reused process water becomes increasingly concentrated and can eventually reach pH values between 1.3 and 2.0 (Wissa 2002).

Hydraulic excavators and long arm backhoes are commonly used for excavating PG from ponds and building up stacks (Unruh 2008, Wissa 2002, Becker 1989). Approximately 10 % of settled PG is moved and used in stack construction (Becker 1989). Rim ditching is a technique for increasing stack elevation, which involves creation of a ditch around the settling pond perimeter (Unruh 2008, Becker 1989). Ditches are filled sequentially with slurry and allowed to dry for a few days prior to decanting excess water for reuse (Becker 1989). PG is allowed to move through strategic ditch openings into the pond where beaches are created. Large particles of PG fall out of solution near the pond perimeter, providing greater strength for stack building. Rim ditching is more effective and economical than conventional direct slurry pumping into settling ponds where

additional machinery and excavations are required (Unruh 2008). Rim ditching exposes more PG for rapid dewatering in beaches and along inside walls. PG berms are disced to increase surface area for drying and mechanical vibrators are used to speed dewatering. As PG dries, a surface crust forms, reducing wind blown material (Agrium 2008a). Side slopes of PG stacks range from 3:1 (horizontal:vertical) to steeper than 2:1 (Richardson et al. 1995).

Water management is critical in PG stack operation (Becker 1989). The water balance is affected by precipitation inputs and outputs of process water, evaporation, percolation and residual PG water, the latter three being difficult to estimate. In Florida, mandatory annual reports are submitted by phosphoric acid producing companies to the Florida Department of Environmental Protection (FDEP) outlining process water balances and water management plans (Wissa 2002). Incoming precipitation on wet stacks can be collected in ponds and ditches, treated and reused in acid production to maintain a closed loop system.

1.1.2.2 Dry stacking

PG disposal by dry stacking involves transport of PG directly from the filtration stage by truck or conveyor to a stack (Wissa 2002). Water is not added to slurry the material. Dry stacking is used in Jordan, Tunisia, Senegal and several former Soviet Union countries.

1.1.2.3 Discharge to water bodies

In some countries where phosphoric acid plants are adjacent to moving salt water bodies, PG is commonly disposed of directly (Wissa 2002). PG solubility is greater in sea water than in fresh water and a moving water body will help prevent build up on the ocean floor which may interfere with navigation. It is politically and environmentally acceptable to pipe PG slurries into large, strong current water bodies where there is no human inhabitation. In Morocco, 25,000 tons of PG per day are discharged into the Atlantic Ocean (Becker 1989). Most active phosphoric acid facilities and those under construction dispose of PG on land as they are not located near water and it is not politically acceptable to discharge directly to rivers or small water bodies (Wissa 2002).

1.1.3 Phosphogypsum reuse

Despite research into numerous reuse options for PG, more than 95 % of that produced annually is disposed of on land or in water (Wissa 2002). New technology, potential markets and decreasing supply of natural gypsum initiated a trend toward PG reuse (Parikh et al. 1988) although presence of impurities such as fluoride, unreacted phosphate rock and radionuclides in PG limit options (Degirmenci et al. 2007, Rutherford et al. 1994). In the United States, reuse of PG containing greater than 370 Bq/kg of radioactivity has been banned since 1992 by the Environmental Protection Agency (Degirmenci et al. 2007).

Commercial applications of PG include use as a soil amendment, back fill and road base material in construction, a component in concrete and concrete blocks, mine reclamation, sulphur recovery (Conklin 1992 as cited in UNSCEAR 1993), and plaster and wall board production (Becker 1989, Collings 1980). Agrium has provided PG to oil sands companies to add to tailings to increase settling (Agrium 2002). Much of the literature on PG reuse has focused on agricultural soil amendments (Rutherford et al. 1994). Research has shown that PG can amend highly weathered, sodic, acid and calcareous soils. PG can improve low fertility soils by supplying Ca, sulphur (S) and phosphorus (P) required for plant growth. PG can ameliorate sodic soils due to the ability of Ca to displace sodium (Na) on the exchange complex, promoting flocculation of soil particles. In many cases, addition of PG to soils can increase infiltration, decrease runoff and limit erosion.

Concerns with PG application on agricultural soils include uptake of radionuclides and chemical impurities by plants and P loading of waterways (Rutherford et al. 1994). Plant and soil characteristics influence extent of radionuclide uptake. When PG was applied to soils with a corn, wheat and soybean rotation, radium (^{226}Ra) did not increase in crops but more than doubled in surface soil (May and Mordvedt 1986 as cited in Rutherford et al. 1994). Conversion of agricultural land treated with PG to residential may not be feasible due to the potential for elevated radon (Rn) concentrations in basements (Korentajer et al. 1991 as cited in Rutherford et al. 1994). Fluoride and trace element uptake by crops can also be detrimental. High application rates of PG onto agricultural soils can lead to runoff of P into surface waters and contribute to eutrophication.

1.2 Phosphogypsum Characteristics

1.2.1 Physical

PG is composed primarily of gypsum (> 90 %) ($CaSO_4 \bullet 2H_2O$) (Luther and Dudas 1993, Collings 1980), a slightly soluble dihydrate calcium sulphate salt (Richardson et al. 1995). Particles of PG are soft and < 0.075 mm in diameter (Wissa 2002). PG crystal size and shape depend on reaction parameters including particle size of phosphate rock, phosphoric acid concentration, slurry solids content, excess sulphuric acid in slurry, phosphate rock impurities, reaction temperature and system processes (Becker 1989).

Water content of PG following filtration is between 25 and 30 % (Wissa 2002). Water content of PG in stacks varies with age and weathering (Rutherford et al. 1994). PG vertical hydraulic conductivity has been measured at 1×10^{-3} to 2×10^{-5} cm/s (SENES 1987). PG density and strength increase and compressibility and permeability decrease with stack depth and age (Wissa 2002).

1.2.2 Chemical

Major components of PG are Ca and SO_4 (Rutherford et al. 1995a) and minor components can include quartz, fluorides, phosphates, organic matter, Al and Fe minerals, residual acidity, trace elements, rare earth elements and radionuclides (Luther et al. 1993). Source rock composition, type of wet acid production, process efficiency, stockpile age and introduced contaminants at the plant dictate which chemical impurities and concentrations may be present (Arman and Seals 1990). Impurities in PG are most numerous with dihydrate production (Rutherford et al. 1994). The most common impurities are fluorine (1.5 to 2.5 % by weight) and phosphate compounds (0.82 % by weight) (Schroeder and Gorecki 1980).

Aluminium (Al), arsenic (As), barium (Ba), Cd, chromium (Cr), F, Pb, mercury (Hg), Se and Ag are commonly found in PG (Wissa 2002). Santos et al. (2006) measured rare earth elements including La, samarium (Sm), neodymium (Nd), Ce, terbium (Tb), europium (Eu), lutetium (Lu) and ytterbium (Yb) in phosphate rock but found concentrations were not enriched in the resulting PG. Luther et al.

(1993) found that Y, La and Nd were enriched in Alberta PG originating from Idaho rock relative to shale although the sum of rare earth elements in PG was comparable to shale.

Hydrogen fluoride (HF) is a byproduct of phosphoric acid production (Rutherford et al. 1994, Becker 1989). HF will combine with reactive and undissolved silica in phosphate rock to form fluorosilicic acid (H_2SiF_6) which tends to remain in solution (Becker 1989). Silica does not react quickly with HF, thus both may exist independently in slurry. Under high processing temperatures, HF and H_2SiF_6 may break down to form gaseous silicon tetrafluoride (SiF_4) and HF. Using scrubbers, gases can be recovered by absorption in water to H_2SiF_6 (Rutherford et al. 1994). Rutherford et al. (1995a) found soluble fluoride concentration of PG extracts ranged from 320 to 360 mg/L in fresh PG from Florida rock. In 20 year old PG soluble fluoride ranged from 7 to 9 mg/L. Fluoride in fresh PG extracts from Togo rock had soluble fluoride concentrations between 110 and 120 mg/L.

PG is acidic with pH generally between 3 and 4 (Collings 1980). Florida PG pH ranged from 2.1 to 5.5 (May and Sweeney 1984 as cited in Rutherford et al. 1994). Aged and leached PG could reach a pH closer to 7 (SENES 1987). At low pH, trace elements may remain in a mobile state (Rutherford et al. 1994) which can have potentially harmful environmental implications. Mean electrical conductivity (EC) of PG samples from Agrium Redwater was 5.8 ± 0.2 dS/m (1:4 solid to water) (Hao et al. 2005). EC of Florida PG samples ranged from 2.3 to 3.8 dS/m (1:2 solid to water) (Richardson et al. 1995).

1.2.3 Radiological

PG contains more radioactivity than most geological and soil materials due to naturally elevated concentrations of radionuclides in phosphate rock (Rutherford et al. 1994). Decay of ^{238}U and ^{232}Th are major sources of radioactivity in phosphate rock. When the radioactive equilibrium of the ^{238}U series in phosphate rock is disturbed, components of the decay series will redistribute into phosphoric acid or PG (Hull and Burnett 1996, Rutherford et al. 1994). Hull and Burnett (1996) found that partitioning of ^{226}Ra, ^{210}Pb and polonium (^{210}Po) into PG was proportional to activities of these radionuclides in the input Florida phosphate

rock. During phosphoric acid production, Th, Pb and over 90 % of U dissolves (May and Sweeney 1980). The major forms of radioactivity transferred into PG are ^{226}Ra and ^{210}Po (Rutherford et al. 1994) as they form insoluble sulphates which accumulate in PG (Hanson and Laird 1990).

^{226}Ra has a half life of 1,620 years and alpha decays to ^{222}Rn, a highly mobile gas with a short (3.82 day) half life (Rutherford et al. 1994). ^{222}Rn decays to radioactive ^{210}Pb and ^{210}Po, which have long half lives (21.3 years and 138 days, respectively). Polonium, commonly ^{210}Po in PG, has been found in ground water below Florida phosphate mines and is most mobile under acidic conditions. The long half life of ^{226}Ra makes radioactivity an ongoing concern with PG stacks (Rutherford et al. 1995a).

1.3 Environmental Hazards of Phosphogypsum Stacks

Environmental concerns associated with PG stacks include fluoride uptake, ground and surface water pollution and exposure to radon gas and gamma radiation (Rutherford et al. 1994). Main vectors for their transport into the environment are wind and water erosion, infiltration and leaching into surface and ground water and airborne emissions of gaseous and radioactive elements.

1.3.1 Wind and water erosion

Fine particles of PG can be picked up and transported by wind (Norlander 1988, SENES 1987) and vehicular traffic on stacks into adjacent areas (Wissa 2002, Berish 1990). Dust particles containing fluoride is a concern for operational and non operational stacks (Rutherford et al. 1994). Elevated levels of fluoride have been found in vegetation adjacent to stacks (Wissa 2002, Rutherford et al. 1994). The rate at which plants uptake fluoride deposited as particulates is dependent on specific leaf weight (g/m^2) (Weinstein and Davison 2004). Fluoride accumulation will be higher in a plant with small specific leaf weight and large particles of fluoride deposited on it. Grazing of fluoride contaminated vegetation by animals can lead to fluorosis (Weinstein and Davison 2004, Wissa 2002, Norlander 1988). Fluoride has a high affinity for calcium in biological systems and

tends to be found where calcium is present, including bones (Weinstein and Davison 2004). Symptoms of fluorosis in animals include dental staining and roughness, larger than normal bones with chalky white deposits, stiffness and lameness (NAS 1974 as cited in Weinstein and Davison 2004).

Water erosion of PG stacks can create solution cavities and instabilities in constructed berms and dykes, lead to surface runoff of PG, erosion around piping systems and gully erosion (SENES 1987). Slopes may become more susceptible to failure and erosion with intense precipitation events.

1.3.2 Infiltration

Following stack closure, a major concern related to ground water quality is contaminant leaching (SENES 1987). Alkalinity, Ca, chloride (Cl), F, magnesium (Mg), Na, SO_4 and potassium (K) are used by the United States Geological Survey as indicator parameters for acid seepage into ground water (Berish 1990). As a result of low pH and high solubility of metallic hydroxides, elevated levels of Al, Cd, Cr, iron (Fe), Mg, nickel (Ni) and vanadium (V) were found in seepage water from a 15 year old Calgary, Alberta PG stack (SENES 1987). As water percolates through the stack, trace elements can become mobile and leach into ground water, negatively impacting ecosystem function (Rutherford et al. 1994) and human health (Norlander 1988). Excessive inputs of nitrogen and phosphorus can cause algae blooms, contributing to eutrophication of waterways, water can become hard and require treatment prior to use, and excess sulphate uptake can have laxative effects (Norlander 1988).

Fluoride in leachate can dissolve silicate minerals present in clay liners and accelerate contaminant movement into the ground water (Rutherford et al. 1995a, Rutherford et al. 1995c). As a result, fluoride concentrations can be indicative of contaminant transport rates into ground water (Rutherford et al. 1995a). The Canadian maximum allowable concentration of fluoride in drinking water is 1.5 mg/L (CCME 2003). Chronic exposure to fluoride concentrations greater than the permissible concentration can cause dental fluorosis and skeletal fluorosis and in some cases, lead to severe crippling in humans (Weinstein and Davison 2004).

1.3.3 Radioactivity and hydrogen fluoride emissions

Radon flux is a measure of the activity of ^{222}Rn gas escaping from an area per unit time (Berish 1990). It is a function of stack area, ^{226}Ra and ^{222}Rn concentrations in the stack, emanation fraction, crust depth, vegetation cover, water content, activity level and climate. Radon emissions from PG stacks tend to be highest on loose, dry material where crusting is not present. Human exposure to radon gas is a serious health concern (Rutherford et al. 1994) as it can be inhaled and accumulate in lungs (Hanson and Laird 1990). Chronic exposure and inhalation of radon gas has been associated with cancer in underground miners (Roessler 1990).

Naturally occurring radionuclides present in PG decay and produce gamma radiation (Hanson and Laird 1990). Emissions of gamma radiation from PG stacks is a function of distance from the stack, stack size and concentration of gamma emitting radionuclides (Florida Institute of Phosphate Research 2004). The amount of gamma emission is an indicator of radioactive decay or atom transformation. Gamma radiation exposure is mainly a concern for people living adjacent to a PG stack or working on a stack since emissions decrease with distance from the stack (Berish 1990). Acute doses of ionizing radiation such as gamma can damage blood forming organs and the central nervous system; high doses can cause skin burns, hair loss and death (Argonne National Laboratory, Environmental Science Division 2005). Cancer is the major health concern related to radiation exposure. Human health hazards associated with radon gas and gamma radiation exposure can be limited by reclamation methods, such as capping (Rutherford et al. 1994).

Concentration of HF gas emanating from PG stacks is a function of the amount of evaporation occurring (Norlander 1988). Hydrogen fluoride gas enters plant leaves through stomata and moves to leaf margins and tips where F becomes concentrated (Weinstein and Davison 2004). These areas can contain several hundred times more fluoride than the leaf interior. Fluoride can interfere with enzyme activities in plant cells, photosynthesis and respiration. Uptake of fluoride by grazing animals can have toxic effects, such as fluorosis (Weinstein and Davison 2004, Wissa 2002, Norlander 1988).

1.4 Phosphogypsum Stack Reclamation

1.4.1 Objectives

When PG stacks reach the end of their operational life or phosphoric acid production ceases permanently, they must be decommissioned (Wissa 2002). Closure plans are designed to prevent off site contaminant migration and minimize post operational maintenance (Berish 1990). An understanding of site topography, hydrology, geology, ground and surface water quality and adjacent land use information are required for closure plan development. Stack closure objectives include preventing contaminated water from migrating to the environment, surface water and ground water; controlling surface water on the stack; and maintaining stack integrity. To achieve this, final cover systems are designed to promote drainage off stack, minimize ponding, minimize erosion, minimize infiltration and function with low maintenance (FDEP 1994). All runoff and seepage water from the stack must be contained on site and treated prior to discharge (Wissa 2002). To minimize environmental hazards, vegetated soil covers are generally employed following closure (Richardson et al. 1995).

1.4.2 Soil capping

Final cover systems for PG stacks commonly involve capping with soil, synthetic membranes or chemically and/or physically amended soil or PG. Frequently referred to as engineered soil caps, these cover systems can provide long term stability for waste, although costs of development can be high (Simon and Müller 2004). Determination of a suitable soil capping depth for PG and other waste is important to minimize effects on borrow areas and minimize costs associated with earth moving and transportation (Richardson et al. 1995).

A cap can prevent wind and water erosion, limit infiltration and percolation, improve runoff water quality and provide a medium for plant growth (Fuleihan et al. 2005). Climate and hydrogeology are important factors in designing appropriate cover systems (Wissa 2002). Cover systems can prevent contaminants in PG from entering the environment but do require ongoing monitoring and maintenance (Norlander 1988).

Selection of cover system material is based primarily on physical characteristics. Norlander (1988) discussed some advantageous cover material properties. Low porosity materials are desirable as radon tends to diffuse through pores and material with high natural water content results in slower movement of radon gas than air filled pores. High density materials reduce radon and gamma radiation while low permeability materials minimize water infiltration. Cover material should be flexible and strong to permit movement due to frost heave, thermal expansion and settling. Desirable cover material does not react chemically with PG, has low contaminant concentrations, supports plant growth, can withstand radioactivity, can resist rodents, prevents deep root penetration and is cost effective. Yet a cover material with all of the aforementioned properties would be difficult to find.

PG stack reclamation in Florida is regulated by FDEP in a Florida Administrative Code effective March 1993 (Patel et al. 2002). Cover systems must encompass the entire stack; top gradients and side slopes must be vegetated. Drought resistant plant species with roots unable to penetrate low permeability barrier layers are required. Cover material depth for side slopes is not specified but must minimize erosion. Top gradient covers must have a 46 cm barrier soil layer below a 46 cm layer of soil or amended PG able to sustain vegetation. Geomembrane liners can substitute for the soil barrier and 61 cm of soil placed on top (FDEP 1994), although this is costly (Patel et al. 2002). Soil capping is used in a variety of reclamation settings including acid generating mining waste and landfills.

With the exception of Alberta and Prince Edward Island, all provinces and territories in Canada generate acid drainage waste from mineral extraction (O'Kane et al. 1998). When sulphide bearing minerals found in waste rock and tailings react with oxygen and water, sulphuric acid is created. Following development of Mine Environment Neutral Drainage (MEND), a government and industry research initiative to address acid mine drainage, interest in engineered soil caps for mine reclamation increased (Yanful et al. 1999).

Soil caps are used to control water and oxygen movement into sulphide bearing mineral waste rock and tailings (Yanful et al. 1999, O'Kane et al. 1998). Caps for mining waste are typically composed of more than one distinct soil layer. O'Kane et al. (1998) evaluated effectiveness of a two layer soil cap containing acid

generating mine waste rock. A 50 cm layer of compacted till below a 30 cm layer of non compacted till was established on waste rock in central British Columbia. Low hydraulic conductivity of the compacted layer minimized water movement and oxygen diffusion into the tailings while the non compacted layer protected against erosion, desiccation and fluctuations from freezing and thawing. Yanful et al. (1999) studied effectiveness of a three layer soil cover in the laboratory for capping acid generating mine waste. Columns contained a 45 cm thick layer of tailings overlain by 15 cm of coarse sand, 30 cm of compacted clay and 15 cm of fine sand. The cover was deemed effective as tailings maintained their water content over the course of the experiment and oxygen diffusion was prevented.

O'Kane et al. (1998) and Yanful et al. (1999) used heterogeneous pore sized soil materials to control water movement above the tailings. By stratifying fine and coarse soil materials in a cover system, an effective oxygen and water barrier was established (Yanful et al. 1999). The coarse grained soil layer above the tailings, or capillary break, will drain quickly when the water table is low, resulting in low water content and hydraulic conductivity in this layer (Simms and Yanful 1997 as cited in Yanful et al. 1999). Since water tends to move where it will be held more tightly in soil (high to low matric potential) (Brady and Weil 2002), water will remain in the fine grained cap layer. As water evaporates from the upper coarse cap layer, hydraulic conductivity of the layer is reduced and water will stay in the fine grained layer with larger capillary forces (Simms and Yanful 1997 as cited in Yanful et al. 1999). Understanding soil physical properties as they relate to water movement is critical for development of an effective soil cap.

Landfill closure and reclamation commonly involve soil capping and revegetation. Similar to caps for PG and mining waste, landfill covers must minimize infiltration and prevent leachate production, control surface erosion and limit landfill gas emissions (Simon and Müller 2004). In Alberta, final landfill cover systems include a 60 cm soil layer with maximum hydraulic conductivity of 1.0×10^{-7} m/s, or alternative material which meets the same requirement, below subsoil and a surface topsoil layer (Government of Alberta 2008). Subsoil and topsoil depth replacement must be equivalent to that prior to construction or suitable for a desired end land use. Pasture or recreational lands require 35 cm subsoil and 20 cm topsoil. Cultivated or forest lands require 80 cm subsoil and 20 cm topsoil.

1.4.3 Revegetation

Once capped, PG stacks are normally seeded to species which can reduce erosion, improve aesthetics and create habitat (Richardson et al. 1995). Plant species selection must account for climate, establishment, palatability, root type, response to herbicides, species origin, maintenance and competitive nature. Desirable plant species commonly include grasses, which establish quickly, are productive, provide good cover and require little maintenance. To minimize percolation into PG, species with high cover potential will maximize surface evapotranspiration (Patel et al. 2002). Patel et al. (2002) found 60 to 70 % less evapotranspiration on bare PG than on vegetated PG. Knowledge of seed bank species in capping materials is necessary to avoid undesirable species, such as those with deep taproots, and to include beneficial species. To obtain a self sustaining vegetation cover on reclaimed mine land, development of a microbial community is critical (Harris and Birch 1990 as cited in Komnitsas et al. 1999).

In Florida, *Cynodon dactylon* (L.) Pers. (Bermuda grass) and *Panicum virgatum* L. (Alamo switchgrass) are commonly seeded on PG stacks (Richardson et al. 1995). *Cynodon dactylon* is a long lived perennial which grows laterally and reaches heights between 10 and 46 cm. It can form dense cover and tolerate pH values of 5.0 to 8.5 and salinity up to 18 mmhos/cm (USDA NRCS PMP 2006a). *Panicum virgatum* is a perennial with a bunch type growth form reaching heights between 90 and 150 cm. It is effective for soil stabilization and erosion control (USDA NRCS PMP 2006b). To maximize evapotranspiration losses from the PG stack, Patel et al. (2002) recommend planting species such as *Cynodon dactylon* and *Panicum virgatum* to maximize cool and warm season evapotranspiration.

1.4.4 Economics, long term stability and aesthetics

PG stack owners must outline cost estimates for closure of the stack, long term management and a water management plan in their closure plan (FDEP 1994). Cost estimates of cover material, topsoil, seed, fertilizer, mulch and labour are to be included. Long term cost estimates must be provided for surface cover material, surface and ground water monitoring, collection and analyses. Water management cost estimates for process and pore water management, treatment

and disposal during closure and post closure must be included. Long term care of the PG stack is the responsibility of the stack owner for 50 years following date of closure unless it can be proven the stack is not a threat to the environment or human health. Until PG becomes economical to utilize in other industries, such as sulphur recovery, containing the waste and establishing a vegetated cover is a realistic option (Norlander 1988).

Long term stability of vegetated PG cover systems may be dependent on management. In Florida, Patel et al. (2002) recommended application of slow release nitrogen fertilizer each spring to maintain plant vigour and winter mowing to encourage new growth and prevent senescence of plants for evapotranspiration maximization during growing seasons. To control undesirable species and encourage new plant growth, controlled burning may be a management option. For example, *Panicum virgatum* responds well to spring burning every 3 to 5 years to remove litter and reduce competition of undesirable species (USDA NRCS PMP 2006b).

While large scale waste piles can never appear as natural features on the landscape (Tordoff et al. 2000), attempts must be made by industry to reduce visual impact. To maintain an aesthetically pleasing landscape, revegetation is a critical component of stack reclamation. Revegetated stacks will blend in better with the surrounding landscape and improve public perception of industrial waste management practices, especially those living in close proximity.

1.5 Phosphogypsum Stack Reclamation in Canada

1.5.1 Regulatory framework

Environmental regulations for PG waste management and stack reclamation do not exist in Canada (SENES 1987). Alberta Environment addresses reclamation protocols for industrial wastes on a case by case basis. In the Agrium Redwater fertilizer plant operating approval a default 1 m soil cap is required for their PG stack unless a shallower depth is found suitable for mitigating environmental hazards associated with stacks (Alberta Environment 2008).

1.5.2 Existing literature

Little research has been conducted on PG stack reclamation in Canada. Characterization of PG and environmental hazards with specific emphasis on radioactivity was studied mainly by Rutherford, Dudas and Arocena during the 1990s (Rutherford et al. 1995a, 1995b, 1995c, 1994). Their research investigated radioactivity and PG chemical composition among different phosphate rock sources, important information for effective management of waste. They found trace element and fluoride concentrations greatly reduced in weathered PG relative to fresh PG although ^{226}Ra in PG leachate was identified as a potential concern despite stacks being highly weathered. In 1988 Norlander assessed the decommissioning of PG tailings in Calgary, Alberta with a focus on radon flux from exposed PG stacks. It was concluded that residential development should be avoided on bare and capped PG stacks to avoid exposure to radon, dust, particulates and gamma radiation. Thorne (1990) identified issues associated with successful reclamation of a PG tailings pond in Calgary, Alberta with a focus on amendments to overcome chemical and physical limitations of PG required for successful revegetation. In greenhouse studies adding soil or lime to PG tailings overcame many limitations associated with vegetation establishment.

The most recent Canadian PG reclamation research was done by Hallin (2009) at the University of Alberta. Her research characterized the quality of a reclaimed PG stack 15 years after initial reclamation efforts in Fort Saskatchewan, Alberta. The effect of a vegetated 15 cm soil cover on water infiltration and percolation into the stack, runoff water quality, radon gas and gamma emissions and plant community development was evaluated. It was concluded that the existing cover system was providing an effective barrier between PG and the environment.

The effect of a topsoil cap and revegetation on radon emissions from PG has not been fully explored in the literature (Dueñas et al. 2007, Rutherford et al. 1994). Research is required to determine an appropriate depth of topsoil for capping PG stacks which limits water percolation into PG, supports a diverse and sustainable plant community and limits emissions of radon gas and gamma radiation in this climatic region. This research will address these aspects of PG caps and contribute to the development of a reclamation plan for PG stacks in Alberta.

1.5.3 Research objectives

The general research objective is to contribute to a reclamation plan for PG stack closure by determining an appropriate depth of soil for capping PG. Specific research objectives are to determine the effect of topsoil cap depth on plant establishment, survival and community development; infiltration under natural precipitation conditions; leaching; and emissions of radon gas, gamma radiation and hydrogen fluoride.

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

2.1 Introduction

Phosphogypsum (PG) is an acidic by product of phosphoric acid production (Richardson et al. 1995, Rutherford et al. 1994). The fertilizer industry generates approximately five tonnes of PG per tonne of phosphoric acid, the latter being required for phosphorus fertilizer production (Rutherford et al. 1995a, Rutherford et al. 1994, Ferguson 1988). Large quantities of PG are produced annually in at least 80 countries around the world (Florida Institute of Phosphate Research 2006). As of January 2006, Florida had at least 20 PG stacks, the greatest number of any state. In Canada there are stacks in British Columbia, Alberta, Ontario, Quebec and New Brunswick with the majority and largest of the stacks in Alberta (Thorne 1990). Ferguson (1988) predicted that worldwide PG production would reach between 220 and 280 million tonnes by the year 2000. Parreira et al. (2003) indicated that PG production was approximately 180 million tonnes per year in 2003. Abril et al. (2009) estimated annual PG production at 170 million tonnes in 2006.

PG is commonly wet stacked on land adjacent to fertilizer production facilities (Luther and Dudas 1993) where they can span hundreds of hectares and tens of meters in height (Rutherford et al. 1995b). The main environmental concerns associated with PG stacks are chemical impurities such as residual acidity, silica, unreacted phosphate rock, radon, uranium and trace elements including fluoride, cadmium, arsenic, lead and silver; their presence and concentration dictated mainly by the composition of the source rock (Wissa 2002). As water percolates through the stack, trace elements can become mobile and leach into ground water, negatively impacting ecosystem function. Exposure to radon gas and gamma radiation can affect human health if emissions are not limited by reclamation methods such as capping (Rutherford et al. 1994).

The most common approach to PG stack reclamation is to cap the PG with soil. A cap can prevent wind and water erosion, limit percolation, provide a plant

substrate, prevent contaminated water from running off stacks and provide a potential landscape conducive to the end land use (Richardson et al. 1995).

Little research has been conducted on PG stack reclamation in Canada. Characterization of PG and environmental hazards with specific emphasis on radioactivity has been studied mainly by Rutherford, Dudas and Arocena during the 1990s (Rutherford et al. 1995a, 1995b, 1995c, 1994). Their research investigated radioactivity and PG chemical composition among different phosphate rock sources, important information for effective management of the waste. They found trace element and fluoride concentrations greatly reduced in weathered PG relative to fresh PG. ^{226}Ra in PG leachate was identified as a potential concern despite stacks being highly weathered. Norlander (1988) assessed the decommissioning of PG tailings in Calgary, Alberta with a focus on radon flux from exposed PG stacks. It was concluded residential development should be avoided on both bare and capped PG stacks to avoid exposure to radon, dust, particulates and gamma radiation. In 1990 Thorne identified key issues associated with successful reclamation of a PG tailings pond in Calgary, Alberta with a specific focus on the use of amendments to overcome chemical and physical limitations of PG required for successful revegetation. In greenhouse studies the addition of soil or lime to PG tailings was effective at overcoming many limitations associated with vegetation establishment.

The most recent Canadian PG reclamation research was done by Hallin (2009) from the University of Alberta. Her research characterized the quality of a reclaimed PG stack 15 years after initial reclamation efforts in Fort Saskatchewan, Alberta. The effect of a vegetated 15 cm soil cover on water infiltration and percolation into the stack, runoff water quality, radon gas and gamma emissions and plant community development was evaluated. It was concluded that the existing cover system was providing an effective barrier between PG and the environment.

Richardson et al. (1995) conducted field, greenhouse and laboratory studies to investigate effective and low cost revegetation strategies for PG stacks in Florida. They found vegetation can be established on PG with pH > 4 or using amendments such as limestone, sand tailings, overburden or composted

garbage. Numerous adapted grass species were used in their experiment and generally responded well to amended PG. Extrapolation of research findings from Florida to Canada is not advisable due to differing climates (particularly lower rainfall), adapted vegetation species, PG characteristics and regulatory framework. Currently, Alberta Environment requires a 1 m soil cap on the Agrium Redwater PG stack after production has ceased (Alberta Environment 2008). With an annual precipitation of 460 mm at the study site, it was hypothesized this cap depth could be reduced while still maintaining sufficient depth for vegetation establishment and development.

2.2 Research Objectives and Hypotheses

2.2.1 Research objectives

The general research objective is to contribute to a reclamation plan for PG stack closure by determining an appropriate depth of soil for capping PG. The specific research objective is to determine the effect of soil cap depth on plant establishment, survival and community development.

2.2.2 Research hypotheses

- Emergence of seeded species on plots without a soil cap will be very low as a result of seed desiccation and the inhospitable growth medium.
- Cover of seeded species will be lowest on 8 cm cap plots where soil depth is variable and higher on 15, 30, 46 and 91 cm caps, although cover will not differ significantly among depths at this early stage of development.
- The *Agropyron trachycaulum* treatment will establish more rapidly than other treatments and be the dominant species on mix treatments, characteristic of the plant species.
- Plots with a high density of unseeded species will hinder establishment and survival of seeded species due to competition for soil resources.
- Over the long term, a mix treatment will be more resilient to variations in climate, faunal activity and nutrient deficiencies and be a more diverse plant community than will monoseeded treatments.

2.3 Materials and Methods

2.3.1 Research site description

Fort Saskatchewan is located approximately 30 km northeast of Edmonton, Alberta, Canada (53° 43' N and 113° 13' W) (Figure 2.1). It is located in the Central Parklands Natural Subregion within the Aspen Parkland Ecoregion, in a transition zone between the Dry Mixedwood and Northern Fescue Natural Subregions to the north and south, respectively (Speiss 2007, Natural Regions Committee 2006). Average annual precipitation is approximately 460 mm with almost half falling as rain during June, July and August (Environment Canada 2008). Average monthly rainfall ranges from 0.4 mm in January to 88.8 mm in June. Historical extreme daily rainfall has ranged from 6.4 mm in December 1958 to 77.7 mm in June 1965. Yearly snow fall approaches 100 cm. Daily average temperatures range from -13.5 ℃ in January to 16.7 ℃ in July.

Geologic sediments of the Fort Saskatchewan area are Upper Cretaceous shales from the Belly River Formation (Alberta Geological Survey 2005). The topography of the Central Parkland is hummocky and has gently rolling till plains with an average elevation of 700 m (City of Fort Saskatchewan 2008, Natural Regions Committee 2006). Lacustrine and fluvioglacial deposits are the dominant surficial sediments and soils are dominated by Black Chernozems (60 %) with a smaller proportion (15 %) of Solonetzes (Natural Regions Committee 2006). Cultivation and development have resulted in loss of native vegetation, which currently composes only 5 % of the plant community in the Central Parkland. Patches of aspen and plains rough fescue grassland remain, although aggressive non native species such as *Bromus inermis* (Leyss) (smooth brome) and other agricultural species dominate (Natural Regions Committee 2006).

Agrium Incorporated (Agrium), located in the industrial district of Fort Saskatchewan, Alberta (Figure 2.2), is a large scale fertilizer manufacturing company which produced monoammonium phosphate ($NH_4H_2PO_4$) fertilizer for 26 years at its Fort Saskatchewan, Alberta facility (Svarich 1999). Currently only anhydrous ammonia (NH_3) and urea ($CO(NH_2)_2$) are being produced at Fort Saskatchewan (Agrium 2009).

PG was wet stacked in five areas between 1965 and 1991 at Fort Saskatchewan, all of which are closed today (Svarich 1999) (Figure 2.3). Stack 1, located adjacent to the North Saskatchewan River, was active from 1983 to 1991. It was built on a high density polyethylene liner and has a base area of 9.3 ha and a settling basin of 4.7 ha. Stack 2, located south of Stack 1, was built into the side of the river valley (Norlander 1988) on a clay liner. It has a base area of 8.5 ha and settling basin area of 4.7 ha and was active from 1974 to 1991.

Each stack has a bare PG road around the perimeter of the settling basin and a road to connect stacks. Following PG production, 10 to 15 cm of soil was applied with a bobcat to the stack outer slopes and a seed mix consisting mainly of *Bromus inermis* and *Brassica napus* L. (canola) was broadcast (Nichol 2009). The outer slopes of both stacks are currently dominated by *Bromus inermis* and *Melilotus alba* Desr. (white sweet clover). The settling basin of Stack 1, where the research plots are located, is recessed about 10 m below the upper stack road and can be accessed on the south side from the stack base and northeast side from the upper stack road. The basin surface is relatively flat with a slight northeast aspect. The side slopes and basin floor are unvegetated except where mushroom compost was applied at the south side of the basin adjacent to the access road; *Kochia scoparia* (L.) Schrad. (kochia) is the dominant plant species. A thick crust has formed over PG on interior basin sloped walls and the floor.

2.3.2 Experimental design

Eighteen experimental research plots (50 m long x 10 m wide) with varying cap depths were constructed in late October 2006 in a complete randomized design in the Stack 1 basin (Figure 2.4). Soil from an old alfalfa pasture approximately 5 km northeast of Agrium was excavated with a Hitachi 200 backhoe. Soil from an average 40 cm depth was pushed into piles, then loaded into tandem trucks and transported to Agrium. Soil was unloaded into staked plots and built to specified depths with a John Deere 750C dozer and Bobcat S300 (Gagnon 2008).

Capping depths of 8, 15, 30, 46 and 91 cm of soil and a control with no soil were replicated three times (1, 2 and 3; Figure 2.4). Each of the plots was subdivided into five 10 x 10 m sections which were seeded to one of five vegetation

treatments in mid June 2007. Vegetation treatments included monocultures of *Agrostis stolonifera* L. (redtop), *Agropyron trachycaulum* (Link) Malte ex H.F. Lewis (slender wheatgrass), *Deschampsia caespitosa* (L.) P. Beauv. (tufted hairgrass) and *Festuca ovina* L. (sheep fescue). A fifth vegetation treatment was a mix of the above grasses with *Trifolium hybridum* L. (alsike clover). The mix was 54 % *Agrostis stolonifera,* 2 % *Agropyron trachycaulum,* 28 % *Deschampsia caespitosa,* 8 % *Festuca ovina* and 8 % *Trifolium hybridum* (Brett Young 2009).

2.3.3 Plant species selection

Plant species selected for reclamation were native or adapted to the area. They were had high germination and establishment, roots effective at providing erosion control, persistence following climatic or environmental fluctuations, low nutrient and water requirements and tolerance of acidic substrates (Table A1).

Agrostis stolonifera is an introduced, early successional perennial grass tolerant of environmental conditions, including drought. It has a dense root system that can be effective as erosion control when conditions are not too wet (Esser 1994). *Festuca ovina* is a long lived perennial grass with wide spread distribution. It has low nutrient requirements and tolerates acidity. *Deschampsia caespitosa* is a native, perennial grass which tolerates moderate acidity and prefers moderately moist to moist soils. *Agropyron trachycaulum* is a native, short lived perennial grass which grows well in semi arid to moist regions. It establishes quickly and provides excellent short term erosion control. If planted with other slow growing species, it will lose dominance over time. *Trifolium hybridum* is a short lived perennial legume. It can tolerate acidic and alkaline conditions and various moisture regimes. It benefits revegetation when planted with other species due to its nitrogen fixing ability (Hardy BBT Limited 1989). All species grow well on medium to coarse textured soils (Esser 1994, Hardy BBT Limited 1989). Certified seed for each species was obtained from Brett Young Seeds in Leduc, Alberta.

2.3.4 Seeding and fertilizer application

Vegetation treatments were drill seeded in mid June 2007 using a plot seeder with eight (23 cm row spacing) double disc openers with independent seeding

depth gauge for precise seed placement (Puurveen 2007a). Seeding was to a depth of 2 cm (USDA-NRCS 2003) and the wheel packed the seed furrow. A seeding rate of 20 kg/ha was used and Vigoro Ultra Turf Starter (20-28-6) fertilizer was applied at a rate of 100 kg/ha. Seed and fertilizer for each treatment were weighed into individual bags then divided evenly with a cone splitter on the seeder. Eight rows were seeded per pass, with four passes per plot for a total of 32 drill seeded rows. A 1 m buffer along each side of the plots was broadcast seeded with the respective vegetation treatment. Bare ground within the basin was broadcast seeded with a mix of grass and clover and no name® 16-20-0 Lawn Food to prevent encroachment into the plots by unseeded species.

2.3.5 Plot management

Annual and perennial weeds from the soil seed bank dominated the plots in spring and summer 2007. Prior to seeding, all plots, edges and buffers were sprayed with 2.47 L/ha of glyphosate (Roundup WeatherMax) herbicide using a tank pulled by a John Deere 5203 tractor; in areas not accessible by the tractor backpack sprayers were used. Glyphosate is recommended for non selective weed control in various cropping systems including those with grasses and legumes. The application rate used is considered appropriate for eradicating annual weeds over 15 cm in height and for many perennial species including *Medicago sativa* L. (alfalfa) and *Linaria vulgaris* Hill. (toadflax) (Alberta Agriculture and Food 2008).

Plots were harrowed twice before seeding with a 1.5 m 3-point hitch spring tooth harrow pulled by a John Deere 5203 tractor driving the plot length (Puurveen 2007a). Weeds were mowed to approximately 10 cm height in early August 2007 with a tractor and 1.8 m Alamo flail mower on plots, plot edges and buffers. Plot edges and buffers were trimmed several times in summer 2008; plots were mowed September 5, 2008. Biomass was left on plots after each of the mowings.

2.3.6 Meteorological data

A meteorological station was situated in the center of the Stack 1 basin between plots B3 and B4 to avoid edge effects. Instrumentation was Campbell Scientific

including a CR10X data logger. Maximum and minimum air temperature (℃) and relative humidity (%) were measured using the HMP45C Vaisala relative humidity and temperature probe (-40 to +60 ℃). Saturation vapour pressure (kPa) was calculated using appropriate formulae from temperature and relative humidity data. Wind speed (m/s) data were obtained using the 05103-10 RM Young wind monitor. A Kipp & Zonen silicon pyranometer measured total incoming radiation (W/m^2) and total rainfall (mm) was measured with a TE525WS Texas Electronics 20 cm tipping bucket rain gauge in addition to a manual rain gauge. Weather data were downloaded periodically from the data logger via a personal pocket computer (Campbell Scientific (Canada) Corp. 2007, Puurveen 2007b).

2.3.7 Capping depth measurements

Capping depths were measured June 5 and 6, 2008 to determine whether changes occurred due to soil settling, compaction or wind and water erosion following plot construction. Measurements were taken at nine locations on each plot using a systematic sampling strategy; in the center of each treatment 2 m right of stakes marking the west side of the plot and 2 m left of stakes marking the east side of the plot, directly on the boundary between treatments.

Using a 5 cm diameter by 19 cm length barrel auger, a hole was cored through the soil until the PG surface was encountered, as indicated by PG on the auger tip. A meter stick was inserted into the hole and depth (cm) recorded prior to backfilling with excavated soil. If the hole was cored past the soil / PG interface and more than 1 cm of PG was encountered, a visual estimate of PG in the auger was subtracted from the total depth indicated by the meter stick.

2.3.8 Capping soil characterization

Soil was sampled on June 12, 2008. The length of each plot was divided into thirds. A pair of random numbers was generated to provide a sampling location for each third. The first random number generated for each third indicated position across the plot. The second random number indicated position down the length of the top third, middle third and bottom third, respectively. Soil was sampled where these points intersected and adjacent to vegetation rows.

A barrel auger of 5 cm diameter and 19 cm length was used to obtain soil samples to a depth of 8 cm. At most sample locations, three to four holes were excavated adjacent to each other to obtain sufficient sample for analyses, approximately two thirds of a 3.7 L Ziploc bag. If PG or large pieces of organic material were mixed with the soil they were removed by hand. Soil samples from the top, middle and bottom thirds of each plot were mixed thoroughly in a large pail with a hand trowel. Soil was split evenly between two 3.7 L Ziploc bags and labelled. One set of samples was refrigerated for further analyses; the second set was sent to ALS Laboratory in Edmonton to be analyzed.

Inorganic carbon was determined gravimetrically for loss of carbon dioxide to approximate carbonate and total carbon by combustion (Bartels et al. 1996). Total organic carbon was determined by subtraction. Cation exchange capacity (CEC) was determined using the $BaCl_2$ method (Carter 1993) and exchangeable cations determined with $BaCl_2$ extraction after water leach (McKeague 1978). Exchangeable sodium percentage (ESP) was determined by calculation (exchangeable sodium / CEC x 100) (Brady and Weil 2002). Available ammonium nitrogen was determined by extraction in 2 M KCl and colorimetric analysis. Available micronutrients were extracted with DTPA solution and analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES). Particle size was determined by hydrometer; electrical conductivity and % saturation were analyzed by saturated paste (Carter 1993). Soil pH was determined in 1:2 water extract (Carter and Gregorich 2008). Available nitrate nitrogen was determined with a cadmium reduction procedure (Carter 1993) and available phosphate phosphorus and potassium with a modified Kelowna extraction (Qian et al. 1994). Available sulphate sulfur was determined by extract in weak $CaCl_2$ and analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Alberta Agriculture 1988). Results were compared to the Soil Quality Criteria Relative to Disturbance and Reclamation (Alberta Agriculture, Food and Rural Development 1987) for soil in the Plains Region.

PG bulk density cores were obtained October 2, 2008 from *Deschampsia caespitosa* treatments on 8 and 15 cm cap depths. *Deschampsia caespitosa* performed poorly compared to other vegetation treatments, and thus represented the worst treatment. Shallow soil depths were selected as plants may root

through soil into PG, requiring characterization of PG. Cores were extracted at three random locations on each *Deschampsia caespitosa* treatment for each cap depth. Locations were determined by generating three pairs of random numbers for each plot. Where the first number (across the top of the plot facing north) and the second number (down the plot length) intersected, a core was obtained.

Soil was excavated to the PG surface from a < 0.5 m^2 area using a round point spade and depth of soil recorded at two opposite points in the excavation. The upper 5 to 10 cm of the PG surface was scraped off with a spade and hand trowel prior to positioning a 7.5 cm diameter by 7.5 cm height Uhland core sleeve. The core was tapped into PG with a mallet and 15 cm long piece of wood on top of the core until flush with the PG surface. PG was cleared from around the core with a hand trowel before being gently removed from the excavation. Excess PG was cleaned off the outside of the core and trimmed on the bottom until PG was flush with the core bottom. The sample was removed from the core and placed in a 3.7 L Ziploc bag. Field weights of samples were determined with a portable scale. Samples were sieved to ≤ 2 mm to break aggregates and promote uniform drying, then oven dried to constant mass at 45 ℃ (Averitt and Gliksman 1990) in a Napco 420 incubator oven. Volume of the Uhland core sleeve ($V = \pi r^2 h$) was 331 cm^3, equal to the PG volume. Bulk density was calculated by dividing the oven dry PG mass by PG volume in the core for each sample (Carter and Gregorich 2008).

Water retention curves for soil and PG were developed using the pressure extractor method (Carter and Gregorich 2008) for samples from the 15 cm cap depths. Pressure plates and 0.5 and 1.5 MPa pressure extractors manufactured by Soilmoisture Corporation were used. Soil samples collected during soil sampling (2.3.8 above) and PG samples collected from 15 cm cap depths for bulk density determination were used. PG samples collected from three random locations for bulk density determination were composited for pressure plate analysis. Samples were sieved to ≤ 2 mm and stored in Ziploc bags.

Three replications per plot for soil and PG (n = 9) were used for each pressure of 0.01, 0.03, 0.1, 0.33, 0.5 and 1.5 MPa. Bags of sample were mixed to achieve uniform particle distribution prior to pouring samples into plastic rings of 1.0 cm

height and 5.3 cm diameter. Samples were gently packed before replacing plates in the chamber. Tap water was poured between sample rings on each plate and left to soak overnight prior to sealing and pressurizing the chamber. Samples were left under pressure for three to 13 days, depending on applied pressure, and weighed immediately following depressurization. Samples were oven dried at 45 ℃ (Averitt and Gliksman 1990) to constant mass and weighed again. Gravimetric water content for each sample was calculated by dividing the mass of water lost during drying by oven dry weight of each sample. Mean and standard deviation were calculated for soil and PG at each pressure and water retention curves developed.

2.3.9 Vegetation assessment

Vegetation was assessed in mid July and late August 2007 to determine seeded species survival. Three rows were randomly selected for each treatment in each plot. The distance (m) of emerged and surviving vegetation was divided by row length (approximately 10 m) and converted to a percent. Vegetation with < 50 % dead material was included and that with > 50 % was not included.

Vegetation was assessed in mid August 2008 to determine treatment responses. A 0.1 m^2 quadrat (0.5 m x 0.2 m) was randomly situated on three locations on each treatment of each plot, determined by generating three pairs of random numbers. Quadrats were situated perpendicular to seeded rows where the first value (across top of plot facing north) and the second value (down side of plot) intersected. This was repeated for a total of 270 assessments, 15 per plot. Plots with 8 cm capping were assessed using five quadrats, which were deemed an appropriate number to characterize the plant community with a species area curve (Kilburn 1966). Only species rooted in the quadrat were assessed.

All species were identified and canopy cover of each species was visually estimated. If cover of a species was estimated as < 1 %, it was recorded as trace (0.0001 %). Following assessment of quadrats on each treatment, a walk through of each 10 m x 10 m treatment was performed to identify species not found in quadrats. Three plants per species (if present) were randomly selected and measured from ground surface to stretched tip with a meter stick (cm). If fewer

than three individuals of a species were present, average height was calculated using available measurements. To characterize ground cover, percent feces, PG, moss, woody debris, live vegetation (at < 3 cm height), bare ground and litter in the quadrat were estimated. Components of ground cover summed to 100 %. Biovolume was determined for each vegetation treatment using a 500 mL cylindrical sample bottle as a template for estimating above ground plant material packed into the bottle with no air space. Biovolume was recorded as trace (< 25 % of plant material occupying bottle) and in increments of 25 %.

Species health was evaluated using a 3 point scale. A value of 1 was assigned to necrotic plants (< 25 % live green material), 2 indicated the plant was exhibiting some unhealthy symptoms (chlorosis or wilting) (25 to 75 % live green material) and 3 indicated a healthy plant (> 75 % live green material). Each species was assigned a heath index representative of all plants of that species in the quadrat. Species stage of physiological development was evaluated using a 3 point scale. A value of 1 was used to indicate a rosette or immature plant, 2 indicated a plant was close to flowering or flowering and 3 indicated the plant had set seed. A single value was assigned to represent all plants of a species in the quadrat.

2.3.10 Seed viability

To determine germination potential of seeds produced by *Agropyron trachycaulum* plants, seed was collected in mid to late August 2009. *Agropyron trachycaulum* plants were deemed ready for harvesting when seeds were falling freely off the rachis or with minimal force and seed was in the hard dough stage (Saskatchewan Forage Council 1998). Harvest locations were determined by generating three pairs of random numbers. Seed heads were collected from a 1 m radius where the first value (across top of plot facing north) and the second value (down side of plot) intersected. At each of three locations on each *Agropyron trachycaulum* treatment of each plot, 10 seed heads were clipped from the stem using scissors (30 seed heads per treatment) and placed in paper bags. No seed was collected from *Agropyron trachycaulum* plants on the 0 cm cap plots, due to lack of growth. After 2 weeks of air drying, seeds were gently shaken from the inflorescence and 50 plump and healthy looking seeds from each plot were selected for germination testing. Seeds were placed on paper

towel moistened with distilled water inside a petri dish and covered. Dishes were placed on a counter in front of a west facing window at room temperature and distilled water was added as required to prevent paper towels from drying. Seeds exhibiting radicle development were counted and recorded daily and removed. The experiment was cut short after a few weeks of very little germination, uncharacteristic of *Agropyron.*

In January 2009, a second batch of 50 seeds per plot underwent germination testing following a three and a half month cold stratification period under frozen conditions. The germination testing protocol was identical to that outlined above. Once germination ceased after approximately 5 weeks, the total number of seeds which germinated were counted and converted to a percentage.

Tetrazolium (TZ) chemical viability tests were conducted in the University of Alberta laboratory in late November 2008. Three plump and healthy looking *Agropyron trachycaulum* seeds were selected from samples taken on each plot. TZ testing protocol as outlined by the Association of Official Seed Analysts (2000) was followed. Seeds were treated for staining by soaking in deionized water overnight and cutting longitudinally to expose the embryo, leaving the distal end intact. Seeds were then placed on paper towels inside petri dishes and 1 % TZ solution applied to cover seeds. Dishes were covered with a petri dish lid and placed inside drawers in the dark for 8 hours. Seed embryos were then evaluated for degree of red tissue staining using a dissecting microscope.

2.3.11 Statistical analyses

Data were organized by plot depth and vegetation treatment in Microsoft Excel and descriptive statistics were calculated. Correlation coefficients (r^2) were determined for parameters exhibiting linear trends with soil depth. Percent survival and cover data collected from three rows or quadrats per treatment, respectively, were averaged to give one value per depth replicate for further use in statistical analyses. Only survival data from the August 2007 assessment were used in statistical analyses. Means for biovolume and height were calculated using available data from all replicates. Health and development indices were converted to percentages of species on each treatment exhibiting that index. On

mix treatments, all five seeded species were combined for analyses. One way ANOVAs were performed in SigmaPlot 11.0 at the 5 % level of significance to determine whether vegetation parameters varied among capping depth treatment for each species. If data failed to pass the tests for normality or homogeneity of variance, a Kruskal-Wallis one way ANOVA on ranks was performed. Tukey's multiple comparison test was used to detect mean differences.

2.4 Results and Discussion

2.4.1 Soil and PG characterization

Measured cap depths were generally comparable to target depths outlined in the experimental design (Table 2.1). Differences were highest for 8 cm and lowest for 46 cm cap plots. Soil properties for all capping depth treatments were generally associated with a hospitable plant growth medium (Table 2.2). Soil texture was sandy loam to loamy sand (clay content 9.7 to 12.0 %), with low CEC and percent saturation. General soil quality was good (low Na, higher Ca, low EC, low SAR). Bulk density of PG on 8 and 15 cm cap plots was 1.32 and 1.35 Mg/m^3, respectively, with volumetric water contents of 26 and 27 % (Table 2.3). Soil bulk density on Stack 1 side slopes was determined by Hallin (2009) as 1.28 (0.14 standard deviation) Mg/m^3. Water retention was much higher for PG than for soil at low suctions and slightly lower at high ones (Figure 2.5). Water holding capacity for the soil (FC – WP) was low (approximately 0.10 g/g).

Available nitrate N, ammonium N, phosphate P and potassium concentrations did not differ significantly with capping depth, although available nitrate N and phosphate P decreased with increased capping depth (r^2 = 0.78 and r^2 = 0.51, respectively, data not shown). SO_4 concentration in 8 cm caps was significantly greater than in 15 and 30 cm caps; 46 cm caps had significantly more SO_4 than 15 cm caps and there were no significant differences between 8 and 46 cm caps. SO_4 in 8 cm caps was likely highest due to PG incorporation during sampling. Depth of 8 cm caps was variable and PG mixing with soil was difficult to avoid during sampling. Higher SO_4 concentrations in the research plots relative to Ah and Bm horizons in Alberta Chernozemic soils (18 and 24 mg/L, respectively)

(Lowe 1965) may result from PG incorporation during seeding when the tractor picked up PG on 0 cm plots and the basin floor, tracking it onto plot surfaces. Generally, plot edges had more PG incorporated than plot centers.

There were no apparent differences in soil properties which could impact plant growth among capping depths, with the exception of bare PG plots. Other than cap depth, soil quality was generally the same for all capped plots.

2.4.2 Vegetation response to capping depth

2.4.2.1 General plant response

Vegetation generally responded positively to all capping depths relative to bare PG (Table 2.4). Capped plots had 8 to 14 % canopy cover and similar amounts of bare ground (41 to 58 %) and litter (34 to 50 %) (Table 2.5 and Table 2.6). As expected, mean vegetation survival in year 1 was significantly higher on capped than uncapped plots and ranged from 22 to 38 %. Canopy cover was greater on soil plots relative to bare PG and differed significantly for 0 and 46 cm cap plots. Biovolume, height, health and development were comparable for all capping depths. Most species were healthy and either flowering or had set seed. Cap depth did not influence general plant response.

Ground cover consisted mainly of bare ground, litter and live vegetation with smaller proportions of woody debris, moss, PG and feces (Table 2.7). Litter consisted mainly of a thin layer of seeds, broken pieces of grass stems and leaves. Bare ground and litter were comparable for all vegetation treatments. Although biomass left on the plots after mowing in summer 2008 created a thick litter layer, vegetation assessments were performed before mowing and thus did not capture this quantitatively.

As plant roots develop they may move into the PG, but after two years there was no negative effect of shallower caps on plant growth and development. Hallin (2009) found *Bromus inermis* rooting as deep as 15 cm into PG after 15 years with no adverse effects. Thus, this and Hallin's study suggest shallow capping may provide a suitable rooting medium for plant establishment and growth.

2.4.2.2 Individual species responses

Agropyron trachycaulum established quickly and vigourously on all caps (Table 2.8). Tetrazolium tests on *Agropyron trachycaulum* seeds indicated 100 % viability, with seed germination from 57 to 72 % within eight days (Table 2.9). High seed viability and good germination of *Agropyron trachycaulum* plants after the second growing season suggests there were no limitations to growth. *Agropyron trachycaulum* treatments had the highest bare ground and lowest litter cover which may be related to its aggressive early establishment and ability to out compete unseeded species (Table 2.7). The early stage of plant community development, where few unseeded species were present, had not allowed much litter or plant biomass to accumulate.

Agrostis stolonifera did not respond significantly to capping depth but was much higher on capped plots than bare PG (Table 2.10). There was little cover at the end of the second growing season, although most plants were healthy and fully developed. Percent cover was weakly correlated to unseeded species cover (r^2 = 0.40, statistics not shown). Year 1 survival of *Festuca ovina* was significantly higher on 15, 46 and 91 cm caps than bare PG (Table 2.11). Cover, biovolume and height did not differ significantly with capping depth. Plants ranged from necrotic to healthy and development from immature to fully developed. Low cover may be due to the slow growing nature of the species as it forms large root masses allowing it to persist (Brett Young 2009). *Festuca ovina* was not correlated to percent cover of unseeded species on the treatment.

Deschampsia caespitosa performance was relatively poor (Table 2.12). Year 1 survival averaged 26 %, was higher on capped than PG plots but did not differ significantly with capping depth. Cover, biovolume and height did not differ significantly with capping depth. Plant health ranged from necrotic to healthy and development from immature to fully developed. Presence of unseeded species was correlated to percent cover of (r^2 = 0.75, statistics not shown). *Deschampsia caespitosa* is adapted to wet conditions and performs best with greater than 508 mm of annual precipitation (Brett Young 2009). Insufficient water and competition from unseeded species may have resulted in the relatively poor performance. *Deschampsia caespitosa* treatments had higher litter compared to bare ground,

which may be related to the relatively cover of unseeded species (Table 2.7). The tufted growth and less aggressive nature of the species may have allowed unseeded species to use resources, as much of the litter appeared to be from unseeded species.

Plant mix treatments were dominated by *Agropyron trachycaulum* with smaller proportions of *Agrostis stolonifera, Festuca ovina* and *Trifolium hybridum* (Table A4). Year 1 survival was significantly higher on 8 and 46 cm caps than on bare PG (Table 2.13); other depths did not differ significantly. Cover was higher with 8 and 30 cm caps than 0 cm caps while biovolume and height did not differ significantly with cap depth. Most plants were moderately healthy to healthy. Seeded species were immature to fully developed. Lack of *Deschampsia caespitosa* on mix treatments may be related to its poor competitive ability with unseeded species and less than optimal water availability. Species performance in the mix was comparable to monoseeded treatments, suggesting no conflicting species characteristics influencing development of the plant community.

2.4.2.3 Unseeded species responses to capping depth

Thirty eight unseeded grasses and forbs, likely from the cap seed bank, were found on the plots (Table A2). Most common species included *Medicago sativa* L. (alfalfa), C*henopodium album* L. (lamb`s quarters), *Kochia scoparia* (L.) Schrad. (kochia) and *Sonchus arvensis* L. (perennial sow thistle). Canopy cover of unseeded species did not differ significantly with capping depth, although they were visibly denser on some plots. This variability was likely a function of depth at which capping soil was excavated from the donor site and mixed during plot construction. Seed quantity and diversity decrease with soil depth as indicated by Iverson and Wali (1982) who found more seeds and greater species diversity in the upper 7.5 cm of soil on grazed and ungrazed prairie in North Dakota than in 7.5 to 15 cm depths. Soil seed banks are important for initiating the trajectory of plant community succession (Iverson and Wali 1982). For example, *Medicago sativa,* a long lived perennial on the Agrium plots, could become a dominant component of the long term plant community if not managed. This would be undesirable for a natural area end land use. There is still controversy whether tap rooted species are desirable for PG stack reclamation. Cover and biovolume of

unseeded species were higher than seeded species on all treatments with the exception of the *Agropyron trachycaulum* treatments (Figure 2.6 and Figure 2.7). Heights of unseeded and seeded species were comparable on all treatments except *Agropyron trachycaulum* where plants were much taller than unseeded species (Figure 2.8).

2.4.2.4 Practical applications

Seeding a mix of grass and legume species is recommended to achieve a plant community on PG stacks which would mimic the surrounding landscape. The current seed mix included species with multiple life forms, one of several indicators of rangeland health of grasslands (Alberta SRD 2005). With minor adjustments to the seed mix, a diverse plant community providing appropriate ecological structure and function could be obtained.

Deschampsia caespitosa could be eliminated from the mix due to its poor performance, or substituted with *Koeleria macrantha* (Ledeb.) J.A. Schultz (june grass), a slightly shorter tufted bunch grass. *Koeleria macrantha* is a native perennial common to the aspen parkland with low nutrient and water requirements and provides good erosion control (Hardy BBT Limited 1989). Seeding grasses and *Trifolium hybridum* in similar proportions to the mix treatment would be appropriate for initiating plant community development on the stacks. The short lived nitrogen fixing species, *Trifolium hybridum,* could provide an important source of nitrogen. *Agropyron trachycaulum* would establish rapidly in the first two growing seasons, provide good cover and stabilize steep slopes of PG stacks before losing dominance as *Festuca ovina, Agrostis stolonifera* and *Koeleria macrantha* increase. Eventually, seeded species could develop into a self sustaining plant community.

2.5 Conclusions

- Vegetation treatments performed as expected, relative to their species characteristics and requirements.

- Capping depth did not affect measurable health and vigour of vegetation treatments after the second growing season.
- Development of grass roots into PG did not have adverse effects on plant health and vigour.
- A minimum capping depth of 8 to 15 cm would provide a sufficient rooting medium for establishing vegetation on PG stacks.
- Unseeded species appeared to influence establishment of seeded species, especially *Deschampsia caespitosa.*
- Seeded species must be compatible with perennial species present in the capping soil seed bank to direct succession toward a self sustaining plant community.
- Seeding a mix of grass and legume species is recommended to initiate plant community development on PG stacks.

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Figure 2.1. Map showing location of Fort Saskatchewan, Alberta, Canada.

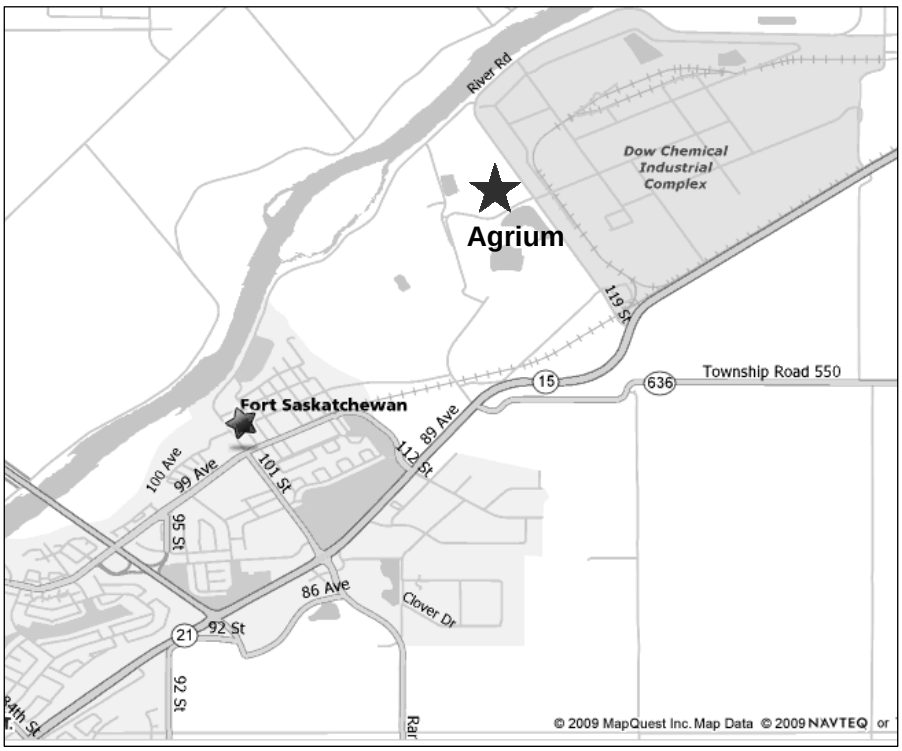

Figure 2.2. Map showing location of Agrium in Fort Saskatchewan, Alberta, Canada.

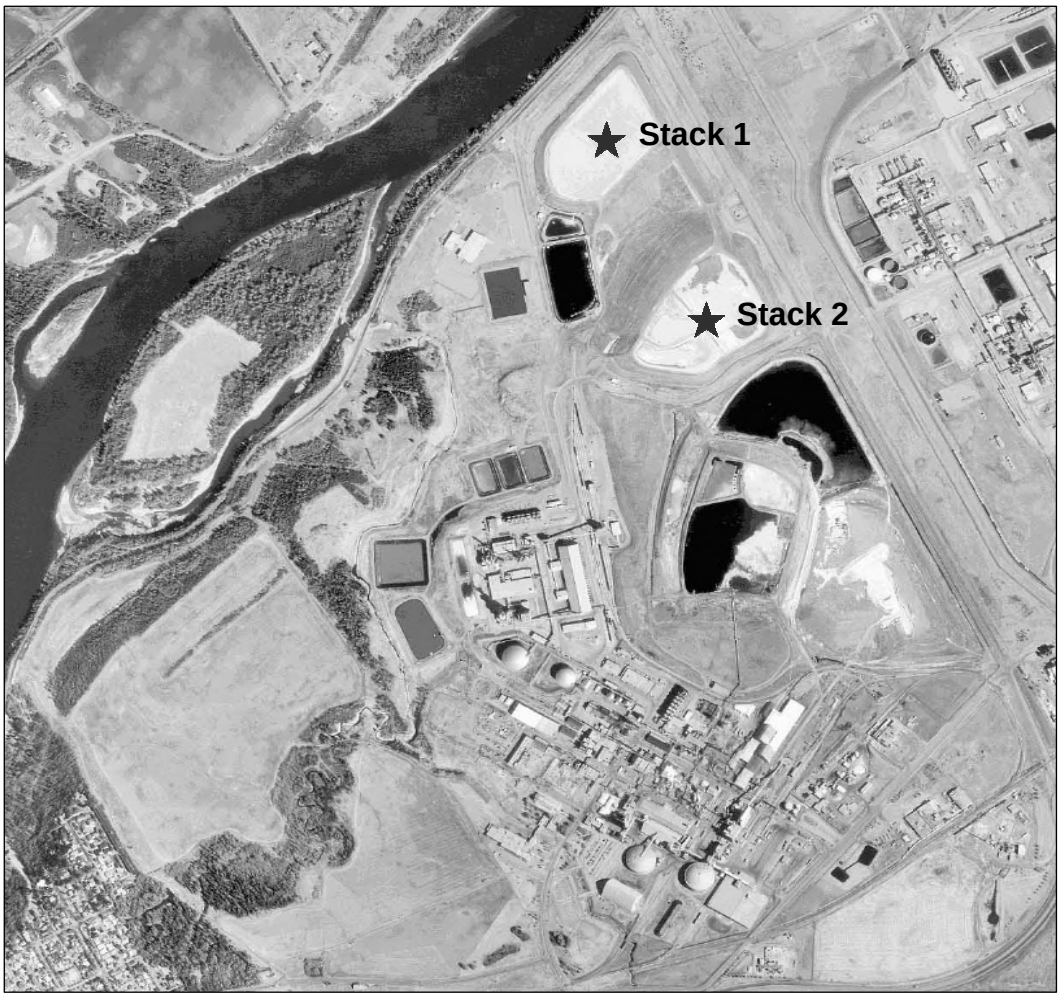

Figure 2.3. Aerial view of Agrium Fort Saskatchewan Nitrogen Operations. North is toward top left corner. North Saskatchewan River is in top left corner.

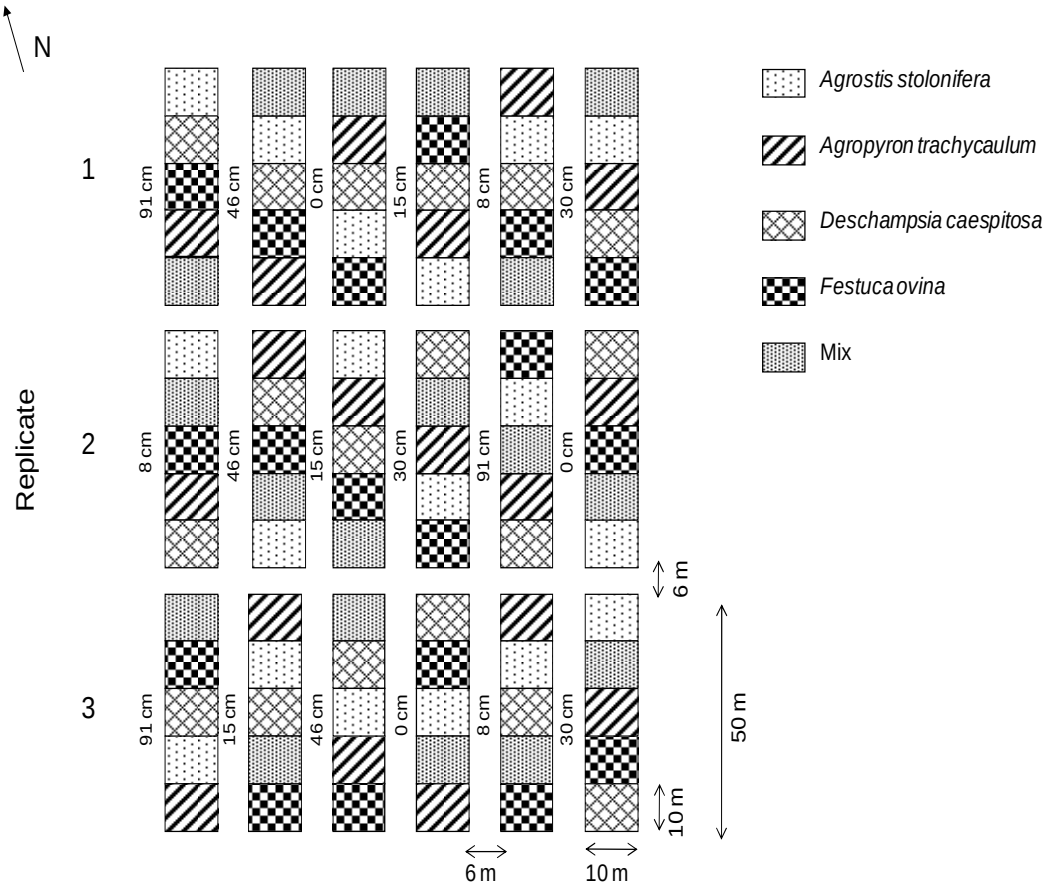

Figure 2.4. Experimental research plots at Agrium Fort Saskatchewan, Alberta.

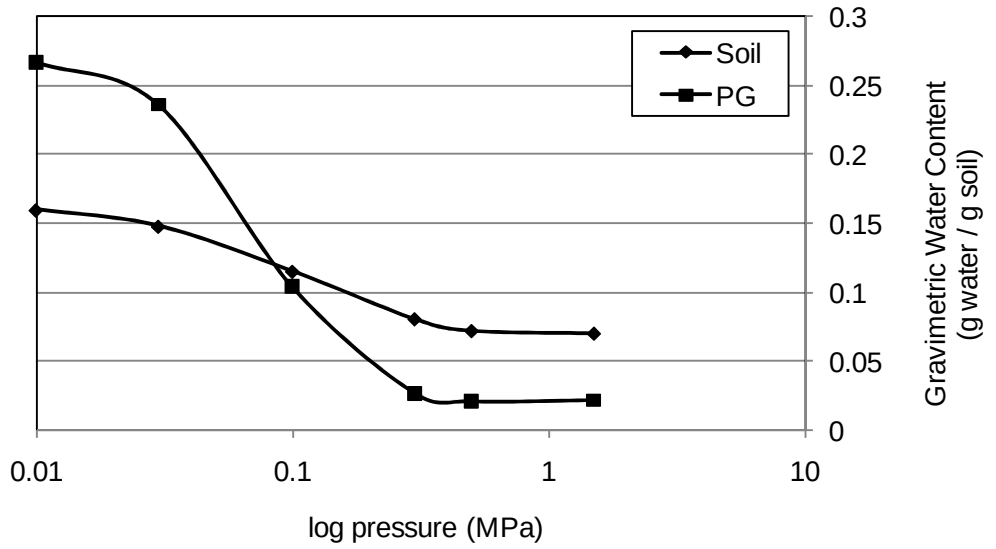

Figure 2.5. Water retention curves for soil and PG from 15 cm cap at Agrium Fort Saskatchewan, Alberta. n = 9.

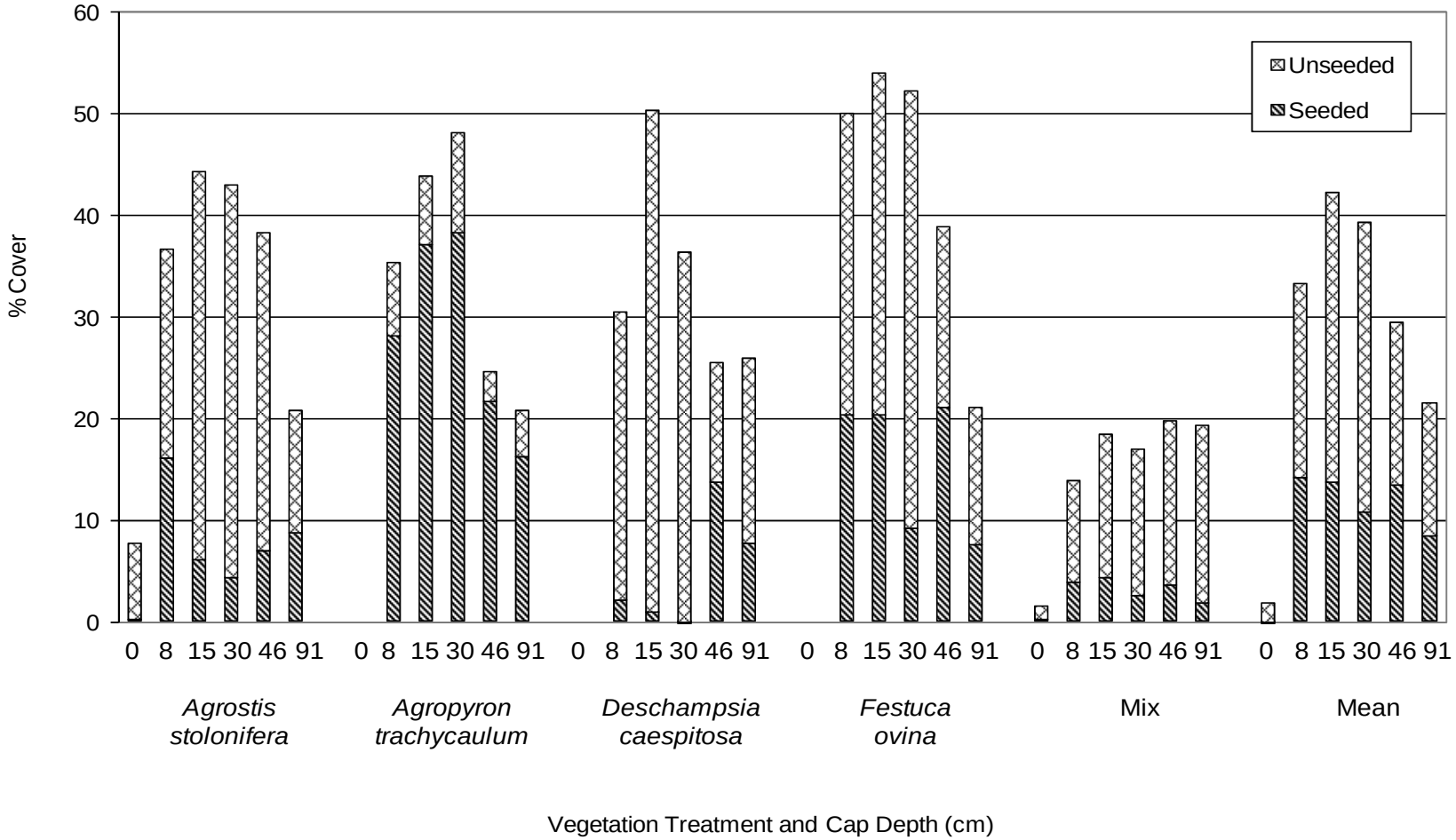

Figure 2.6. Canopy cover of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta.

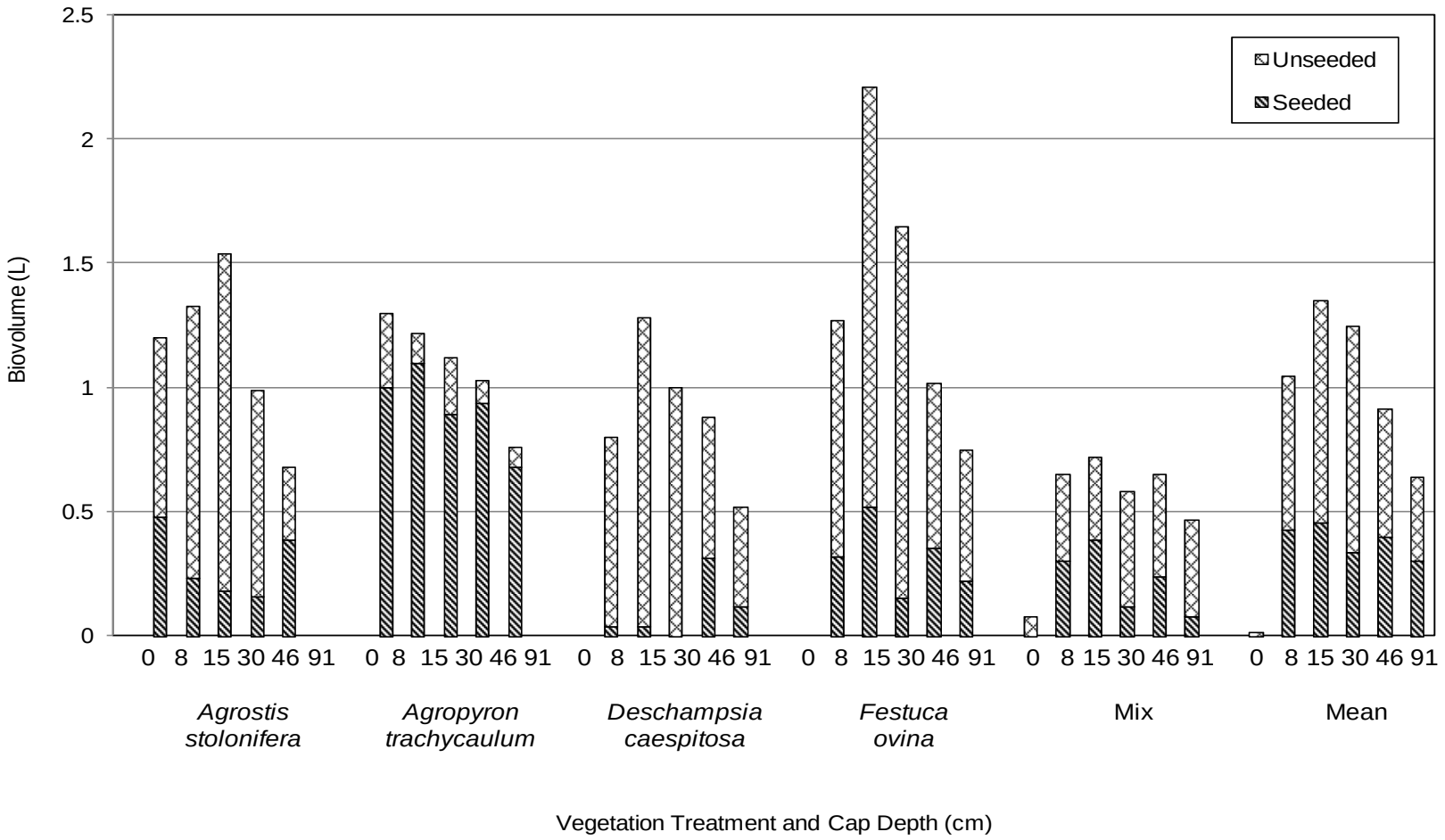

Figure 2.7. Biovolume of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta.

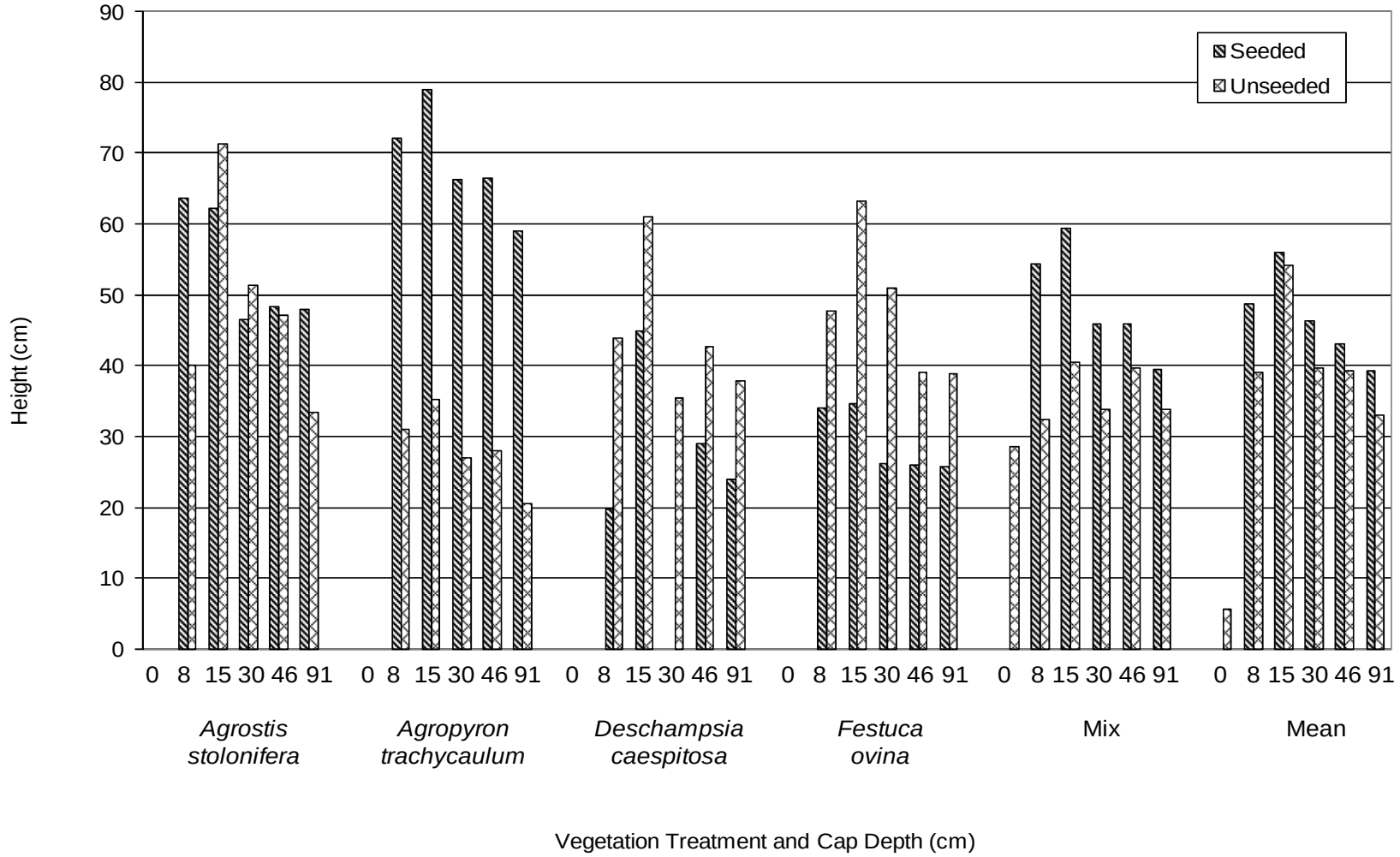

Figure 2.8. Height of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta.

Table 2.1. Capping depth for research plots at Agrium Fort Saskatchewan, Alberta.

Target Cap Depth (cm)	Cap Depth (cm)
8	11.3 (3.4)
15	19.3 (3.3)
30	28.4 (5.5)
46	46.7 (8.9)
91	96.9 (8.7)

Data are means with standard deviations in brackets.
n = 27.

Table 2.2. Capping soil properties for experimental research plots at Agrium Fort Saskatchewan, Alberta.

	Capping Depth (cm)				
	8	15	30	46	91
Cation Exchange Capacity (meq/100 g)	17.8 (2.2)	20.5 (4.0)	19.7 (3.4)	16.0 (0.1)	16.6 (1.5)
Electrical Conductivity (dS/m)	2.8 (0.4)	1.2 (0.8)	2.4 (0.5)	2.6 (0.1)	2.5 (0.1)
Saturation (%)	33.7 (1.5)	38.3 (4.5)	37.0 (1.0)	32.7 (0.6)	34.0 (1.0)
pH	6.3 (1.3)	7.1 (0.8)	6.7 (0.8)	6.1 (0.6)	6.8 (0.8)
Sand (%)	79.00 (1.00)	80.67 (0.58)	81.00 (1.00)	81.67 (2.52)	80.67 (2.31)
Silt (%)	9.33 (1.15)	9.67 (0.58)	9.33 (1.15)	9.00 (1.73)	7.00 (2.65)
Clay (%)	11.67 (0.58)	9.67 (0.58)	10.00 (1.00)	9.67 (0.58)	12.00 (2.65)
Texture	SL	SL/LS	LS/SL	SL/LS	SL/LS
Available Nitrate - N (mg/kg)	23.5 (17.8)	9.5 (4.2)	10.5 (3.4)	5.7 (3.7)	3.97 (1.7)
Available Phosphate - P (mg/kg)	55.0 (28.2)	22.0 (11.1)	30.7 (9.1)	31.3 (6.5)	18.0 (10.4)
Available Potassium (mg/kg)	63.3 (14.2)	83.3 (52.2)	106.3 (16.3)	83.0 (45.9)	54.0 (19.1)
Available Sulphate - S (mg/kg)	802.3 (55.7)	63.0 (56.4)	273.0 (184.7)	710.0 (234.2)	384.7 (238.2)
Sodium (Na) (meq/100 g)	0.4 (0.2)	*	*	0.3 (0.1)	0.3 (0.1)
Potassium (K) (meq/100 g)	*	0.6 (0.2)	0.6 (0.1)	0.3 (0.1)	0.5 (0.1)
Calcium (Ca) (meq/100 g)	19.1 (6.5)	19.1 (4.6)	21.2 (5.9)	15.6 (2.5)	20.3 (5.1)
Magnesium (Mg) (meq/100 g)	1.2 (0.2)	1.4 (0.5)	1.5 (0.1)	1.4 (0.3)	1.4 (0.1)
ESP (%)	2.5 (1.3)	*	*	1.7 (0.7)	1.8 (0.8)
SAR	0.4 (0.2)	*	*	0.3 (0.1)	0.3 (0.1)
Total Organic Carbon (%)	1.9 (0.2)	2.4 (0.6)	2.4 (0.3)	1.7 (0.2)	2.0 (0.2)
Total Carbon by Combustion (%)	2.0 (0.2)	2.4 (0.6)	2.4 (0.3)	1.7 (0.2)	2.0 (0.2)
Available Ammonium - N (mg/kg)	8.4 (8.6)	2.1 (0.3)	2.3 (0.3)	2.5 (0.4)	2.2 (0.3)
Copper (Cu) (mg/kg)	0.4 (0.1)	0.4 (0.1)	0.4 (0.0)	0.4 (0.1)	0.4 (0.1)
Iron (Fe) (mg/kg)	55.7 (30.4)	57.3 (15.5)	58.3 (31.3)	58.3 (15.2)	60.3 (35.0)
Manganese (Mn) (mg/kg)	9.9 (10.7)	4.4 (1.3)	4.9 (1.8)	6.4 (2.4)	4.0 (1.3)
Zinc (Zn) (mg/kg)	3.2 (1.6)	3.8 (2.2)	3.7 (1.4)	2.7 (0.7)	2.8 (1.6)

Data are means with standard deviations in brackets.
n = 3.
*Incomplete data set available for calculation of mean.
SL = sandy loam, LS = loamy sand.
Inorganic carbon and $CaCO_3$ equivalent were not included due to incomplete data set available for calculation of mean.

Table 2.3. Bulk density and volumetric water content of phosphogypsum from 8 and 15 cm capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Bulk Density (Mg/m^3)	Volumetric Water Content (m^3 water/m^3 PG)
8	1.32 (0.10)	0.27 (0.07)
15	1.35 (0.07)	0.26 (0.03)

Data are means with standard deviations in brackets.
n = 9.
Samples taken from 5 to 12 cm in PG.

Table 2.4. Vegetation treatment characteristics on capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Treatment	Year 1 Survival[†] (%)	Cover[‡] (%)	Biovolume (L)	Height (cm)	Health[ŧ] (%)			Development[ŧ] (%)		
						1	2	3	1	2	3
0	*Agrostis stolonifera*	5 (12)	0 (0)	-	*	*	*	*	*	*	*
	Agropyron trachycaulum	0 (0)	-	-	-	-	-	-	-	-	-
	Deschampsia caespitosa	4 (8)	-	-	-	-	-	-	-	-	-
	Festuca ovina	0 (1)	-	-	-	*	*	*	*	*	*
	Mix	1 (2)	0 (1)	*	28 (2)	0	0	100	0	100	0
8	*Agrostis stolonifera*	48 (21)	16 (27)	0.5 (0.5)	64 (26)	0	0	100	0	29	71
	Agropyron trachycaulum	60 (11)	28 (15)	1.0 (1.0)	72 (34)	0	0	100	11	0	89
	Deschampsia caespitosa	13 (11)	2 (4)	0.0 (0.1)	20 (15)	14	29	57	57	14	29
	Festuca ovina	19 (12)	20 (18)	0.3 (0.4)	34 (15)	0	22	78	0	78	22
	Mix	38 (15)	4 (11)	0.3 (0.5)	54 (35)	0	25	75	19	6	75
15	*Agrostis stolonifera*	48 (18)	6 (7)	0.2 (0.3)	62 (18)	12	25	63	12	0	88
	Agropyron trachycaulum	61 (13)	37 (33)	1.1 (0.7)	79 (12)	0	0	100	0	0	100
	Deschampsia caespitosa	8 (8)	1 (2)	0.0 (0.1)	45 (10)	0	67	33	0	67	33
	Festuca ovina	26 (10)	20 (27)	0.5 (0.6)	35 (8)	0	17	83	0	50	50
	Mix	35 (10)	4 (13)	0.4 (0.5)	60 (36)	5	0	95	21	16	63
30	*Agrostis stolonifera*	34 (24)	4 (6)	0.2 (0.2)	47 (10)	0	40	60	0	20	80
	Agropyron trachycaulum	35 (14)	38 (29)	0.9 (0.7)	66 (15)	0	11	89	0	11	89
	Deschampsia caespitosa	3 (4)	0 (0)	*	*	*	*	*	*	*	*
	Festuca ovina	18 (14)	9 (9)	0.2 (0.2)	26 (8)	11	33	56	67	33	0
	Mix	21 (15)	3 (5)	0.1 (0.2)	46 (26)	0	20	80	40	0	60
46	*Agrostis stolonifera*	50 (28)	7 (6)	0.2 (0.1)	48 (9)	0	12	88	0	12	88
	Agropyron trachycaulum	56 (15)	22 (15)	0.9 (0.3)	66 (7)	0	0	100	0	0	100
	Deschampsia caespitosa	16 (12)	14 (19)	0.3 (0.4)	29 (15)	17	33	50	17	66	17
	Festuca ovina	23 (13)	21 (12)	0.4 (0.2)	26 (7)	0	0	100	22	67	11
	Mix	44 (27)	4 (7)	0.2 (0.4)	46 (27)	9	13	78	30	13	57
91	*Agrostis stolonifera*	37 (24)	9 (9)	0.4 (0.4)	48 (6)	0	14	86	0	0	100
	Agropyron trachycaulum	44 (23)	16 (8)	0.7 (0.3)	59 (5)	0	0	100	0	0	100
	Deschampsia caespitosa	25 (16)	8 (13)	0.1 (0.2)	24 (17)	14	0	86	43	14	43
	Festuca ovina	24 (13)	8 (4)	0.2 (0.1)	26 (5)	0	37	63	0	100	0
	Mix	29 (14)	2 (4)	0.1 (0.1)	39 (26)	0	21	79	33	13	54

Data are means with standard deviations in brackets.
$3 \leq n \leq 9$ for all treatments except mix where $3 \leq n \leq 45$; [†]n = 9, August 200; [‡]n = 9 for 0, 15, 30, 46, 91 cm (n = 45 for mix), n = 15 for 8 cm (n = 75 for mix).
-Data not available; *Incomplete data set available for calculation of mean.
[ŧ]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.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.

Table 2.5. Vegetation characteristics for capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Year 1 Survival (%)	Cover (%)	Biovolume (L)	Height (cm)	Health[t] (%)			Development[t] (%)		
					1	2	3	1	2	3
0	2 (4)[b]	0 (0)[b]	*	*	*	*	*	*	*	*
8	35 (20)[a]	14 (11)[ab]	0.43 (0.36)[a]	49 (22)[a]	3	15	82	18	25	57
15	36 (21)[a]	14 (15)[ab]	0.46 (0.40)[a]	56 (17)[a]	3	22	75	7	29	64
30	22(18)[a]	11 (16)[ab]	0.34 (0.37)[a]	46 (16)[a]	3	26	71	31	11	58
46	38 (21)[a]	13 (8)[a]	0.40 (0.31)[a]	43 (16)[a]	5	12	83	14	32	54
91	32 (12)[a]	8 (5)[ab]	0.30 (0.24)[a]	39 (15)[a]	3	15	82	15	25	60

Data are means with standard deviations in brackets.
$4 \leq n \leq 5$.
*Incomplete data set available for calculation of mean.
[t]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.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.

Table 2.6. Mean ground cover for capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Feces (%)	PG (%)	Moss (%)	Wood (%)	Vegetation (%)	Bare (%)	Litter (%)
0	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	99 (2)	1 (2)
8	0 (0)	0 (0)	1 (1)	0 (0)	10 (4)	49 (4)	40 (7)
15	0 (0)	0 (0)	0 (0)	0 (0)	11 (3)	52 (6)	37 (8)
30	0 (0)	0 (0)	0 (1)	0 (1)	9 (2)	41 (6)	50 (8)
46	0 (0)	0 (0)	0 (1)	0 (0)	10 (1)	49 (13)	41 (14)
91	0 (0)	0 (0)	0 (0)	0 (0)	8 (2)	58 (8)	34 (9)

Data are means with standard deviations in brackets.
n = 5.

Table 2.7. Ground cover for capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Treatment	Ground Cover (%)						
		Feces	PG	Moss	Wood	Vegetation	Bare	Litter
0	*Agrostis stolonifera*	0 (0)	0 (0)	0 (0)	0 (0)	0 (2)	96 (13)	4 (11)
	Agropyron trachycaulum	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	100 (0)	0 (0)
	Deschampsia caespitosa	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	100 (0)	0 (0)
	Festuca ovina	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	100 (0)	0 (0)
	Mix	0 (0)	0 (0)	0 (0)	0 (0)	1 (2)	97 (7)	2 (5)
8	*Agrostis stolonifera*	0 (1)	0 (0)	1 (3)	0 (0)	9 (5)	47 (28)	43 (28)
	Agropyron trachycaulum	0 (0)	0 (2)	2 (3)	0 (0)	11 (6)	45 (16)	42 (18)
	Deschampsia caespitosa	0 (0)	0 (0)	1 (3)	0 (0)	5 (3)	49 (35)	45 (35)
	Festuca ovina	0 (0)	0 (0	1 (1)	0 (0)	17 (11)	54 (34)	28 (31)
	Mix	0 (0)	0 (1)	0 (0)	0 (0)	10 (5)	51 (27)	39 (25)
15	*Agrostis stolonifera*	0 (0)	0 (0)	0 (0)	0 (0)	8 (3)	51 (27)	41 (27)
	Agropyron trachycaulum	0 (0)	0 (0)	0 (2)	0 (0)	15 (9)	53 (21)	32 (19)
	Deschampsia caespitosa	0 (0)	0 (0)	0 (0)	0 (0)	8 (3)	45 (28)	47 (26)
	Festuca ovina	0 (0)	0 (0)	0 (0)	1 (2)	12 (8)	50 (26)	37 (29)
	Mix	0 (1)	0 (0)	1 (3)	0 (1)	10 (5)	61 (16)	28 (15)
30	*Agrostis stolonifera*	0 (0)	0 (0)	0 (0)	1 (4)	9 (2)	46 (26)	44 (26)
	Agropyron trachycaulum	0 (0)	0 (0)	1 (3)	0 (0)	13 (5)	43 (29)	43 (31)
	Deschampsia caespitosa	0 (0)	0 (0)	0 (0)	0 (0)	6 (2)	31 (23)	63 (24)
	Festuca ovina	0 (0)	0 (0)	0 (0)	0 (1)	9 (4)	40 (25)	51 (24)
	Mix	0 (0)	0 (1)	0 (0)	0 (0)	8 (3)	42 (21)	50 (23)
46	*Agrostis stolonifera*	0 (0)	0 (0)	0 (0)	0 (0)	9 (3)	29 (29)	62 (31)
	Agropyron trachycaulum	0 (0)	0 (0)	2 (2)	0 (0)	11 (6)	62 (12)	25 (13)
	Deschampsia caespitosa	0 (0)	0 (0)	0 (1)	0 (0)	8 (3)	55 (23)	37 (24)
	Festuca ovina	0 (0)	0 (0)	0 (0)	0 (0)	11 (5)	45 (25)	44 (24)
	Mix	0 (0)	0 (0)	0 (1)	0 (1)	8 (3)	54 (25)	38 (25)
91	*Agrostis stolonifera*	0 (0)	0 (0)	0 (0)	0 (0)	6 (2)	58 (33)	36 (35)
	Agropyron trachycaulum	0 (0)	0 (1)	0 (0)	0 (0)	10 (3)	71 (9)	19 (7)
	Deschampsia caespitosa	0 (0)	0 (0)	0 (0)	0 (0)	7 (7)	55 (30)	38 (32)
	Festuca ovina	0 (0)	0 (0)	0 (0)	0 (0)	7 (2)	58 (28)	35 (28)
	Mix	0 (0)	0 (1)	0 (0)	0 (0)	7 (3)	50 (31)	43 (32)

Data are means with standard deviations in brackets.
n = 9 (for 0, 15, 30, 46 and 91 cm cap plots); n = 15 (for 8 cm cap plots).

Table 2.8. Characteristics of *Agropyron trachycaulum* on capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Year 1 Survival[†] (%)	Cover[‡] (%)	Biovolume (L)	Height (cm)	Health[ŧ] (%)			Development[ŧ] (%)		
					1	2	3	1	2	3
0	0 (0)[a]	-	-	-	-	-	-	-	-	-
8	60 (11)[b]	28 (15)[a]	1.0 (1.0)[a]	72 (34)[ab]	0	0	100	11	0	89
15	61 (13)[b]	37 (33)[a]	1.1 (0.7)[a]	79 (12)[a]	0	0	100	0	0	100
30	35 (14)[b]	38 (29)[a]	0.9 (0.7)[a]	66 (15)[ab]	0	11	89	0	11	89
46	56 (15)[b]	22 (15)[a]	0.9 (0.3)[a]	66 (7)[ab]	0	0	100	0	0	100
91	44 (23)[b]	16 (8)[a]	0.7 (0.3)[a]	59 (5)[b]	0	0	100	0	0	100

Data are means with standard deviations in brackets.
$3 \leq n \leq 9$ for all treatments except mix where $3 \leq n \leq 45$; [†]n = 9; [‡]n = 9 for 0, 15, 30, 46, 91 cm (n = 45 for mix), n = 15 for 8 cm (n = 75 for mix).
-Data not available; *Incomplete data set available for calculation of mean.
[ŧ]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.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.

Table 2.9. Viability and germination of *Agropyron trachycaulum* seeds from second growing season at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Viability[†] (%)	Germination[‡] (%)
8	100 (0)	64 (16)
15	100 (0)	72 (11)
30	100 (0)	68 (12)
46	100 (0)	70 (7)
91	100 (0)	57 (15)

Data are means with standard deviations in brackets.
[†]n = 3.
[‡]n = 50.

Table 2.10. Characteristics of *Agrostis stolonifera* on capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Year 1 Survival[†] (%)	Cover[‡] (%)	Biovolume (L)	Height (cm)	Health[ŧ] (%)			Development[ŧ] (%)		
					1	2	3	1	2	3
0	5 (12)[a]	0 (0)[a]	-	*	*	*	*	*	*	*
8	48 (21)[a]	16 (27)[a]	0.5 (0.5)[a]	64 (26)[a]	0	0	100	0	29	71
15	48 (18)[a]	6 (7)[a]	0.2 (0.3)[a]	62 (18)[a]	12	25	63	12	0	88
30	34 (24)[a]	4 (6)[a]	0.2 (0.2)[a]	47 (10)[a]	0	40	60	0	20	80
46	50 (28)[a]	7 (6)[a]	0.2 (0.1)[a]	48 (9)[a]	0	12	88	0	12	88
91	37 (24)[a]	9 (9)[a]	0.4 (0.4)[a]	48 (6)[a]	0	14	86	0	0	100

Data are means with standard deviations in brackets.
$3 \leq n \leq 9$ for all treatments except mix where $3 \leq n \leq 45$; [†]n = 9; [‡]n = 9 for 0, 15, 30, 46, 91 cm (n = 45 for mix), n = 15 for 8 cm (n = 75 for mix).
-Data not available; *Incomplete data set available for calculation of mean.
[ŧ]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.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.

Table 2.11. Characteristics of *Festuca ovina* on capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Year 1 Survival[†] (%)	Cover[‡] (%)	Biovolume (L)	Height (cm)	Health[ŧ] (%)			Development[ŧ] (%)		
					1	2	3	1	2	3
0	0 (1)[a]	-	-	-	-	-	-	-	-	-
8	19 (12)[ab]	20 (18)[a]	0.3 (0.4)[a]	34 (15)[a]	0	22	78	0	78	22
15	26 (10)[b]	20 (27)[a]	0.5 (0.6)[a]	35 (8)[a]	0	17	83	0	50	50
30	18 (14)[ab]	9 (9)[a]	0.2 (0.2)[a]	26 (8)[a]	11	33	56	67	33	0
46	23 (13)[b]	21 (12)[a]	0.4 (0.2)[a]	26 (7)[a]	0	0	100	22	67	11
91	24 (13)[b]	8 (4)[a]	0.2 (0.1)[a]	26 (5)[a]	0	37	63	0	100	0

Data are means with standard deviations in brackets.
$3 \leq n \leq 9$ for all treatments except mix where $3 \leq n \leq 45$; [†]n = 9; [‡]n = 9 for 0, 15, 30, 46, 91 cm (n = 45 for mix), n = 15 for 8 cm (n = 75 for mix).
-Data not available; *Incomplete data set available for calculation of mean.
[ŧ]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.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.

Table 2.12. Characteristics of *Deschampsia caespitosa* on capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Year 1 Survival[†] (%)	Cover[‡] (%)	Biovolume (L)	Height (cm)	Health[ŧ] (%)			Development[ŧ] (%)		
					1	2	3	1	2	3
0	4 (8)[a]	-	-	-	-	-	-	-	-	-
8	13 (11)[a]	2 (4)[a]	0.0 (0.1)[a]	20 (15)[a]	14	29	57	57	14	29
15	8 (8)[a]	1 (2)[a]	0.0 (0.1)[a]	45 (10)[a]	0	67	33	0	67	33
30	3 (4)[a]	0 (0)[a]	*	*	*	*	*	*	*	*
46	16 (12)[a]	14 (19)[a]	0.3 (0.4)[a]	29 (15)[a]	17	33	50	17	66	17
91	25 (16)[a]	8 (13)[a]	0.1 (0.2)[a]	24 (17)[a]	14	0	86	43	14	43

Data are means with standard deviations in brackets.
$3 \leq n \leq 9$ for all treatments except mix where $3 \leq n \leq 45$; [†]n = 9; [‡]n = 9 for 0, 15, 30, 46, 91 cm (n = 45 for mix), n = 15 for 8 cm (n = 75 for mix).
-Data not available; *Incomplete data set available for calculation of mean.
[ŧ]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.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.

Table 2.13. Characteristics of mix species treatments on capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Year 1 Survival[†] (%)	Cover[‡] (%)	Biovolume (L)	Height (cm)	Health[ŧ] (%)			Development[ŧ] (%)		
					1	2	3	1	2	3
0	1 (2)[a]	0 (1)[a]	*	28 (2)[a]	*	*	*	*	*	*
8	38 (15)[b]	4 (11)[b]	0.3 (0.5)[a]	54 (35)[a]	0	25	75	19	6	75
15	35 (10)[ab]	4 (13)[ab]	0.4 (0.5)[a]	60 (36)[a]	5	0	95	21	16	63
30	21 (15)[ab]	3 (5)[b]	0.1 (0.2)[a]	46 (26)[a]	0	20	80	40	0	60
46	44 (27)[b]	4 (7)[ab]	0.2 (0.4)[a]	46 (27)[a]	9	13	78	30	13	57
91	29 (14)[ab]	2 (4)[ab]	0.1 (0.1)[a]	39 (26)[a]	0	21	79	33	13	54

Data are means with standard deviations in brackets.
$3 \leq n \leq 9$ for all treatments except mix where $3 \leq n \leq 45$; [†]n = 9; [‡]n = 9 for 0, 15, 30, 46, 91 cm (n = 45 for mix), n = 15 for 8 cm (n = 75 for mix).
-Data not available; *Incomplete data set available for calculation of mean.
[ŧ]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.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.

3. EFFECT OF SOIL CAP DEPTH ON WATER QUALITY AND QUANTITY IN PHOSPHOGYPSUM STACKS AT FORT SASKATCHEWAN, ALBERTA

3.1 Introduction

Phosphogypsum (PG) is an acidic by product of phosphoric acid production (Richardson et al. 1995, Rutherford et al. 1994). The fertilizer industry generates approximately five tonnes of PG per tonne of phosphoric acid, the latter being required for phosphorus fertilizer production (Rutherford et al. 1995a, Rutherford et al. 1994, Ferguson 1988). Large quantities of PG are produced annually in at least 80 countries around the world (Florida Institute of Phosphate Research 2006). As of January 2006, Florida had at least 20 PG stacks, the greatest number of any state. In Canada there are stacks in British Columbia, Alberta, Ontario, Quebec and New Brunswick with the majority and largest of the stacks in Alberta (Thorne 1990). Ferguson (1988) predicted that worldwide PG production would reach between 220 and 280 million tonnes by the year 2000. Parreira et al. (2003) indicated that PG production was approximately 180 million tonnes per year in 2003. Abril et al. (2009) estimated annual PG production at 170 million tonnes in 2006.

PG is commonly wet stacked on land adjacent to fertilizer production facilities (Luther and Dudas 1993) where they can span hundreds of hectares and tens of meters in height (Rutherford et al. 1995b). The main environmental concerns associated with PG stacks are chemical impurities such as residual acidity, silica, unreacted phosphate rock, radon, uranium and trace elements including fluoride, cadmium, arsenic, lead and silver; their presence and concentration dictated mainly by the composition of the source rock (Wissa 2002). As water percolates through the stack, trace elements can become mobile and leach into ground water, negatively impacting ecosystem function. Exposure to radon gas and gamma radiation can affect human health if emissions are not limited by reclamation methods such as capping (Rutherford et al. 1994).

The most common approach to PG stack reclamation is to cap the PG with soil. A cap can prevent wind and water erosion, limit percolation, provide a plant

growth medium, prevent contaminated water from running off the stacks and provide a potential landscape conducive to the desired end land use (Richardson et al. 1995).

Little research has been conducted on PG stack reclamation in Canada. Characterization of PG and environmental hazards with specific emphasis on radioactivity has been studied mainly by Rutherford, Dudas and Arocena during the 1990s (Rutherford et al. 1995a, 1995b, 1995c, 1994). Their research investigated radioactivity and PG chemical composition among different phosphate rock sources, important information for effective management of the waste. They found trace element and fluoride concentrations greatly reduced in weathered PG relative to fresh PG although ^{226}Ra in PG leachate was identified as a potential concern despite stacks being highly weathered. In 1988 Norlander assessed the decommissioning of PG tailings in Calgary, Alberta with a focus on radon flux from exposed PG stacks. It was concluded that residential development should be avoided on bare and capped PG stacks to avoid exposure to radon, dust, particulates and gamma radiation. Thorne (1990) identified issues associated with successful reclamation of a PG tailings pond in Calgary, Alberta with a specific focus on the use of amendments to overcome chemical and physical limitations of PG required for successful revegetation. In greenhouse studies the addition of soil or lime to PG tailings was effective at overcoming many limitations associated with vegetation establishment.

The most recent Canadian PG reclamation research was done by Hallin (2009) from the University of Alberta. Her research characterized the quality of a reclaimed PG stack 15 years after initial reclamation efforts in Fort Saskatchewan, Alberta. The effect of a vegetated 15 cm soil cover on water infiltration and percolation into the stack, runoff water quality, radon gas and gamma emissions and plant community development was evaluated. It was concluded that the existing cover system was providing an effective barrier between PG and the environment.

The effect of soil cap depth on water infiltration and percolation in PG stacks is not well known in Canada. Hallin (2009) found that water movement through a 20 to 27 cm thick soil cap into PG was very low during rainfall events of varying

magnitudes. In Florida, Fuleihan et al. (2005) evaluated the effect of top and side slope cover systems on runoff volumes and quality, infiltration and changes in soil and PG water content. Leached PG side slopes with dolomitic limestone disked into the upper 15 cm followed by sod planting was the most effective. Runoff water was of suitable quality for discharge following vegetation planting. The 15 cm soil cap over leached PG had similar runoff water quality.

Extrapolation of research findings from Florida to Canada is not advisable due to differing climates (particularly lower rainfall), adapted vegetation species, PG characteristics and regulatory framework. Currently, Alberta Environment requires a 1 m soil cap on the Agrium Redwater PG stack after production has ceased (Alberta Environment 2008). With an annual precipitation of 460 mm at the study site, it was hypothesized this cap depth could be reduced while still maintaining a sufficient barrier to water movement across the soil / PG interface.

3.2 Research Objectives and Hypotheses

3.2.1 Research objectives

The general research objective is to contribute to a reclamation plan for PG stack closure by determining an appropriate depth of soil for capping PG. Specific research objectives are to determine the effect of soil cap depth on water movement across the soil / PG interface under natural precipitation conditions and leaching.

3.2.2 Research hypotheses

- Fluctuations in water content will be greatest for the shallowest cap plots and lowest for the deepest.
- Depth of water moving past the soil / PG interface following storm events will be very low on all capped plots with the exception of bare PG plots.
- Subsurface water quality will be related to cap depth.
- Several PG water quality parameters will exceed criteria defined by CCME (2003) and Alberta Environment (2009, 1999) due to the inherent chemical

composition of PG but will generally be comparable to upstream and downstream water quality of the North Saskatchewan River in the vicinity of Agrium Fort Saskatchewan.

3.3 Materials and Methods

3.3.1 Research site description

Fort Saskatchewan is located approximately 30 km northeast of Edmonton, Alberta, Canada (53° 43' N and 113° 13' W) (Figure 3.1). It is located in the Central Parklands Natural Subregion within the Aspen Parkland Ecoregion, in a transition zone between the Dry Mixedwood and Northern Fescue Natural Subregions to the north and south, respectively (Speiss 2007, Natural Regions Committee 2006). Average annual precipitation is approximately 460 mm with almost half falling as rain during June, July and August (Environment Canada 2008). Average monthly rainfall ranges from 0.4 mm in January to 88.8 mm in June. Historical extreme daily rainfall has ranged from 6.4 mm in December 1958 to 77.7 mm in June 1965. Yearly snow fall approaches 100 cm. Daily average temperatures range from -13.5 ℃ in January to 16.7 ℃ in July.

Geologic sediments of the Fort Saskatchewan area are Upper Cretaceous shales from the Belly River Formation (Alberta Geological Survey 2005). The topography of the Central Parkland is hummocky and has gently rolling till plains with an average elevation of 700 m (City of Fort Saskatchewan 2008, Natural Regions Committee 2006). Lacustrine and fluvioglacial deposits are the dominant surficial sediments and soils are dominated by Black Chernozems (60 %) with a smaller proportion (15 %) of Solonetzes (Natural Regions Committee 2006). Cultivation and development have resulted in loss of native vegetation, which currently composes only 5 % of the plant community in the Central Parkland. Patches of aspen and plains rough fescue grassland remain, although aggressive non native species such as *Bromus inermis* (Leyss) (smooth brome) and other agricultural species dominate (Natural Regions Committee 2006).

Agrium Incorporated (Agrium), located in the industrial district of Fort Saskatchewan, Alberta (Figure 3.2), is a large scale fertilizer manufacturing

company which produced monoammonium phosphate ($NH_4H_2PO_4$) fertilizer for 26 years at its Fort Saskatchewan, Alberta facility (Svarich 1999). Currently only anhydrous ammonia (NH_3) and urea ($CO(NH_2)_2$) are being produced at Fort Saskatchewan (Agrium 2009).

PG was wet stacked in five areas between 1965 and 1991 at Fort Saskatchewan, all of which are closed today (Svarich 1999) (Figure 3.3). Stack 1, located adjacent to the North Saskatchewan River, was active from 1983 to 1991. It was built on a high density polyethylene liner and has a base area of 9.3 ha and a settling basin of 4.7 ha. Stack 2, located south of Stack 1, was built into the side of the river valley (Norlander 1988) on a clay liner. It has a base area of 8.5 ha and settling basin area of 4.7 ha and was active from 1974 to 1991. Each stack has a bare PG road around the perimeter of the settling basin and a road to connect stacks.

Following PG production, 10 to 15 cm of soil was applied with a bobcat to the stack outer slopes and a seed mix consisting mainly of *Bromus inermis* and *Brassica napus* L. (canola) was broadcast (Nichol 2009). The outer slopes of both stacks are currently dominated by *Bromus inermis* and *Melilotus alba* Desr. (white sweet clover). The settling basin of Stack 1, where the research plots are located, is recessed approximately 10 m below the upper stack road and can be accessed on the south side from the stack base and northeast side from the upper stack road. The basin surface is relatively flat with a slight northeast aspect. The side slopes and basin floor are unvegetated except where mushroom compost was applied at the south side of the basin adjacent to the access road; *Kochia scoparia* (L.) Schrad. (kochia) is the dominant plant species. A thick crust has formed over PG on interior basin sloped walls and the floor.

3.3.2 Experimental design

Eighteen experimental research plots (50 m long x 10 m wide) with varying capping depths were constructed in late October 2006 in a complete randomized design in the basin of Stack 1 (Figure 3.4). Soil from an old alfalfa pasture approximately 5 km northeast of Agrium was excavated using a Hitachi 200 backhoe. Soil taken from an average depth of 40 cm was pushed into piles, then

loaded into tandem trucks and transported to Agrium. Soil was unloaded into the staked area of the plots and built up to specified depths using a John Deere 750C dozer and Bobcat S300 (Gagnon 2008).

Capping depths of 8, 15, 30, 46 and 91 cm of soil and a control with no soil were replicated three times (1, 2 and 3 Figure 3.4). Each of the plots was subdivided into five 10 x 10 m sections which were seeded to one of five vegetation treatments in mid June 2007. Vegetation treatments included monocultures of *Agrostis stolonifera* L. (redtop), *Agropyron trachycaulum* (Link) Malte ex H.F. Lewis (slender wheatgrass), *Deschampsia caespitosa* (L.) P. Beauv. (tufted hairgrass) and *Festuca ovina* L. (sheep fescue). A fifth vegetation treatment was a mix of the above grasses with *Trifolium hybridum* L. (alsike clover). The mix was 54 % *Agrostis stolonifera,* 2 % *Agropyron trachycaulum,* 28 % *Deschampsia caespitosa,* 8 % *Festuca ovina* and 8 % *Trifolium hybridum* (Brett Young 2009).

3.3.3 Plant species selection

Plant species selected for reclamation were native or adapted to the area. They were characterized by high germination and establishment, roots effective at providing erosion control, persistence following climatic or environmental fluctuations, low nutrient and water requirements and tolerance of acidic substrates (Table A1).

Agrostis stolonifera is an introduced and early successional perennial grass that tolerates a wide variety of environmental conditions, including drought. It has a dense root system that can be effective as erosion control when conditions are not too wet (Esser 1994). *Festuca ovina* is a long lived perennial grass with wide spread distribution. It has low nutrient requirements and tolerates acidity. *Deschampsia caespitosa* is a native, perennial grass which tolerates moderate acidity and prefers moderately moist to moist soils. *Agropyron trachycaulum* is a native, short lived perennial grass which grows well in semi arid to moist regions. It establishes quickly and provides excellent short term erosion control. If planted with other slow growing species, it will become less dominant over time. *Trifolium hybridum* is a short lived perennial legume. It can tolerate acidic and alkaline conditions and a variety of moisture regimes. It can benefit revegetation efforts

when planted with other species due to its nitrogen fixing ability (Hardy BBT Limited 1989). All five seeded species grow well on medium to coarse textured soils (Esser 1994, Hardy BBT Limited 1989). Certified seed for each species was obtained from Brett Young Seeds in Leduc, Alberta.

3.3.4 Seeding and fertilizer application

Vegetation treatments were drill seeded in mid June 2007 using a plot seeder with eight (23 cm row spacing) double disc openers with independent seeding depth gauge for precise seed placement (Puurveen 2007a). Seeding was to a depth of 2 cm (USDA-NRCS 2003) and the wheel packed the seed furrow. A seeding rate of 20 kg/ha was used and Vigoro Ultra Turf Starter (20-28-6) fertilizer was applied at a rate of 100 kg/ha. Seed and fertilizer for each treatment were weighed into individual bags then divided evenly with a cone splitter on the seeder. Eight rows were seeded per pass, with four passes per plot for a total of 32 drill seeded rows. A 1 m buffer along each side of the plots was broadcast seeded with the respective vegetation treatment. Bare ground within the basin was broadcast seeded with a mix of grass and clover and no name® 16-20-0 Lawn Food to prevent encroachment into the plots by unseeded species.

3.3.5 Plot management

Annual and perennial weeds from the soil seed bank dominated the plots in spring and summer 2007. Prior to seeding, all plots, edges and buffers were sprayed with 2.47 L/ha of glyphosate (Roundup WeatherMax) herbicide using a tank pulled by a John Deere 5203 tractor; in areas not accessible by the tractor backpack sprayers were used. Glyphosate is recommended for non selective weed control in various cropping systems including those with grasses and legumes. The application rate used is considered appropriate for eradicating annual weeds over 15 cm in height and for many perennial species including *Medicago sativa* L. (alfalfa) and *Linaria vulgaris* Hill. (toadflax) (Alberta Agriculture and Food 2008).

Plots were harrowed twice before seeding with a 1.5 m 3-point hitch spring tooth harrow pulled by a John Deere 5203 tractor driving the length of the plots

(Puurveen 2007a). Weeds were mowed to approximately 10 cm height in early August 2007 with a tractor and 1.8 m Alamo flail mower on plots, plot edges and buffers. Plot edges and buffers were trimmed several times in summer 2008; plots were mowed September 5, 2008. Biomass was left on plots after mowing.

3.3.6 Meteorological data

A meteorological station was situated in the center of the Stack 1 basin between plots B3 and B4 to avoid edge effects. Instrumentation was Campbell Scientific including a CR10X data logger. Maximum and minimum air temperature (℃) and relative humidity (%) were measured using the HMP45C Vaisala relative humidity and temperature probe (-40 to +60 ℃). Saturation vapour pressure (kPa) was calculated using appropriate formulae from temperature and relative humidity data. Wind speed (m/s) data were obtained using the 05103-10 RM Young wind monitor. A Kipp & Zonen silicon pyranometer measured total incoming radiation (W/m^2) and total rainfall (mm) was measured with a TE525WS Texas Electronics 20 cm tipping bucket rain gauge in addition to a manual rain gauge. Weather data were downloaded periodically from the data logger via a personal pocket computer (Campbell Scientific (Canada) Corp. 2007, Puurveen 2007b).

3.3.7 Capping depth measurements

Capping depths were measured June 5 and 6, 2008 to determine whether changes occurred due to soil settling, compaction or wind and water erosion following plot construction. Measurements were taken at nine locations on each plot using a systematic sampling strategy; in the center of each treatment 2 m right of stakes marking the west side of the plot and 2 m left of stakes marking the east side of the plot, directly on the boundary between treatments.

Using a 5 cm diameter by 19 cm length barrel auger, a hole was cored through the soil until the PG surface was encountered, as indicated by PG on the auger tip. A meter stick was inserted into the hole and depth (cm) recorded prior to backfilling with excavated soil. If the hole was cored past the soil / PG interface and more than 1 cm of PG was encountered, a visual estimate of PG in the auger was subtracted from the total depth indicated by the meter stick.

3.3.8 Capping soil characterization

Soil was sampled on June 12, 2008. The length of each plot was divided into thirds. A pair of random numbers was generated to provide a sampling location for each third. The first random number generated for each third indicated position across the plot. The second random number indicated position down the length of the top third, middle third and bottom third, respectively. Soil was sampled where these points intersected and adjacent to vegetation rows.

A barrel auger of 5 cm diameter and 19 cm length was used to obtain soil samples to a depth of 8 cm. At most sample locations, three to four holes were excavated adjacent to each other to obtain sufficient sample for analyses, approximately two thirds of a 3.7 L Ziploc bag. If PG or large pieces of organic material were mixed with the soil they were removed by hand. Soil samples from the top, middle and bottom thirds of each plot were mixed thoroughly in a large pail with a hand trowel. Soil was split evenly between two 3.7 L Ziploc bags and labelled. One set of samples was refrigerated for further analyses; the second set was sent to ALS Laboratory in Edmonton to be analyzed.

Inorganic carbon was determined using the gravimetric method for loss of carbon dioxide to approximate carbonate content and total carbon by combustion (Bartels et al. 1996). Total organic carbon was determined by subtraction. Cation exchange capacity (CEC) was determined using the $BaCl_2$ method (Carter 1993) and exchangeable cations determined with $BaCl_2$ extraction after water leach (McKeague 1978). Exchangeable sodium percentage (ESP) was determined by calculation (exchangeable sodium / CEC x 100) (Brady and Weil 2002). Available ammonium nitrogen was determined by extraction in 2 M KCl and colorimetric analysis. Available micronutrients were extracted with DTPA solution and analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES). Particle size was determined by hydrometer; electrical conductivity and % saturation were analyzed by saturated paste (Carter 1993). Soil pH was determined in a 1:2 water extract (Carter and Gregorich 2008). Available nitrate nitrogen was determined with the cadmium reduction procedure (Carter 1993) and available phosphate phosphorus and potassium with a modified Kelowna extraction (Qian et al. 1994). Available sulphate sulfur was determined by extract

in weak $CaCl_2$ and analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Alberta Agriculture 1988). Results were compared to the Soil Quality Criteria Relative to Disturbance and Reclamation (Alberta Agriculture, Food and Rural Development 1987) for soil in the Plains Region.

PG bulk density cores were obtained October 2, 2008 from *Deschampsia caespitosa* treatments on 8 and 15 cm cap depths. *Deschampsia caespitosa* performed poorly compared to other vegetation treatments, and thus represented the worst treatment. Shallow soil depths were selected as plants may root through soil into PG, requiring characterization of PG. Cores were extracted at three random locations on each *Deschampsia caespitosa* treatment for each cap depth. Locations were determined by generating three pairs of random numbers for each plot. Where the first number (across the top of the plot facing north) and the second number (down the plot length) intersected, a core was obtained.

Soil was excavated to the PG surface from a < 0.5 m^2 area using a round point spade and depth of soil recorded at two opposite points in the excavation. The upper 5 to 10 cm of the PG surface was scraped off with a spade and hand trowel prior to positioning a 7.5 cm diameter by 7.5 cm height Uhland core sleeve. The core was tapped into PG with a mallet and 15 cm long piece of wood on top of the core until flush with the PG surface. PG was cleared from around the core with a hand trowel before being gently removed from the excavation. Excess PG was cleaned off the outside of the core and trimmed on the bottom until PG was flush with the core bottom. The sample was removed from the core and placed in a 3.7 L Ziploc bag. Field weights of samples were determined with a portable scale. Samples were sieved to ≤ 2 mm to break aggregates and promote uniform drying, then oven dried to constant mass at 45 ℃ (Averitt and Gliksman 1990) in a Napco 420 incubator oven. Volume of the Uhland core sleeve ($V = \pi r^2 h$) was 331 cm^3, equal to the PG volume. Bulk density was calculated by dividing the oven dry PG mass by PG volume in the core for each sample (Carter and Gregorich 2008).

Water retention curves for soil and PG were developed using the pressure extractor method (Carter and Gregorich 2008) for samples from the 15 cm cap depths. Pressure plates and 0.5 and 1.5 MPa pressure extractors manufactured

by Soilmoisture Corporation were used. Soil samples collected during soil sampling (3.3.8 above) and PG samples collected from 15 cm cap depths for bulk density determination were used. PG samples collected from three random locations for bulk density determination were composited for pressure plate analysis. Samples were sieved to ≤ 2 mm and stored in Ziploc bags.

Three replications per plot for soil and PG (n = 9) were used for each pressure of 0.01, 0.03, 0.1, 0.33, 0.5 and 1.5 MPa. Bags of sample were mixed to achieve uniform particle distribution prior to pouring into plastic rings of 1.0 cm height and 5.3 cm diameter. Samples were gently packed before replacing plates in the chamber. Tap water was poured between sample rings on each plate and left to soak overnight prior to chamber sealing and pressurizing. Samples were left under pressure for 3 to 13 days, depending on applied pressure, and weighed immediately following depressurization. Samples were oven dried at 45 ℃ (Averitt and Gliksman 1990) to constant mass and weighed again. Gravimetric water content for each sample was calculated by dividing mass of water lost during drying by oven dry weight. Mean and standard deviation were calculated for soil and PG at each pressure and water retention curves developed.

3.3.9 Volumetric water content

Six Campbell Scientific 615 and twelve CS616 probes with custom lead lengths were installed in the research plots to measure PG volumetric water content (Table A9). Probe specific calibration equations were developed for PG since the EC of PG (5.8 dS/m in a 1:4 solid to water ratio (Hao et al. 2005)) fell outside the recommended range of 0.5 to 5 dS/m for a typical soil used for calibration by the manufacturer (Campbell Scientific 2006). Equations were required to convert response times recorded by the data logger to volumetric water contents. In spring 2008, PG was collected from the Stack 1 basin floor, sieved to ≤ 2 mm, then dried to constant mass at 45 ℃ (Averitt and G liksman 1990) in a Napco 420 incubator oven. Oven dried PG was used in a 20 L pail for calibrations.

CS615 and CS616 probes were wired to Campbell Scientific CR10X data loggers and laptop computers for calibration. Each probe was immersed into a pail of dry, sieved PG and response time recorded. The process was repeated after adding

1, 2, 3, 4, 5 and 5.5 L increments of tap water to the pail. Water was mixed thoroughly into the PG with a metal pole and shovel and hand packed after each addition. Readings at 5.5 L were considered to be at the PG saturation point. Volumetric water content for each addition of water was calculated by dividing water volume added by PG volume. PG volume was calculated using the equation for cylinder volume ($V = \pi r^2 h$) and average pail diameter and PG depth. A second order polynomial equation was fit to the relationship between volumetric water content and response time for each TDR probe.

TDR probes were installed June 25, July 2 and July 3, 2008. A single probe was installed horizontally into PG approximately 10 cm below the soil / PG interface in the center of each *Agropyron trachycaulum* treatment, 2 m west of the east plot edge (Figure 3.5). Relative to other vegetation, *Agropyron trachycaulum* was considered a better representation of the future plant community for determining effect of water movement across the interface. A pit was dug and excavated soil and PG were kept separate. Probes were installed on the north facing wall of each pit avoiding disturbance to the plot surface above the installation point. On 0 cm caps, the probe was installed 10 cm below the PG surface. Rods were pushed into PG parallel to one another and the ground surface. Where PG was too hard to push the probe by hand, holes were drilled using a DeWalt 18 V cordless drill with a 0.3 cm diameter steel rod, slightly smaller than the TDR waveguides diameter. Probes were pushed in by hand as far as possible then pushed with the back of a flat shovel. If probes appeared to be going in on an angle or were not aligned properly, a new pit face was carved and the installation location moved left or right depending on space and quality of pit face. PG and soil were backfilled separately into the pits and packed with a few cm of material added. To prevent damage by rabbits or water, all cables were trenched along the length of the plots from the installation point to its respective data logger.

Three Campbell Scientific CR10X data loggers were situated between plots in replicate 2. Data loggers and 12 V, 7.0 A rechargeable batteries were enclosed in Campbell Scientific data logger housings and mounted on metal stakes above the ground. Solar panels, 0.1 m^2 in area, were clamped above the data logger on the pole to provide continuous power to data logger batteries. Six TDR probes were wired to each data logger, two from each replicate. Data loggers began

recording response times July 28, 2008. Data loggers were programmed to log average hourly response times, point hourly response times and a daily point reading for each probe. Data were downloaded regularly. Probe outputs were organized by soil depth and probe specific calibration equations applied to convert response times to volumetric water contents.

Using rainfall data from the meteorological station in the basin, a distinct storm event was classified as ≥ 5 mm recorded between two 24 hour periods of no precipitation. According to this definition, 8 distinct storm events occurred between July 28, 2008 and April 24, 2009. A 7.1 mm precipitation event in mid January was neglected in the event that snow melted on the rain gauge and was therefore not representative of the event. Low magnitude events were classified as ≤ 10 mm of precipitation, medium as 10 ≤ x ≤ 19 and high as ≥ 20 mm. An average probe installation depth was calculated for each soil depth and used to convert volumetric water content to a depth of water (mm) in the PG. The change in depth of water in PG (ΔW) following a storm event was calculated using Equation 1; where $\overline{W}_i$ is the depth of water in the uppermost 10 cm of PG immediately preceding the rainfall event and $\overline{W}_f$ is the depth of water in the uppermost 10 cm of PG immediately following the event. Initial and final water depths were determined using an average of water depths four hours pre and post storm event, respectively.

$$\Delta W = \overline{W}_i - \overline{W}_f \qquad \text{Equation 1}$$

3.3.10 Snow depth and density

Snow cores were collected from the plots on February 29, 2008 and March 30, 2009 to determine spring snow melt water quantity. A pair of random numbers was generated for each plot and a core taken where the first random number across the plot top facing north and the second down the plot length intersected. The snow core sampling device consisted of a black polyvinyl chloride pipe with serrated metal edge with 3.8 cm radius and 1.2 m height. Eight random depth measurements were made along each plot length using a meter stick. The snow core was pushed by hand vertically into the snow until resistance of the soil surface was encountered. Snow depth was recorded and snow emptied from the core into a 3.7 L Ziploc bag and weighed with a portable digital scale.

Snow density and snow water equivalent (SWE) were calculated according to Equations 1A and 2A. The average of nine snow depth measurements per plot was used in SWE calculations. An assumption was made that snow density for each plot would be approximately equal that calculated for the snow core.

3.3.11 Antecedent precipitation index

Proportions of rain water becoming infiltration and runoff are partially dictated by soil water conditions preceding a rainfall event. The antecedent precipitation index (API) quantifies water depth in the soil using precipitation data from a desired number of days prior to the rainfall event according to Equation 2; where P_a is the antecedent precipitation index (mm), k is the recession factor and P_x is amount of precipitation (mm) occurring x days prior to the rainfall event (Kohler and Linsley 1951). Generally, a higher API indicates a higher potential for runoff since soil is likely wetter and infiltration may be reduced. Using precipitation data from five days preceding the rainfall event and a recession factor of 0.85 (Kohler and Linsley 1951), an API was calculated for each distinct rainfall event.

$$P_a = kP_1 + k^2P_2 + \ldots + k^xP_x \qquad \text{Equation 2}$$

3.3.12 Lysimeters

Lysimeters were installed June 3, 2008. Eighteen model 1900 soil water samplers, of 30 cm length and 4.3 cm diameter, were obtained from Soilmoisture Equipment Corporation and one unit installed in each plot 3 m east and 3 m north of a stake at the southwest corner of *Agropyron trachycaulum* treatments (Figure 3.5). Lysimeters were installed between parallel rows of vegetation following Soilmoisture Equipment Corporation (1999) protocol. A hand operated pump was used to apply a vacuum of 70 to 80 kPa to the sampler. Rubber access tubes were folded in half and secured with a plastic ring between samplings.

Soil water was sampled six times between June 3 and September 4, 2008 (Table 3.1). Water samples could be collected from all replicates on 0, 8, 15 and 30 cm cap plots at each sampling time but rarely on 46 and 91 cm cap plots (Table 3.2). Ceramic cups of lysimeters on 0, 8 and 15 cm cap plots were installed in PG. On 30 cm cap plots the ceramic cup was installed in a mix of PG and soil close to

the interface as mean soil depth of 30 cm caps was 28.4 cm (Table 3.3). On 46 and 91 cm cap plots the ceramic cup was installed in soil. Thus, the lysimeter cup was located at or below the soil / PG interface for all 0, 8, 15 and 30 cm cap plots. Lysimeters were considered empty when the pressure gauge on the pump did not increase with pumping. Water was transferred via funnel from a collection flask to a 500 mL graduated cylinder and volume recorded. Samples were transferred to sterile 500 mL sample bottles and stored in coolers until transported to the laboratory. A 70 to 80 kPa vacuum was reapplied to lysimeters following sample extraction.

Water samples were analyzed at ALS Laboratory. Ammonia nitrogen, nitrate + nitrite nitrogen, nitrite nitrogen, nitrate nitrogen and chloride (Cl) were determined using APHA 4500 colorimetry. Fluoride (F) was determined in water using an APHA 4500 ion specific electrode. Calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), sulphate (SO_4), dissolved iron (Fe) and dissolved manganese (Mn) were determined using APHA 3120 B inductively coupled plasma with optical emission spectroscopy (ICP-OES). The pH, conductivity and total alkalinity were determined with APHA 4500-H, 2510, 2320. Ion balance calculations were completed with APHA 1030E. Silver (Ag), aluminium (Al), arsenic (As), boron (B), barium (Ba), beryllium (Be), bismuth (Bi), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), tin (Sn), strontium (Sr), titanium (Ti), thallium (Tl), uranium (U), vanadium (V) and zinc (Zn) were determined by inductively coupled plasma mass spectrometry (ICP-MS) (EPA 6020).

If a PG stack or liner failed, water quality of the North Saskatchewan River could be directly impacted due to its close proximity. Parameter concentrations were compared to water quality of the North Saskatchewan River 3 km upstream and 3 km downstream of Agrium Fort Saskatchewan (LeClair 2009). Upstream and downstream data illustrate the effect on river water quality with and without Agrium and other industries in the area. Parameters in exceedance of North Saskatchewan River water quality were compared against criteria defined by the Canadian Environmental Quality Guidelines (aquatic life) (CCME 2003) and Alberta Tier 1 Soil and Groundwater Remediation Guidelines (industrial land use) (Alberta Environment 2009). Data were also compared to Surface Water Quality

Guidelines for Use in Alberta (Alberta Environment 1999). These guidelines were selected for having criteria designed for the protection of aquatic life, of interest for the ecology of the North Saskatchewan River and for water quality on industrially zoned and agricultural land. Those parameters exceeding at least one set of guidelines were used for further analyses.

3.3.13 Statistical analyses

Data obtained from water quality analyses were compiled in Microsoft Excel and a mean calculated for each parameter at each cap depth. Correlation coefficients (r^2) were calculated for parameters exhibiting linear trends with cap depth. One way ANOVAs were performed in SigmaPlot 11.0 at the 5 % level of significance to determine whether each exceeded water quality parameter varied among cap depth. If data failed to pass the tests for normality or homogeneity of variance, a Kruskal-Wallis one way ANOVA on ranks was performed. Tukey's multiple comparison test was used to detect mean differences.

3.4 Results and Discussion

3.4.1 Soil and PG characterization

Measured cap depths were generally comparable to target depths outlined in the experimental design (Table 3.3). Differences were highest for 8 cm and lowest for 46 cm cap plots. Soil properties for all capping depths were generally associated with a hospitable plant medium (Table 3.4). Soil texture was sandy loam to loamy sand (clay content 9.7 to 12.0 %), with low CEC and percent saturation. General soil quality was good (low Na, higher Ca, low EC, low SAR). PG bulk density on 8 and 15 cm caps was 1.32 and 1.35 Mg/m^3, respectively, with volumetric water contents of 26 and 27 % (Table 3.5). Soil bulk density on Stack 1 side slopes was determined by Hallin (2009) as 1.28 (0.14 standard deviation) Mg/m^3. Water retention was much higher for PG than for soil at low suctions and slightly lower at high ones (Figure 3.6). Water holding capacity for soil (FC – WP) was low (approximately 0.10 g/g). Apparent limitations to plant growth based solely on soil properties were not evident.

3.4.2 Water movement across the soil / PG interface

3.4.2.1 Seasonal trends

Water content in the upper 10 cm of PG declined slightly for all cap depths during the 2008 growing season (Figure 3.7). Water content on 0 cm caps decreased markedly in mid November and early and mid December 2008 before reaching a steady state unfrozen water content over winter. Water contents of 8 cm caps differed from other cap depths. Fluctuations were small and began decreasing tin mid November as water in PG began to freeze. Water content in 15, 30 and 46 cm caps began decreasing in early, mid and late December, respectively, as water began freezing below the interface. Beginning in late August, water in 91 cm caps began a slow decreasing trend before a slightly steeper decrease in early to mid January 2009, then maintained a similar water content over winter.

The shallowest caps showed a slight soil water response to storm events during the growing season. Over winter unfrozen water contents remained low with little fluctuation as soil and PG at sensor installation depths likely remained frozen. Regardless of PG water content during late summer and fall, plots approached relatively similar unfrozen values (4 to 8 %) before snow melt. Unfrozen water contents began to increase relatively quickly for all cap depths as snow melted in early spring and soil began to thaw, permitting water movement through the cap into the PG. Resultant water contents post melt approached those in July 2008.

As expected, fluctuations in water content were greatest on 0 cm caps and lowest on 91 cm caps. On 0 cm caps water contents below the surface varied more than those with caps. Topographic variability on bare PG plots can promote localized ponding of water in depressions which may foster local infiltration into the PG. Generally plots with thicker caps had fewer, and less pronounced, fluctuations in water content below the interface.

3.4.2.2 Storm events and snowmelt

Storm events were grouped by magnitude (Table 3.6). With the exception of 8 cm cap plots, $\overline{W}_i$ below the interface was generally comparable for all cap

thicknesses. For low and medium magnitude storm events, ΔW was considered negligible for all caps. On 0 cm caps water content increased by a maximum of 1.2 mm from a 5.8 mm storm event. The API for this storm event was zero (soil likely dry) which may partly explain the relative water content increase. An overall trend between ΔW and API did not exist for other caps. Sufficient wetting of the PG surface on 0 cm caps and/or ponding of rain water in surface depressions may soften or break the crust, allowing water to infiltrate the PG on these caps. Increases in volumetric water content were slightly greater for high magnitude storm events compared to low and medium magnitude events, although increases did not exceed 3.2 mm, which occurred on 0 cm caps from a 22.4 mm event. Small increases in water content in the PG were observed in 8, 15, 30, 46 and 91 cm caps from a 26.2 mm storm event in April 2009; all were less than 1.6 mm, although PG and soil may not have been fully thawed at this point.

In 2009, snow depths and subsequent snow water equivalents, were greater on shallower caps (r^2 = 0.88, statistics not shown) (Figure 3.8). Snow was likely blown from higher elevation surfaces and accumulated between plots and on low elevation plots. Such a clear trend in 2008 snow water equivalents did not exist, suggesting wind, snow density, vegetation cover or measurement time may have influenced water equivalents. Spring snow melt coupled with a high magnitude storm during mid April 2009 resulted in approximately 50 mm of standing water throughout the basin between plots and on 0 cm caps. Water remained ponded on the surface for a few days before evaporating and/or infiltrating into PG. Water content increased quickly on 0 cm caps before initiating a decreasing trend approximately 11 hours after the storm event midday April 14 (Figure 3.7). Soil plots generally did not respond as quickly as bare PG but all depths had sharp increases in water content before approaching an equilibrium.

While the actual amount of snow melt water infiltrating plots is unknown, water content below the interface does not exceed field capacity of PG despite increases in unfrozen water content as PG thaws. Water content below the interface is between permanent wilting point and field capacity for the entire 9 month monitoring period, with the exception of the anomalous 8 cm cap which falls slightly below the permanent wilting point during the winter (Figure 3.7).

Precipitation amount and antecedent precipitation index did not appear to influence water content below the soil / PG interface. Hallin (2009) similarly found high magnitude storm events resulted in small ΔW in PG (0.3 to 1.9 mm) on sites with cover material between 20 and 27 cm. Data from additional storm events, particularly those of high magnitude, would be useful for evaluating the effect of cap depth on ΔW. Installation of reflectometry probes at the surface of caps and just above the soil / PG interface would provide valuable information on amount of infiltration occurring during storm events and whether water uptake by vegetation is in equilibrium with precipitation inputs.

3.4.3 Quality of subsurface water

Water may be moving quickly through the sandy loam / loamy sand soil past the upper 30 cm of the profile, as indicated by zero or relatively small volumes of sample extracted on 46 and 91 cm caps (Table 3.1). The large volumes of water extracted from plots where the cup was in PG or soil / PG mixtures may be due to the relatively higher water content of the PG compared to topsoil on the wetter portion of the water retention curve (Figure 3.6).

All water quality parameters except Ba, Bi, nitrite N, bicarbonate and alkalinity were in exceedance of upstream and downstream water quality of the North Saskatchewan River. Numerous parameters exceeded at least one criterion in the Canadian Environmental Quality Guidelines (aquatic life) (CCME 2003), Alberta Tier 1 Soil and Groundwater Remediation Guidelines (industrial land use) (Alberta Environment 2009) and Surface Water Quality Guidelines for Use in Alberta (Alberta Environment 1999) (Table 3.7). Calcium was included despite lack of criteria in CCME and Alberta Environment guidelines because of its high concentrations and presence in PG. Of the included parameters, 10 differed significantly with cap depth although trends in overall water quality with depth were not evident. Selenium (r^2 = 0.97), sulphate (r^2 = 0.86), antimony (r^2 = 0.88) and thallium (r^2 = 0.74) decreased in concentration with an increase in cap depth (statistics not shown). Aluminium, nickel, cadmium and fluoride had the highest percent exceedances compared to most conservative criterion (data not shown) (Equation 3A). Most parameters were generally comparable to surface water quality guidelines. For individual parameters with three or more cap depths in

exceedance, five had the highest exceedance on 0 cm caps, two on 8 cm cap and 9 on 15 cm caps. The 30 cm caps never had the highest exceedance.

Water quality in PG did not appear to be influenced by cap depth. Individual parameters varied with cap depth and trends in overall water quality with cap depth were not evident. The irregularity in parameter concentration among cap depth could be attributed to the inherent chemical variability of the cover soil or PG. Lack of water samples collected from the 46 and 91 cm caps suggests that precipitation is moving below the 30 cm lysimeter depth on these plots.

Sample volumes collected from the 0, 8, 15 and 30 cm caps were not significantly different, suggesting volume is independent of precipitation amount. As PG stacks age and are leached, concentrations of trace elements and radionuclides decrease. Stacks will leach trace metals and radionuclides farther down through the stack out of the plant rooting zone. It is possible that a soil cap may slow the leaching process as it can minimize percolation into PG, reducing the movement of PG water within the stack and to greater depths.

3.5 Conclusions

- Water content below the soil / PG interface generally declined slightly and fluctuated most on 0 cm caps and least on 91 cm caps.
- Water content below the interface was generally between field capacity and permanent wilting point for the 9 month monitoring period, regardless of cap depth.
- Changes in water content immediately below the interface as a result of rainfall events were generally negligible.
- Amount of precipitation and antecedent precipitation index did not appear to influence water content below the interface.
- Volume of water collected in lysimeters at a depth of 30 cm was generally similar for the lowest 4 caps ($\leq$ the depth to the interface), but negligible for the greatest 2 caps ($\geq$ the depth to the interface).
- Almost all water quality parameters exceeded quality of the North Saskatchewan River upstream and downstream of Agrium Fort Saskatchewan

and numerous parameters exceeded at least one criterion outlined by CCME (2003) or Alberta Environment (2009, 1999). The large number of exceedances is likely related to the inherent chemical composition and variability associated with cover soil or PG.

- Aluminium, nickel, cadmium and fluoride were in greatest exceedance.
- Water quality does not appear to be influenced by soil cap depth $\leq$ 30 cm.

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Figure 3.1. Map showing location of Fort Saskatchewan, Alberta, Canada.

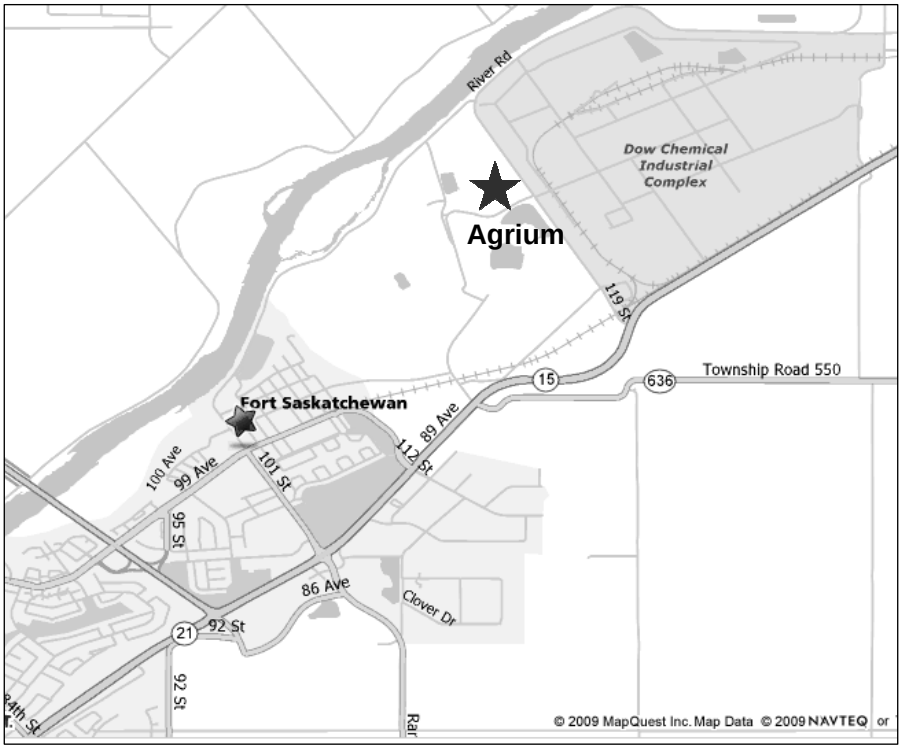

Figure 3.2. Map showing location of Agrium in Fort Saskatchewan, Alberta, Canada.

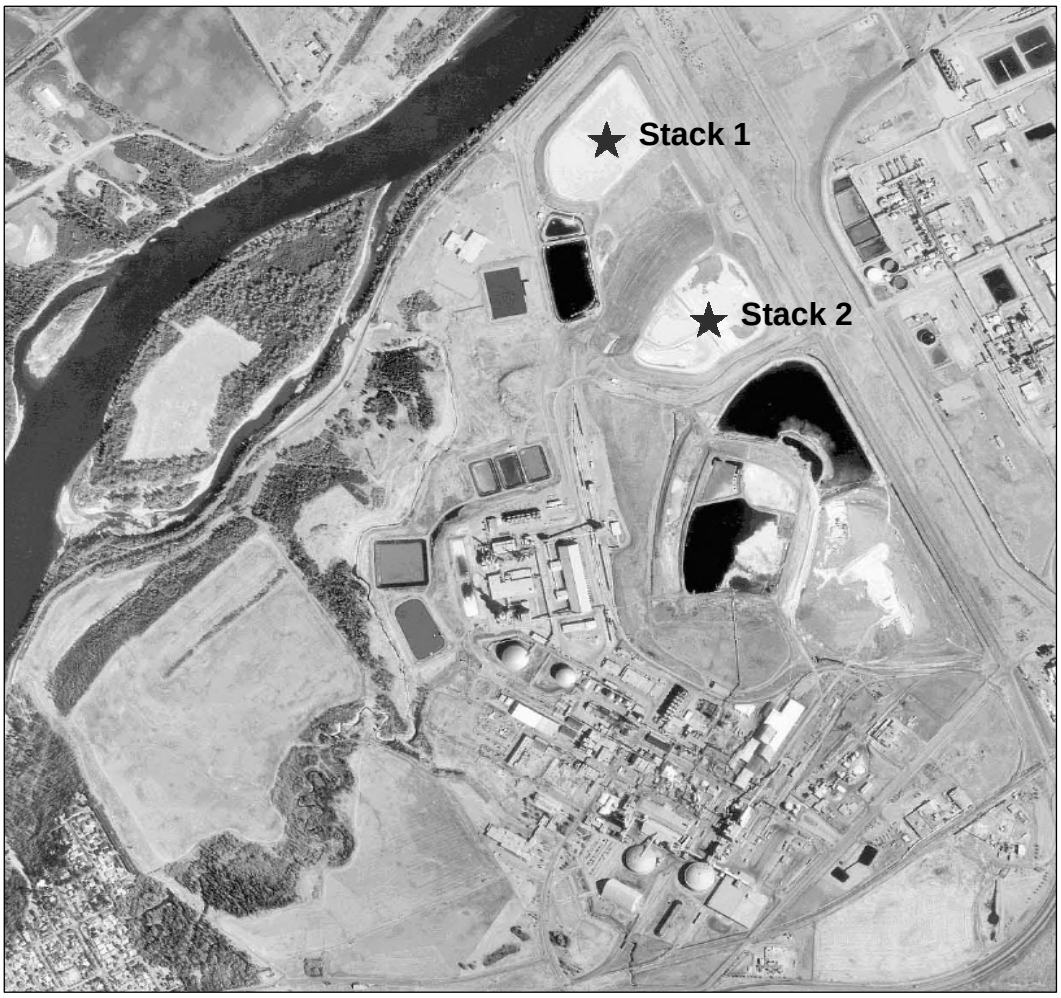

Figure 3.3. Aerial view of Agrium Fort Saskatchewan Nitrogen Operations. North is toward top left corner. North Saskatchewan River is in top left corner.

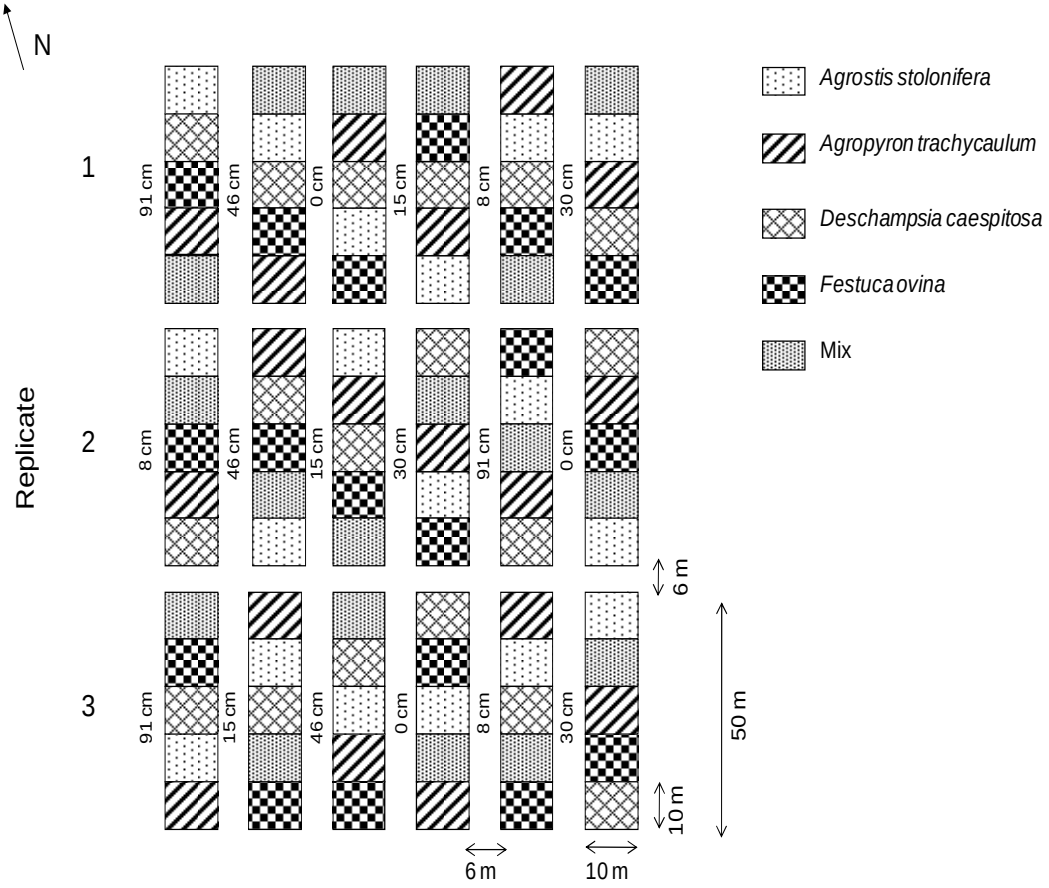

Figure 3.4. Experimental research plots at Agrium Fort Saskatchewan, Alberta.

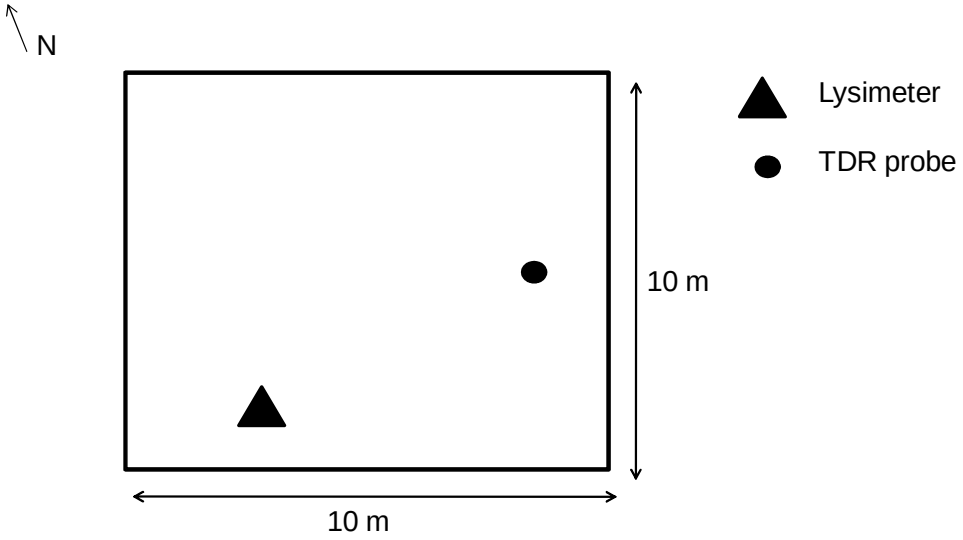

Figure 3.5. Location of lysimeter and TDR probe on *Agropyron trachycaulum* treatments at Agrium Fort Saskatchewan, Alberta.

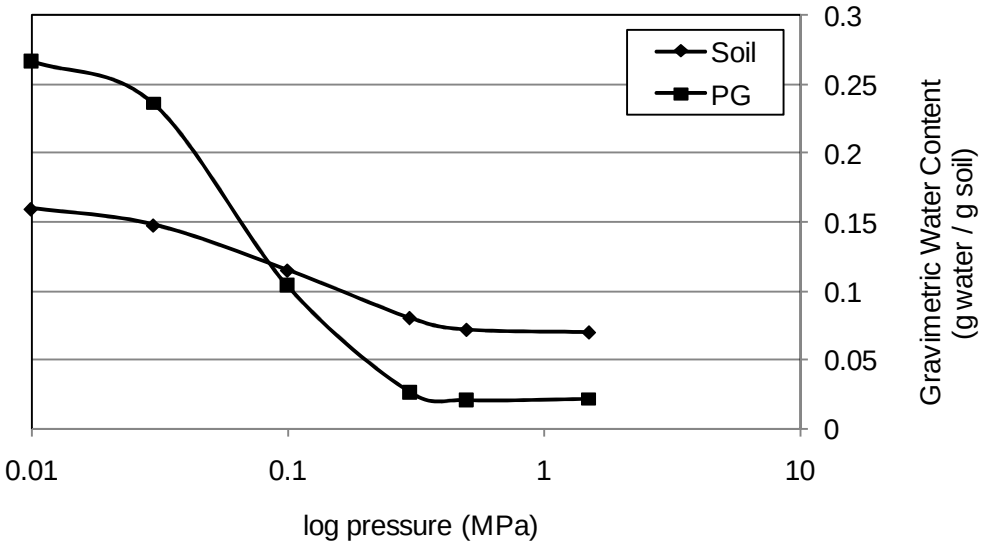

Figure 3.6. Water retention curves for soil and PG from 15 cm caps at Agrium Fort Saskatchewan, Alberta. n = 9.

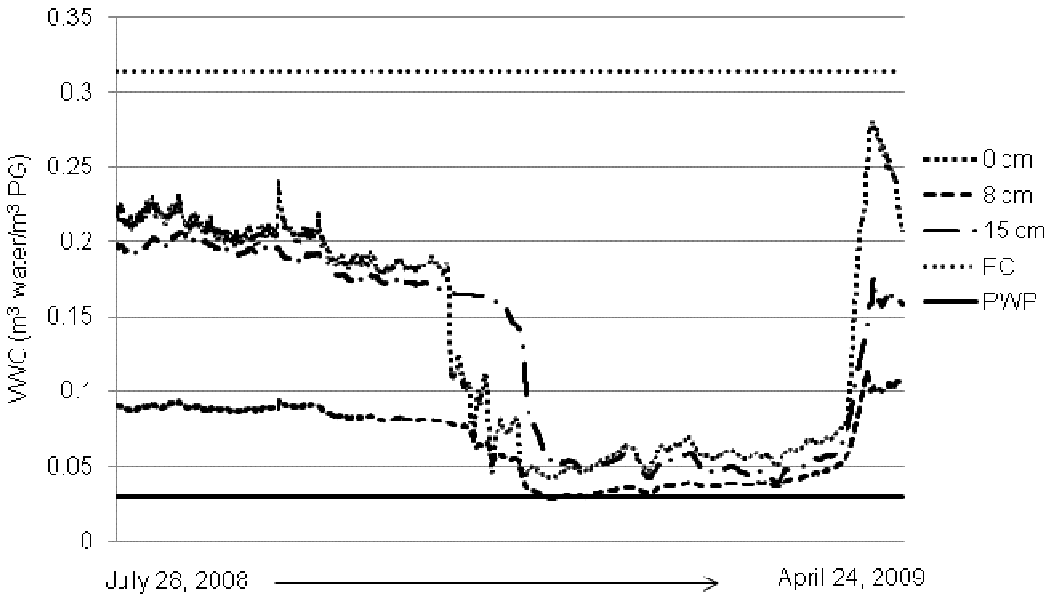

Figure 3.7a. Time series of VWC (m^3 water / m^3 PG) in the uppermost 10 cm of PG on 0, 8 and 15 cm caps at Agrium Fort Saskatchewan, Alberta between July 28, 2008 and April 24, 2009. Field capacity and permanent wilting point are indicated.

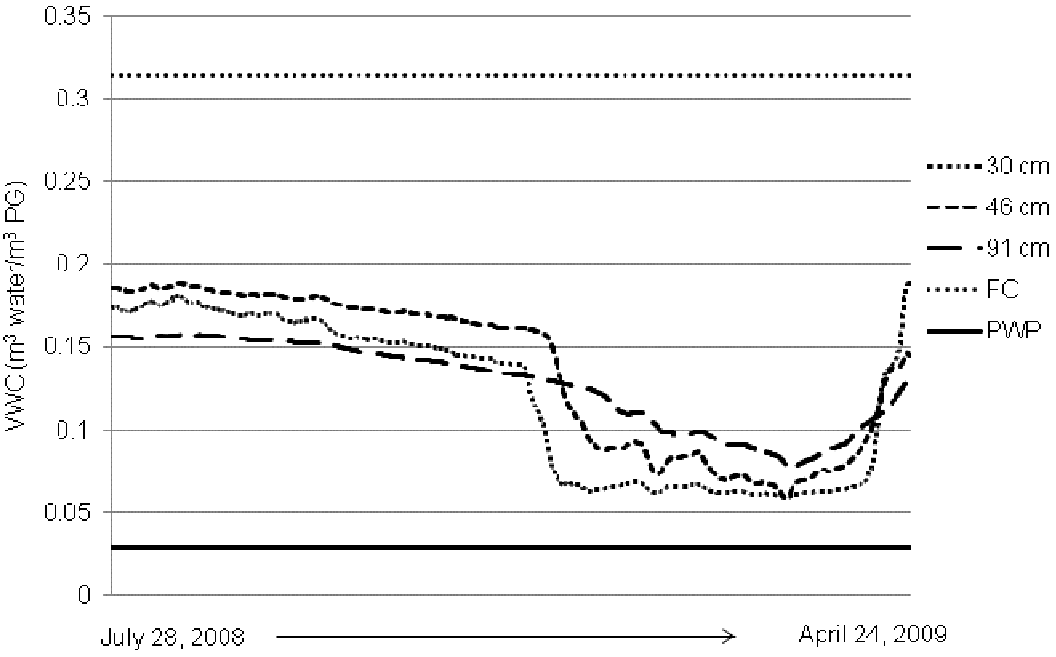

Figure 3.7b. Time series of VWC (m^3 water / m^3 PG) in the uppermost 10 cm of PG on 30, 46 and 91 cm caps at Agrium Fort Saskatchewan, Alberta between July 28, 2008 and April 24, 2009. Field capacity and permanent wilting point are indicated.

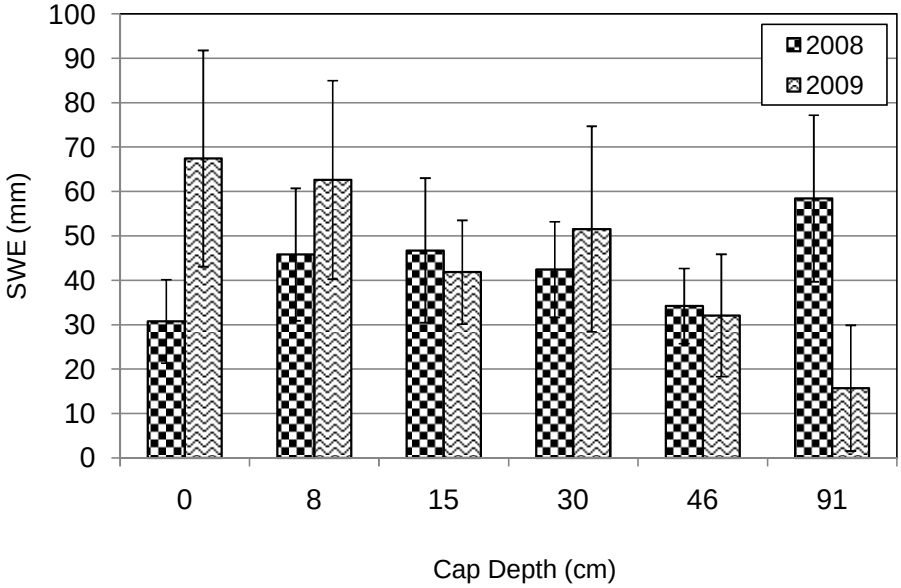

Figure 3.8. Snow water equivalent (SWE) (mm) for capping depth plots at Agrium Fort Saskatchewan, Alberta in spring 2008 and 2009. Error bars are standard deviation. n = 27.

Table 3.1. Total rainfall between soil water sampler monitoring periods and mean sample volume collected per capping depth at Agrium Fort Saskatchewan, Alberta.

Sample Date	Total Rainfall (mm)		Mean Sample Volume (mL)					
			0	8	15	30	46	91
Jun 16/08[†]	Jun 3 to Jun 16	21.6	236.3 (10.0)	218.3 (24.7)	221.7 (14.4)	229.0 (25.2)	-	12.3 (21.4)
Jun 19/08	Jun 17 to Jun 19	6.8	274.7 (11.2)	253.0 (24.4)	246.7 (11.2)	266.3 (10.4)	4.3 (7.5)	5.7 (9.8)
Jul 23/08[†]	Jun 20 to Jul 23	83.6	279.0 (39.7)	253.3 (41.9)	245.0 (47.7)	246.3 (20.7)	-	-
Jul 31/08	Jul 24 to Jul 31	8.9	292.3 (36.8)	281.3 (36.5)	253.3 (69.0)	298.7 (20.8)	-	-
Aug 16/08[†]	Aug 1 to Aug 16	18.5	301.7 (2.9)	297.3 (6.8)	289.3 (33.0)	290.0 (5.0)	-	-
Sept 4/08[†]	Aug 17 to Sept 4	17.0	289.7 (4.5)	270.0 (8.7)	271.7 (14.0)	275.7 (19.1)	-	-

Data are means with standard deviations in brackets.
n = 18.
[†]Samples were submitted to laboratory for analyses.
-No sample collected (samplers were dry).

Table 3.2. Sample volume collected from soil water samplers on June 16 and 19, July 23 and 31, August 16 and September 4, 2008 at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Mean Sample Volume (mL)
0	278.9 (29.0)
8	262.2 (34.4)
15	254.6 (38.7)
30	267.7 (29.1)
46	0.7 (3.1)
91	3.0 (9.4)

Data are means with standard deviations in brackets.
n = 18.

Table 3.3. Capping depth for research plots at Agrium Fort Saskatchewan, Alberta.

Target Cap Depth (cm)	Cap Depth (cm)
8	11.3 (3.4)
15	19.3 (3.3)
30	28.4 (5.5)
46	46.7 (8.9)
91	96.9 (8.7)

Data are means with standard deviations in brackets.
n = 27.

Table 3.4. Capping soil properties for experimental research plots at Agrium Fort Saskatchewan, Alberta.

	Capping Depth (cm)				
	8	15	30	46	91
Cation Exchange Capacity (meq/100 g)	17.8 (2.2)	20.5 (4.0)	19.7 (3.4)	16.0 (0.1)	16.6 (1.5)
Electrical Conductivity (dS/m)	2.8 (0.4)	1.2 (0.8)	2.4 (0.5)	2.6 (0.1)	2.5 (0.1)
Saturation (%)	33.7 (1.5)	38.3 (4.5)	37.0 (1.0)	32.7 (0.6)	34.0 (1.0)
pH	6.3 (1.3)	7.1 (0.8)	6.7 (0.8)	6.1 (0.6)	6.8 (0.8)
Sand (%)	79.00 (1.00)	80.67 (0.58)	81.00 (1.00)	81.67 (2.52)	80.67 (2.31)
Silt (%)	9.33 (1.15)	9.67 (0.58)	9.33 (1.15)	9.00 (1.73)	7.00 (2.65)
Clay (%)	11.67 (0.58)	9.67 (0.58)	10.00 (1.00)	9.67 (0.58)	12.00 (2.65)
Texture	SL	SL/LS	LS/SL	SL/LS	SL/LS
Available Nitrate - N (mg/kg)	23.5 (17.8)	9.5 (4.2)	10.5 (3.4)	5.7 (3.7)	3.97 (1.7)
Available Phosphate - P (mg/kg)	55.0 (28.2)	22.0 (11.1)	30.7 (9.1)	31.3 (6.5)	18.0 (10.4)
Available Potassium (mg/kg)	63.3 (14.2)	83.3 (52.2)	106.3 (16.3)	83.0 (45.9)	54.0 (19.1)
Available Sulphate - S (mg/kg)	802.3 (55.7)	63.0 (56.4)	273.0 (184.7)	710.0 (234.2)	384.7 (238.2)
Sodium (Na) (meq/100 g)	0.4 (0.2)	*	*	0.3 (0.1)	0.3 (0.1)
Potassium (K) (meq/100 g)	*	0.6 (0.2)	0.6 (0.1)	0.3 (0.1)	0.5 (0.1)
Calcium (Ca) (meq/100 g)	19.1 (6.5)	19.1 (4.6)	21.2 (5.9)	15.6 (2.5)	20.3 (5.1)
Magnesium (Mg) (meq/100 g)	1.2 (0.2)	1.4 (0.5)	1.5 (0.1)	1.4 (0.3)	1.4 (0.1)
ESP (%)	2.5 (1.3)	*	*	1.7 (0.7)	1.8 (0.8)
SAR	0.4 (0.2)	*	*	0.3 (0.1)	0.3 (0.1)
Total Organic Carbon (%)	1.9 (0.2)	2.4 (0.6)	2.4 (0.3)	1.7 (0.2)	2.0 (0.2)
Total Carbon by Combustion (%)	2.0 (0.2)	2.4 (0.6)	2.4 (0.3)	1.7 (0.2)	2.0 (0.2)
Available Ammonium - N (mg/kg)	8.4 (8.6)	2.1 (0.3)	2.3 (0.3)	2.5 (0.4)	2.2 (0.3)
Copper (Cu) (mg/kg)	0.4 (0.1)	0.4 (0.1)	0.4 (0.0)	0.4 (0.1)	0.4 (0.1)
Iron (Fe) (mg/kg)	55.7 (30.4)	57.3 (15.5)	58.3 (31.3)	58.3 (15.2)	60.3 (35.0)
Manganese (Mn) (mg/kg)	9.9 (10.7)	4.4 (1.3)	4.9 (1.8)	6.4 (2.4)	4.0 (1.3)
Zinc (Zn) (mg/kg)	3.2 (1.6)	3.8 (2.2)	3.7 (1.4)	2.7 (0.7)	2.8 (1.6)

Data are means with standard deviations in brackets.
n = 3.*Incomplete data set available for calculation of mean.
SL = sandy loam, LS = loamy sand.
Inorganic carbon and $CaCO_3$ equivalent were not included due to incomplete data set available for calculation of mean.

Table 3.5. Bulk density and volumetric water content of phosphogypsum from 8 and 15 cm capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Bulk Density (Mg/m^3)	Volumetric Water Content (m^3 water/m^3 PG)
8	1.32 (0.10)	0.27 (0.07)
15	1.35 (0.07)	0.26 (0.03)

Data are means with standard deviations in brackets.
n = 9.
Samples taken from 5 to 12 cm in PG.

Table 3.6. Change in water content in PG for rainfall events of varying magnitude on capping depth plots at Agrium Fort Saskatchewan, Alberta.

Event Start Date	Duration (hours)	P (mm)	API (mm)	Cap Depth (cm) 0		8		15		30		46		91	
				$\overline{W}_i$ (mm)	ΔW (mm)	$\overline{W}_i$ (mm)	ΔW (mm)	$\overline{W}_i$ (mm)	ΔW (mm)	$\overline{W}_i$ (mm)	ΔW (mm)	$\overline{W}_i$ (mm)	ΔW (mm)	$\overline{W}_i$ (mm)	ΔW (mm)
Jul 30/08	15	8.6	0.2	22.1	0.0	10.5	-0.2	20.1	-0.0	17.4	0.0	18.2	-0.0	16.4	0.0
Aug 28/08	4	5.3	1.2	20.4	0.9	10.2	0.0	20.3	-0.1	17.5	-0.0	18.2	-0.0	16.6	-0.0
Aug 29/08	3	6.1	4.9	21.1	0.6	10.2	0.1	20.1	0.1	17.4	0.0	18.1	-0.0	16.5	0.0
Oct 5/08	4	5.8	0.0	20.5	1.2	10.5	0.0	19.6	0.0	16.7	0.0	17.7	-0.0	16.0	0.0
Nov 12/08	16	7.4	0.2	18.4	0.2	9.4	0.0	17.5	-0.0	15.0	-0.0	16.6	-0.0	14.9	-0.0
Aug 9/08	61	17.3	0.1	22.9	-0.8	10.6	-0.3	20.4	-0.3	17.6	-0.1	18.3	-0.0	16.4	0.1
Sept 22/08	11	22.4	0.0	20.4	3.2	10.3	0.6	20.0	-0.1	17.0	-0.0	17.9	-0.1	16.2	-0.0
Apr 13/09	19	26.2	0.3	27.6	-0.2	11.7	0.3	16.1	1.5	11.0	1.6	10.9	0.8	11.4	0.1

P = precipitation.
$API = kP_{day\ 1} + k^2P_{day\ 2} + \ldots + k^5P_{day\ 5}$
k = 0.85.
$\Delta W = \overline{W}_i - \overline{W}_f$
$\overline{W}_i$ = Depth of water (mm) in the uppermost 10 cm of PG immediately preceding the rainfall event (mean of four hours).
$\overline{W}_f$ = Depth of water (mm) in the uppermost 10 cm of PG immediately following the event (mean of four hours).

Table 3.7. Water quality of lysimeter samples from 0, 8, 15 and 30 cm capping depth plots at Agrium Fort Saskatchewan, Alberta.

	Aluminum (Al) (mg/L)	Antimony (Sb) (mg/L)	Arsenic (As) (mg/L)	Cadmium (Cd) (mg/L)	Calcium (Ca) (mg/L)
NSR (US)	0.09	0.00015	0.0004	0.000011	38
NSR (DS)	0.07	0.00014	0.0004	0.000011	41
CEQG	0.005		0.005	0.000017	
AB Tier 1		0.006	0.005		
SWQG	5		0.100	0.0051	
0	3.65 (2.77)[a]	0.007 (0.006)[ab]	0.279 (0.224)[a]	0.012 (0.006)[a]	517 (103)[ac]
8	7.76 (5.32)[a]	0.007 (0.002)[a]	0.248 (0.120)[a]	0.014 (0.006)[a]	499 (70)[a]
15	6.20 (5.95)[a]	0.005 (0.006)[ab]	0.256 (0.103)[a]	0.017 (0.012)[a]	640 (100)[bc]
30	6.54 (6.28)[a]	0.003 (0.000)[b]	0.250 (0.131)[a]	0.012 (0.010)[a]	671 (61)[b]

Data are means with standard deviations in brackets.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.
$3 \leq n \leq 12$.
NSR (US) = North Saskatchewan River water quality 3 km upstream of Agrium Fort Saskatchewan (LeClair 2009).
NSR (DS) = North Saskatchewan River water quality 3 km downstream of Agrium Fort Saskatchewan (LeClair 2009).
CEQG = Canadian Environmental Quality Guidelines (aquatic life) (CCME 2003).
AB Tier 1 = Alberta Tier 1 Soil and Groundwater Remediation Guidelines (industrial land use) (Alberta Environment 2009).
SWQG = Surface Water Quality Guidelines (agricultural (irrigation) use) (Alberta Environment 1999).

Table 3.7. Water quality of lysimeter samples from 0, 8, 15 and 30 cm capping depth plots at Agrium Fort Saskatchewan, Alberta (continued).

	Chloride (Cl) (mg/L)	Chromium (Cr) (mg/L)	Copper (Cu) (mg/L)	Fluoride (F) (mg/L)	Lead (Pb) (mg/L)
NSR (US)	2	0.0003	0.0023	0.14	0.00007
NSR (DS)	2	0.0002	0.0021	0.12	0.00006
CEQG		0.0089/0.001[†]	0.002		0.001
AB Tier 1	230			0.12	
SWQG	100 to 700	0.0049/0.008[†]	0.2 to 1.0	1	0.2
0	50 (32)[a]	0.004 (0.005)[a]	0.062 (0.018)[a]	16.73 (8.57)[a]	0.000 (0.000)[a]
8	55 (65)[a]	0.003 (0.002)[a]	0.095 (0.118)[ab]	21.50 (11.46)[a]	0.000 (0.000)[a]
15	272 (438)[a]	0.007 (0.009)[a]	0.216 (0.406)[abc]	15.99 (10.50)[a]	0.001 (0.002)[a]
30	36 (22)[a]	0.002 (0.003)[a]	0.026 (0.006)[d]	16.73 (11.85)[a]	0.000 (0.000)[a]

Data are means with standard deviations in brackets.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.
$3 \leq n \leq 12$.
[†]Guidelines for trivalent/hexavalent forms of chromium.
NSR (US) = North Saskatchewan River water quality 3 km upstream of Agrium Fort Saskatchewan (LeClair 2009).
NSR (DS) = North Saskatchewan River water quality 3 km downstream of Agrium Fort Saskatchewan (LeClair 2009).
CEQG = Canadian Environmental Quality Guidelines (aquatic life) (CCME 2003).
AB Tier 1 = Alberta Tier 1 Soil and Groundwater Remediation Guidelines (industrial land use) (Alberta Environment 2009).
SWQG = Surface Water Quality Guidelines (agricultural (irrigation) use) (Alberta Environment 1999).

Table 3.7. Water quality of lysimeter samples from 0, 8, 15 and 30 cm capping depth plots at Agrium Fort Saskatchewan, Alberta (continued).

	Manganese (Mn) (mg/L)	Nickel (Ni) (mg/L)	Nitrate-N (mg/L)	Nitrite-N (mg/L)	Selenium (Se) (mg/L)	Sodium (Na) (mg/L)
NSR (US)	0.0015	0.0006	0.093	0.003	0.0003	4.3
NSR (DS)	0.0011	0.0005	0.128	0.007	<0.0001	5.0
CEQG		0.025	13	0.06	0.001	
AB Tier 1	0.05		13	0.06	0.001	200
SWQG	0.2	0.2			0.02 to 0.05	
0	1.77 (1.14)[a]	26.287 (20.375)[a]	200 (93)[bc]	0.11 (0.04)[ab]	0.062 (0.066)[ab]	215 (127)[a]
8	2.16 (0.90)[ab]	22.928 (17.761)[a]	116 (37)[c]	*	0.047 (0.025)[a]	160 (90)[a]
15	5.45 (3.11)[a]	51.424 (47.917)[a]	471 (168)[a]	0.18 (0.08)[a]	0.026 (0.021)[ab]	219 (141)[a]
30	4.34 (2.17)[b]	27.976 (29.030)[a]	409 (270)[ab]	0.08 (0.02)[b]	0.019 (0.008)[b]	160 (72)[a]

Data are means with standard deviations in brackets.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.
$3 \leq n \leq 12$.
*Incomplete data set available for calculation of mean.
NSR (US) = North Saskatchewan River water quality 3 km upstream of Agrium Fort Saskatchewan (LeClair 2009).
NSR (DS) = North Saskatchewan River water quality 3 km downstream of Agrium Fort Saskatchewan (LeClair 2009).
CEQG = Canadian Environmental Quality Guidelines (aquatic life) (CCME 2003).
AB Tier 1 = Alberta Tier 1 Soil and Groundwater Remediation Guidelines (industrial land use) (Alberta Environment 2009).
SWQG = Surface Water Quality Guidelines (agricultural (irrigation) use) (Alberta Environment 1999).

Table 3.7. Water quality of lysimeter samples from 0, 8, 15 and 30 cm capping depth plots at Agrium Fort Saskatchewan, Alberta (continued).

	Sulphate (SO_4) (mg/L)	Thallium (Tl) (mg/L)	Zinc (Zn) (mg/L)	EC (dS/m)	pH	TDS (mg/L)
NSR (US)	29.33	0.000008	0.0014	0.289	8.2	171
NSR (DS)	28.43	0.000007	0.0014	0.293	8.2	169
CEQG		0.0008	0.03		6.5 to 9.0	
AB Tier 1	500		0.03		6.5 to 8.5	500
SWQG			1 to 5			500 to 3500
0	8,209 (4,913)[a]	0.0149 (0.0120)[a]	0.48 (0.36)[a]	17.395 (10.157)[a]	5.4 (0.4)[a]	10,119 (5,231)[a]
8	4,389 (2,506)[ab]	0.0071 (0.0036)[a]	0.58 (0.28)[a]	9.502 (5.135)[ac]	5.2 (0.3)[ab]	6,019 (2,627)[c]
15	3.698 (1,630)[ab]	0.0073 (0.0048)[a]	0.67 (0.39)[a]	10.857 (4.407)[abc]	5.0 (0.4)[b]	8,044 (3,553)[abc]
30	2,546 (1,127)[b]	0.0054 (0.0047)[a]	0.61 (0.21)[a]	7.933 (4.357)[b]	5.1 (0.4)[ab]	5,491 (2,392)[bc]

Data are means with standard deviations in brackets.
Different letters in a column denote significant differences between cap depths at $p < 0.05$.
$3 \leq n \leq 12$.
NSR (US) = North Saskatchewan River water quality 3 km upstream of Agrium Fort Saskatchewan (LeClair 2009).
NSR (DS) = North Saskatchewan River water quality 3 km downstream of Agrium Fort Saskatchewan (LeClair 2009).
CEQG = Canadian Environmental Quality Guidelines (aquatic life) (CCME 2003).
AB Tier 1 = Alberta Tier 1 Soil and Groundwater Remediation Guidelines (industrial land use) (Alberta Environment 2009).
SWQG = Surface Water Quality Guidelines (agricultural (irrigation) use) (Alberta Environment 1999).

4. INFLUENCE OF SOIL CAPPING DEPTH ON RADON GAS, GAMMA RADIATION AND HYDROGEN FLUORIDE EMISSIONS ON PHOSPHOGYPSUM STACKS AT FORT SASKATCHEWAN, ALBERTA

4.1 Introduction

Phosphogypsum (PG) is an acidic by product of phosphoric acid production (Richardson et al. 1995, Rutherford et al. 1994). The fertilizer industry generates approximately five tonnes of PG per tonne of phosphoric acid, the latter required for phosphorus fertilizer production (Rutherford et al. 1995a, Rutherford et al. 1994, Ferguson 1988). Large quantities of PG are produced annually in at least 80 countries around the world (Florida Institute of Phosphate Research 2006). As of January 2006, Florida had at least 20 PG stacks, more than any other state. In Canada there are stacks in British Columbia, Alberta, Ontario, Quebec and New Brunswick with the majority and largest of the stacks in Alberta (Thorne 1990). Ferguson (1988) predicted that worldwide PG production would reach between 220 and 280 million tonnes by the year 2000. Parreira et al. (2003) indicated that PG production was approximately 180 million tonnes per year in 2003. Abril et al. (2009) estimated annual PG production at 170 million tonnes in 2006.

PG is commonly wet stacked on land adjacent to fertilizer production facilities (Luther and Dudas 1993) where they can span hundreds of hectares and tens of meters in height (Rutherford et al. 1995b). The main environmental concerns associated with PG stacks are chemical impurities such as residual acidity, silica, unreacted phosphate rock, radon, uranium and trace elements including fluoride, cadmium, arsenic, lead and silver; their presence and concentration dictated mainly by the composition of the source rock (Wissa 2002). As water percolates through the stack, trace elements can become mobile and leach into ground water, negatively impacting ecosystem function. Exposure to radon gas and gamma radiation can affect human health if emissions are not limited by reclamation methods such as capping (Rutherford et al. 1994).

The most common approach to PG stack reclamation is to cap the PG with soil. A cap can prevent wind and water erosion, limit percolation, provide a plant

substrate, prevent contaminated water from running off the stacks and provide a landscape conducive to the desired end land use (Richardson et al. 1995).

Little research has been conducted on PG stack reclamation in Canada. Characterization of PG and environmental hazards with specific emphasis on radioactivity has been studied mainly by Rutherford, Dudas and Arocena during the 1990s (Rutherford et al. 1995a, 1995b, 1995c, 1994). Their research investigated radioactivity and PG chemical composition among different phosphate rock sources, important information for effective management of the waste. They found trace element and fluoride concentrations greatly reduced in weathered PG relative to fresh PG although ^{226}Ra in PG leachate was identified as a potential concern despite stacks being highly weathered. In 1988 Norlander assessed the decommissioning of PG tailings in Calgary, Alberta with a focus on radon flux from exposed PG stacks. It was concluded that residential development should be avoided on both bare and capped PG stacks to avoid exposure to radon, dust, particulates and gamma radiation. Thorne (1990) identified issues associated with successful reclamation of a PG tailings pond in Calgary, Alberta with a specific focus on the use of amendments to overcome chemical and physical limitations of PG required for successful revegetation. In greenhouse studies the addition of soil or lime to PG tailings was effective at overcoming many limitations associated with vegetation establishment.

The most recent Canadian PG reclamation research was done by Hallin (2009) at the University of Alberta. Her research characterized the quality of a reclaimed PG stack 15 years after initial reclamation efforts in Fort Saskatchewan, Alberta. The effect of a vegetated 15 cm soil cover on water infiltration and percolation into the stack, runoff water quality, radon gas and gamma emissions and plant community development was evaluated. It was concluded that the existing cover system was providing an effective barrier between PG and the environment.

The effect of soil cap depth and revegetation on radon emissions from PG has not been fully explored (Dueñas et al. 2007, Rutherford et al. 1994). In southwest Spain a 25 cm soil cap was constructed on an inactive PG stack (Dueñas et al. 2007). This depth was effective for reducing gamma emissions to background concentrations although effect on radon emissions was unclear. Radon

emissions were eight times lower on the capped and revegetated stack than on a nearby active stack. Hydrogen fluoride emissions arise from fugitive PG dust (Wissa 2002) and the effect of capping is unknown. Currently, Alberta Environment requires a 1 m soil cap on the Agrium Redwater PG stack after production has ceased (Alberta Environment 2008). With an annual precipitation of 460 mm at the study site, it was hypothesized this cap depth could be reduced while minimizing radiation and hydrogen fluoride emissions.

4.2 Research Objectives and Hypotheses

4.2.1 Research objectives

The general research objective is to contribute to a reclamation plan for PG stack closure by determining an appropriate depth of soil for capping PG. The specific research objective is to determine the effect of soil cap depth on emissions of radon gas, gamma radiation and hydrogen fluoride gas.

4.2.2 Research hypotheses

- Emissions of radon gas, gamma radiation and hydrogen fluoride will decrease with increasing cap depth. Thicker caps may provide a more effective barrier to emissions than shallow depths.
- Emissions measured on the capped plots will not be present in concentrations considered harmful to human health due to the weathered nature of the PG.

4.3 Materials and Methods

4.3.1 Site description

Fort Saskatchewan is located approximately 30 km northeast of Edmonton, Alberta, Canada (53° 43’ N and 113° 13’ W) (Figure 4.1). It is located in the Central Parklands Natural Subregion within the Aspen Parkland Ecoregion, in a transition zone between the Dry Mixedwood and Northern Fescue Natural Subregions to the north and south, respectively (Speiss 2007, Natural Regions

Committee 2006). Average annual precipitation is approximately 460 mm with almost half falling as rain during June, July and August (Environment Canada 2008). Average monthly rainfall ranges from 0.4 mm in January to 88.8 mm in June. Historical extreme daily rainfall has ranged from 6.4 mm in December 1958 to 77.7 mm in June 1965. Yearly snow fall approaches 100 cm. Daily average temperatures range from -13.5 ℃ in January to 16.7 ℃ in July.

Geologic sediments of the Fort Saskatchewan area are Upper Cretaceous shales from the Belly River Formation (Alberta Geological Survey 2005). The topography of the Central Parkland is hummocky and has gently rolling till plains with an average elevation of 700 m (City of Fort Saskatchewan 2008, Natural Regions Committee 2006). Lacustrine and fluvioglacial deposits are the dominant surficial sediments and soils are dominated by Black Chernozems (60 %) with a smaller proportion (15 %) of Solonetzes (Natural Regions Committee 2006). Cultivation and development have resulted in loss of native vegetation, which currently composes only 5 % of the plant community in the Central Parkland. Patches of aspen and plains rough fescue grassland remain, although aggressive non native species such as *Bromus inermis* (Leyss) (smooth brome) and other agricultural species dominate (Natural Regions Committee 2006).

Agrium Incorporated (Agrium), located in the industrial district of Fort Saskatchewan, Alberta (Figure 4.2), is a large scale fertilizer manufacturing company which produced monoammonium phosphate ($NH_4H_2PO_4$) fertilizer for 26 years at its Fort Saskatchewan, Alberta facility (Svarich 1999). Currently only anhydrous ammonia (NH_3) and urea ($CO(NH_2)_2$) are being produced at Fort Saskatchewan (Agrium 2009).

PG was wet stacked in five areas between 1965 and 1991 at Fort Saskatchewan, all of which are closed today (Svarich 1999) (Figure 4.3). Stack 1, located adjacent to the North Saskatchewan River, was active from 1983 to 1991. It was built on a high density polyethylene liner (Svarich 1999) and has a base area of 9.3 ha and a settling basin of 4.7 ha. Stack 2, located south of Stack 1, was built into the side of the river valley (Norlander 1988) on a clay liner. It has a base area of 8.5 ha and settling basin area of 4.7 ha and was active from 1974 to 1991. Each stack has a bare PG road around the perimeter of the settling basin

and a road to connect stacks. Following PG production, 10 to 15 cm of soil was applied with a bobcat to the stack outer slopes and a seed mix consisting mainly of *Bromus inermis* and *Brassica napus* L. (canola) was broadcast (Nichol 2009). Outer slopes of both stacks are currently dominated by *Bromus inermis* and *Melilotus alba* Desr. (white sweet clover). The settling basin of Stack 1, where the research plots are located, is recessed 10 m below the upper stack road and can be accessed on the south from the stack base and on the northeast from the upper stack road. The basin surface is relatively flat with a slight northeast aspect. The side slopes and basin floor are unvegetated except where mushroom compost was applied at the south side of the basin adjacent to the access road; *Kochia scoparia* (L.) Schrad. (kochia) is the dominant plant. A thick crust has formed over PG on interior basin sloped walls and the floor.

4.3.2 Experimental design

Eighteen experimental research plots (50 m long x 10 m wide) with varying capping depths were constructed in late October 2006 in a complete randomized design in the basin of Stack 1 (Figure 4.4). Soil from an old alfalfa pasture approximately 5 km northeast of Agrium was excavated using a Hitachi 200 backhoe. Soil taken from an average depth of 40 cm was pushed into piles, then loaded into tandem trucks and transported to Agrium. Soil was unloaded into the staked area of the plots and built up to specified depths using a John Deere 750C dozer and Bobcat S300 (Gagnon 2008).

Capping depths of 8, 15, 30, 46 and 91 cm of soil and a control with no soil were replicated three times (1, 2 and 3 Figure 4.4). Each of the plots was subdivided into five 10 x 10 m sections which were seeded to one of five vegetation treatments in mid June 2007. Vegetation treatments included monocultures of *Agrostis stolonifera* L. (redtop), *Agropyron trachycaulum* (Link) Malte ex H.F. Lewis (slender wheatgrass), *Deschampsia caespitosa* (L.) P. Beauv. (tufted hairgrass) and *Festuca ovina* L. (sheep fescue). A fifth vegetation treatment was a mix of the above grasses with *Trifolium hybridum* L. (alsike clover). The mix was 54 % *Agrostis stolonifera,* 2 % *Agropyron trachycaulum,* 28 % *Deschampsia caespitosa,* 8 % *Festuca ovina* and 8 % *Trifolium hybridum* (Brett Young 2009).

4.3.3 Plant species selection

Plant species selected for reclamation were native or adapted to the area. They had high germination and establishment, roots effective at providing erosion control, persistence following climatic or environmental fluctuations, low nutrient and water requirements and tolerance of acidic substrates (Table A1).

Agrostis stolonifera is an introduced, early successional perennial grass tolerant of environmental conditions, including drought. It has a dense root system that can control erosion when conditions are not too wet (Esser 1994). *Festuca ovina* is a long lived perennial grass with wide distribution. It requires low nutrients and tolerates acidity. *Deschampsia caespitosa* is a native, perennial grass which tolerates moderate acidity and prefers moderately moist to moist soils. *Agropyron trachycaulum* is a native, short lived perennial grass which grows well in semi arid to moist regions. It establishes quickly and provides excellent short term erosion control. If planted with other slow growing species, it will become less dominant over time. *Trifolium hybridum* is a short lived perennial legume. It can tolerate acidic and alkaline conditions and a variety of moisture regimes. It can benefit revegetation efforts when planted with other species due to its nitrogen fixing ability (Hardy BBT Limited 1989). All five seeded species grow well on medium to coarse textured soils (Esser 1994, Hardy BBT Limited 1989). Certified seed for each species was obtained from Brett Young Seeds in Leduc, Alberta.

4.3.4 Plot management

Annual and perennial weeds from the soil seed bank dominated the plots in spring and summer 2007. Prior to seeding, all plots, edges and buffers were sprayed with 2.47 L/ha of glyphosate (Roundup WeatherMax) herbicide using a tank pulled by a John Deere 5203 tractor; in areas not accessible by the tractor backpack sprayers were used. Glyphosate is recommended for non selective weed control in various cropping systems including those with grasses and legumes. The application rate used is considered appropriate for eradicating annual weeds over 15 cm in height and for many perennial species including *Medicago sativa* L. (alfalfa) and *Linaria vulgaris* Hill. (toadflax) (Alberta Agriculture and Food 2008).

Plots were harrowed twice before seeding with a 1.5 m 3-point hitch spring tooth harrow pulled by a John Deere 5203 tractor driving the length of the plots (Puurveen 2007a). Weeds were mowed to approximately 10 cm height in early August 2007 with a tractor and 1.8 m Alamo flail mower on plots, plot edges and buffers. Plot edges and buffers were trimmed several times in summer 2008; plots were mowed September 5, 2008. Biomass was left on plots after mowing.

4.3.5 Meteorological data

A meteorological station was situated in the center of the Stack 1 basin between plots B3 and B4 to avoid edge effects. Instrumentation was Campbell Scientific including a CR10X data logger. Maximum and minimum air temperature (℃) and relative humidity (%) were measured using the HMP45C Vaisala relative humidity and temperature probe (-40 to +60 ℃). Saturation vapour pressure (kPa) was calculated using appropriate formulae from temperature and relative humidity data. Wind speed (m/s) data were obtained using the 05103-10 RM Young wind monitor. A Kipp & Zonen silicon pyranometer measured total incoming radiation (W/m^2) and total rainfall (mm) was measured with a TE525WS Texas Electronics 20 cm tipping bucket rain gauge in addition to a manual rain gauge. Weather data were downloaded periodically from the data logger via a personal pocket computer (Campbell Scientific (Canada) Corp. 2007, Puurveen 2007b).

4.3.6 Capping depth measurements

Capping depths were measured June 5 and 6, 2008 to determine whether changes occurred due to soil settling, compaction or wind and water erosion following plot construction. Measurements were taken at nine locations on each plot using a systematic sampling strategy; in the center of each treatment 2 m right of stakes marking the west side of the plot and 2 m left of stakes marking the east side of the plot, directly on the boundary between treatments.

Using a 5 cm diameter by 19 cm length barrel auger, a hole was cored through the soil until the PG surface was encountered, as indicated by PG on the auger tip. A meter stick was inserted into the hole and depth (cm) recorded prior to backfilling with excavated soil. If the hole was cored past the soil / PG interface

and more than 1 cm of PG was encountered, a visual estimate of PG in the auger was subtracted from the total depth indicated by the meter stick.

4.3.7 Capping soil characterization

Soil was sampled on June 12, 2008. The length of each plot was divided into thirds. A pair of random numbers was generated to provide a sampling location for each third. The first random number generated for each third indicated position across the plot. The second random number indicated position down the length of the top third, middle third and bottom third, respectively. Soil was sampled where these points intersected and adjacent to vegetation rows.

A barrel auger of 5 cm diameter and 19 cm length was used to obtain soil samples to a depth of 8 cm. At most sample locations, three to four holes were excavated adjacent to each other to obtain sufficient sample for analyses, approximately two thirds of a 3.7 L Ziploc bag. If PG or large pieces of organic material were mixed with the soil they were removed by hand. Soil samples from the top, middle and bottom thirds of each plot were mixed thoroughly in a large pail with a hand trowel. Soil was split evenly between two 3.7 L Ziploc bags and labelled. One set of samples was refrigerated for further analyses; the second set was sent to ALS Laboratory in Edmonton to be analyzed.

Inorganic carbon was determined using the gravimetric method for loss of carbon dioxide to approximate carbonate content and total carbon by combustion (Bartels et al. 1996). Total organic carbon was determined by subtraction. Cation exchange capacity (CEC) was determined using the $BaCl_2$ method (Carter 1993) and exchangeable cations determined with $BaCl_2$ extraction after water leach (McKeague 1978). Exchangeable sodium percentage (ESP) was determined by calculation (exchangeable sodium / CEC x 100) (Brady and Weil 2002). Available ammonium nitrogen was determined by extraction in 2 M KCl and colorimetric analysis. Available micronutrients were extracted with DTPA solution and analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES). Particle size was determined by hydrometer; electrical conductivity and % saturation were analyzed by saturated paste (Carter 1993). Soil pH was determined in 1:2 water extract (Carter and Gregorich 2008). Available nitrate

nitrogen was determined with cadmium reduction (Carter 1993) and available phosphate phosphorus and potassium with a modified Kelowna extraction (Qian et al. 1994). Available sulphate sulfur was determined by extract in weak $CaCl_2$ and analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Alberta Agriculture 1988). Analytical results were compared to the Soil Quality Criteria Relative to Disturbance and Reclamation (Alberta Agriculture, Food and Rural Development 1987) for soil in the Plains Region.

4.3.8 Radon gas

Landauer Inc. Radtrak® alpha track long term detectors (Landauer Inc. 2005) were installed May 27, 2008. A single detector was installed 3 m east and 3 m south of a stake marking the northwest corner of *Agropyron trachycaulum* treatments on each plot, directly on top of a row of seeded grass (Figure 4.5). Relative to other vegetation treatments, *Agropyron trachycaulum* best represented the vigour and development of the future plant community for determining the effect of radon emissions. If the location was not representative of the health and development of the treatment, the location was shifted to within a 1 m radius. Detectors were kept sealed in aluminium foil bags to prevent premature exposure to radon gas or contamination prior to installation.

A 30 cm diameter by 5 cm wide by 9 cm deep circular trough was excavated and a wooden stake was hammered into the center of the vegetation, soil or PG mass inside the trough. The plastic cup housing the radon detector was inverted and attached to the top of the stake using two cable ties, approximately 29 cm above plot surface. A 20 L white utility bucket was inverted over the stake with the rim of the bucket directly in the trough; the area between the outer wall of the bucket and trough was backfilled with excavated material. Pails were secured using four metal pigtail stakes and tie wire fed through drilled holes in the bucket lip. Soil or PG was then packed between the metal stakes. Canisters were removed after 140 days and sent to Landauer Inc. in Illinois, USA for analysis.

Radon canisters were installed August 11, 2008 following the protocol outlined above at Agrium in Redwater on non replicated 0, 15, 30, 46 and 91 cm cap plots. Plots were located on the east side of the active PG stack close to the

bottom on a slight grade. Dominant vegetation cover was grass species. Canisters were removed after 92 days and sent to Landauer Inc. for analysis.

Radon canisters were installed around the perimeter of Agrium in Fort Saskatchewan on June 3, 2008. Eight sites for radon detectors were based on proximity to PG stacks and achieving relatively uniform detector spacing (Figure 4.6). Radon canisters inside transparent plastic cups were inverted and secured with industrial strength Velcro to the inside bottom of a round beige plastic 19 cm diameter by 15 cm height flower pot. Tie wire was fed through drainage holes in the bottom of the pot and tied to form handles. A single inverted pot was attached approximately 1 m above ground surface to chain link fence at each site. Cable ties were used to secure pots parallel to the ground surface. Global positioning system (GPS) coordinates were recorded at each site and the meteorological station in the basin of Stack 1 for reference using a Garmin GPS III Plus.

Radon canisters were installed outside Fort Saskatchewan for background data on radon gas concentrations. One radon canister housed inside a pot similar to those around the Agrium perimeter, was installed 1 m above ground in Sherwood Park, Alberta, 25 km from Fort Saskatchewan. A second canister was installed at Morinville, Alberta, 41 km west of Fort Saskatchewan. The radon canister was secured inside a plastic housing designed for outdoor radon detectors on a wooden fence post 1 m above ground surface. Housings were thick plastic with styrofoam insulation. Canisters around the perimeter and at reference locations were installed between 133 and 137 days and sent to Landauer Inc. for analysis.

4.3.9 Gamma emissions

Gamma radiation was measured using a Thermo FH40GL digital survey reader on June 16, July 18 and August 18, 2008. The device was manufactured by Thermo Electron Corporation and provides instantaneous measurements in nSv/hr (Thermo Electron Corporation 2003). Readings were taken at three locations on each *Agropyron trachycaulum* plot; 1 m north of the radon pail, 1 m south of the lysimeter and in the plot center 2 m left of the east plot stakes (Figure 4.5). Due to large fluctuations in readings from the survey reader, maximum, minimum and consistent (most common value) readings were

recorded during one minute. Readings were taken 1 m above ground and at ground level (0 m). A sheet of paper was placed between the ground surface and survey reader for ground level readings to avoid detector contamination. Vegetation was pushed over for placement of the survey reader for ground level measurements. Background gamma was measured at Sherwood Park, Twin Brooks and Ellerslie Research Farm, 21, 36 and 37 km from Fort Saskatchewan, respectively. Maximum, minimum and consistent readings were recorded during one minute at three locations per background site, 1 m above ground.

4.3.10 Hydrogen fluoride gas emissions

Hydrogen fluoride (HF) gas emissions were measured using passive HF detectors from the AMEC Center for Passive Technology (Tang 2009). Radon canisters were replaced by HF detectors in overturned 20 L utility buckets in the same location on each *Agropyron trachycaulum* treatment for 30 day monitoring periods (mid October to mid November 2008) (Figure 4.5). One HF detector was installed on the upper east side of the basin on the road 1 m above the surface. This detector was housed under a plastic disc with metal clips on the underside to hold up to three HF detectors. For background HF concentrations, a single detector was installed approximately 1 m above the ground surface in Sherwood Park. Detectors were removed and sent to AMEC for analysis.

4.3.11 Statistical analyses

Radon, gamma and HF data were organized by cap depth in Microsoft Excel and descriptive statistics were calculated. Correlation coefficients (r^2) were determined for parameters exhibiting linear trends with cap depth. Gamma radiation data were averaged over the three measurement days and locations to obtain means for 0 and 1 m at each cap depth. Background gamma measurements were averaged across sites to provide a single value. One way ANOVAs were performed in SigmaPlot 11.0 at the 5 % level of significance to determine whether emissions varied with cap depth. If data failed to pass the tests for normality or homogeneity of variance, a Kruskal-Wallis one way ANOVA on ranks was performed. Tukey's multiple comparison test was used to detect which means differed from one another.

4.4 Results and Discussion

4.4.1 Capping soil characterization

Measured cap depths were generally comparable to target depths outlined in the experimental design (Table 4.1). Differences were highest for 8 cm and lowest for 46 cm cap plots. Soil properties for all capping depths were generally associated with a hospitable plant growth medium (Table 4.2). Soil texture was sandy loam to loamy sand (clay 9.7 to 12.0 %), with low CEC and percent saturation. General soil quality was good (low Na, high Ca, low EC, low SAR). Bulk density of Stack 1 side slopes was determined by Hallin (2009) as 1.28 (0.14 standard deviation) Mg/m^3. Soil quality did not influence performance of *Agropyron trachycaulum,* which established quickly and vigourously on capped plots, characteristic of the species. Thus, it was considered representative of the health and developmental stage of the future plant community.

4.4.2 Radon gas emissions

Radon gas emissions exceeded upper detectable analytical limits of 140,000 piC/L-day on all 0, 8 and 15 cm cap plots and two replicates each of 30 and 46 cm cap plots in Fort Saskatchewan (Table 4.3). Emissions from the single replications on 30 and 46 cm caps were 984 and 1,107 piC/L, respectively, and emissions on 91 cm caps were 522 (175 standard deviation) piC/L.

By trapping air inside pails, gas emitted from the soil or PG surface accumulated in high concentrations during the 140 day monitoring period. While emissions concentrations may not be representative of ambient concentrations for Fort Saskatchewan PG stacks, a few interesting points were noted. Emissions from 0, 8 and 15 cm caps may be higher than from 30 and 46 cm caps due to their exceedance of detectable limits on all replicates. Incomplete data for 30 and 46 cm caps cannot confirm this. Radon emissions from 30 and 46 cm caps were comparable and had approximately 50 % higher emissions than 91 cm caps.

Results from canisters installed on non replicated 0, 15, 30, 46 and 91 cm caps at Agrium in Redwater exhibited similar trends to the sites at Fort Saskatchewan.

Emissions exceeded detectable limits on the 0 cm cap and lowest on the 91 cm cap (Figure 4.7). Decreasing radon emissions were strongly correlated to increasing cap depth (r^2 = 0.93, data not shown) although lack of replication cannot confirm this. Data from Fort Saskatchewan and Redwater cannot be compared or combined due to differences in length of detection period and site conditions. Despite experimental error, data from both sites may indicate a relationship between radon emissions and cap depth exists.

Four of eight radon canisters installed around the perimeter of Agrium fell out of housings onto the ground during the detection period. Radon emissions were 0.43 (0.17 standard deviation) piC/L for uncontaminated detectors (Figure 4.6). Background radon emissions were 1.10 (1.13 standard deviation) piC/L. In Canada, the Derived Working Limit for radon exposure is 4 piC/L (Health Canada 2000). Areas where concentrations exceeded this criterion were classified as NORM Management or Radiation Protection Management, depending on degree of exceedance (Health Canada 2000). Mean ambient radon emissions around the perimeter did not exceed this guideline criterion.

Future monitoring of radon gas emissions from different cap depths should involve a modified pail apparatus and shorter detection period. The objective of using the overturned pail was to provide shelter to the detector from wind and eliminate the influence of other plots in close proximity. To prevent build up of radon inside the pail, the bottom of the pail could be cut out so the canister remains sheltered but allows air to move vertically. Representative data could be obtained over a three month detection period using this modified pail technique. It is possible that a compacted clay cap may be more effective than soil at providing a barrier between PG stack radon emissions and the atmosphere (Hunt 2009) although more conclusive data are required to confirm this.

4.4.3 Gamma emissions

Gamma emissions decreased with increasing cap depth and ranged from 132 ± 16 to 279 ± 56 nSv/hr (mean ± standard deviation) (Table 4.4) (Figure 4.8). At the cap surface (0 m) mean gamma emissions were significantly higher on 0 cm caps than on 8, 15, 30, 46 and 91 cm caps. The 8 cm cap had significantly higher

emissions than 46 and 91 cm caps. At 1 m above the cap surface mean emissions were significantly higher on bare PG than on 8, 15, 30, 46 and 91 cm caps. The 8 cm cap had significantly higher emissions than 30, 46 and 91 cm caps. There was no significant difference in gamma emissions at the cap surface and 1 m above. Background gamma radiation for the area was 89 ± 16 nSv/hr (mean (consistent) ± standard deviation). Average gamma radiation for the Edmonton region was measured by Tracy et al. (1996) at 84 nSv/hr, slightly higher than the Canadian nationwide average of 76 nSv/hr.

While mean gamma emissions on all caps exceeded background concentrations for Fort Saskatchewan and Edmonton areas, values did not exceed 320 nSv/hr (2 to 3 mSv/yr), the approximate amount of radiation humans are exposed to by natural and anthropogenic sources (Canadian Nuclear Association 2007, World Nuclear Association 2002, Health Canada 2000). Natural sources include cosmic radiation, external terrestrial, inhalation (radon) and ingestion while human induced sources include medical imaging, nuclear bomb testing and nuclear power (Canadian Nuclear Association 2007). While background concentrations of human exposure to gamma will be approached more quickly with prolonged exposure to bare PG, the relatively low concentrations present are unlikely to create serious health effects.

4.4.4 Hydrogen fluoride gas emissions

HF emissions were calculated by AMEC as monthly averages for each plot and were highest on 15 cm caps followed by 46, 0, 91, 30 and 8 cm caps (Figure 4.9). Mean emissions ranged from 0.02 ± 0.01 to 0.15 ± 0.12 ppb (mean ± standard deviation). There were no obvious trends and emissions did not differ significantly among cap depths. On bare PG road east of the plots HF emissions were 0.32 ppb and the ambient background concentration of HF measured in Sherwood Park was 0.33 ppb.

CCME (1997) air quality guidelines for HF are 0.61 ppb for a seven day averaging period and Alberta Environment (2006) has criteria of 6 ppb over a one hour averaging period. It is unlikely plot emissions exceeded these guidelines although lack of hourly or daily emissions data cannot confirm this. In Manitoba,

criteria for HF emissions over a 30 day averaging period were 0.44 ppb (Manitoba Conservation 2005). HF emission data from all treatments meet this criterion. In Alberta, mean ambient inorganic fluoride in rural and non industrialized areas typically does not exceed 0.13 ppb and in the vicinity of emission sources levels are generally < 1.09 ppb (Alberta Environment 2006). All emissions were within ambient levels of HF in and out of the vicinity of emissions sources, except the 15 cm cap treatment which slightly exceeded rural levels. Despite lack of replicated background detectors in pail apparatus, the concentrations measured at Sherwood Park and east side of Stack 1 basin were within the range of values measured in the vicinity of emission sources.

While a relationship between HF emissions and cap depth does not exist, all detected concentrations were low and not considered hazardous to human health. On dry and bare PG surfaces HF emissions are created by fugitive PG dust (Wissa 2002). Vehicular activity on bare PG roads on top of the Fort Saskatchewan PG stacks can create dust, especially in dry summer months, and be transported by wind to vegetation and soil. This may explain the higher HF emissions on the road compared to plots. Vegetating bare surfaces including roads on PG stacks may help reduce HF emissions. Higher HF emissions would be expected on an active PG stack such as Agrium Redwater since material is wet and largely unvegetated. HF gas may not have accumulated inside the pail apparatus similar to radon emissions because it originated from PG particles in the air and concentrations are likely to be low on capped plots where PG is covered and on bare plots where a PG crust has formed. In contrast to radioactive materials which continue to decay and release radioactivity, HF gas evolves from dust particles on inactive stacks and is of little concern when capped with a material such as soil.

4.5 Conclusions

- Although radon emissions for site perimeter detectors were well below working limits for radon exposure, further studies are required to confirm whether a trend exists between radon gas emissions and soil cap depth.

- Evaluating the influence of compacted clay versus soil on radon emissions from PG stacks would be useful.
- Gamma radiation emissions decreased with an increase in cap depth. Emissions did not vary with distance from cap surface. Emissions exceeded background concentrations for the Fort Saskatchewan area but were below concentrations considered hazardous to humans.
- A relationship between hydrogen fluoride gas emissions and cap depth did not exist. Concentrations of HF detected on plots were well below ambient concentrations typical in the vicinity of emissions sources. Reducing fugitive PG dust on inactive stacks by capping with soil is effective at limiting hydrogen fluoride gas emissions.

4.6 References

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Figure 4.1. Map showing location of Fort Saskatchewan, Alberta, Canada.

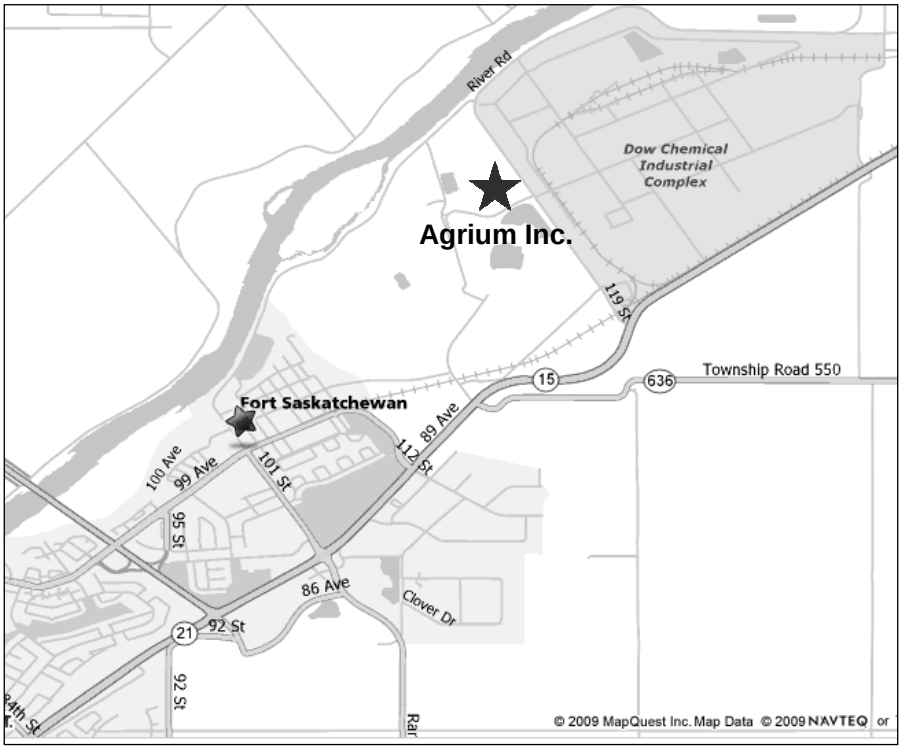

Figure 4.2. Map showing location of Agrium in Fort Saskatchewan, Alberta, Canada.

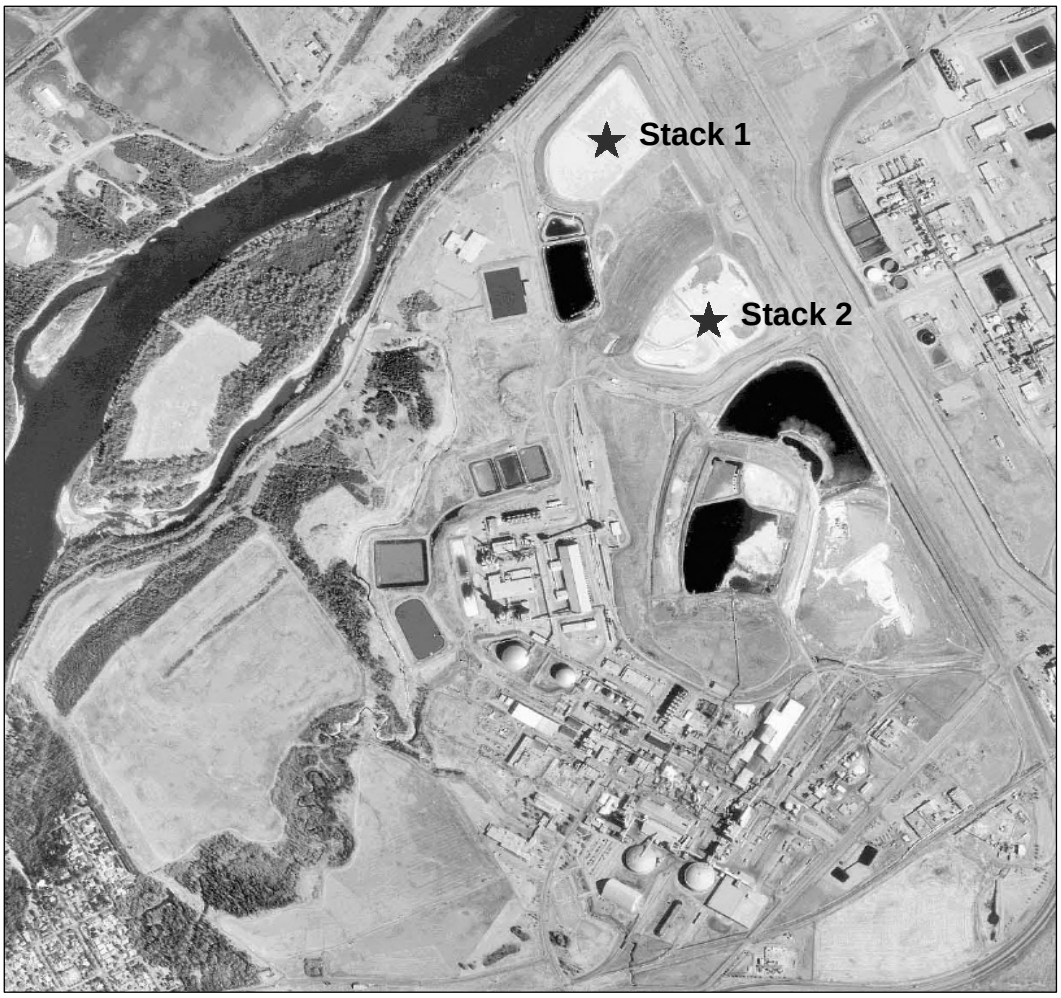

Figure 4.3. Aerial view of Agrium Fort Saskatchewan Nitrogen Operations. North is toward top left corner. North Saskatchewan River is in top left corner.

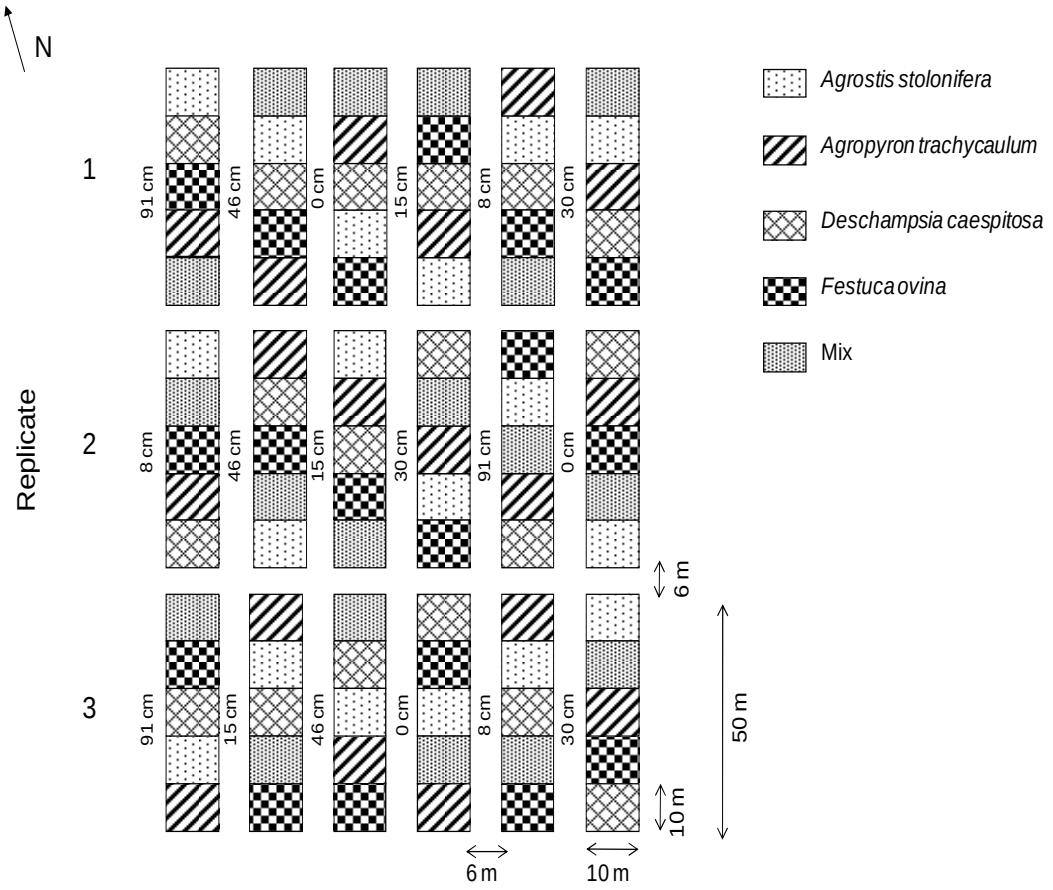

Figure 4.4. Experimental research plots at Agrium Fort Saskatchewan, Alberta.

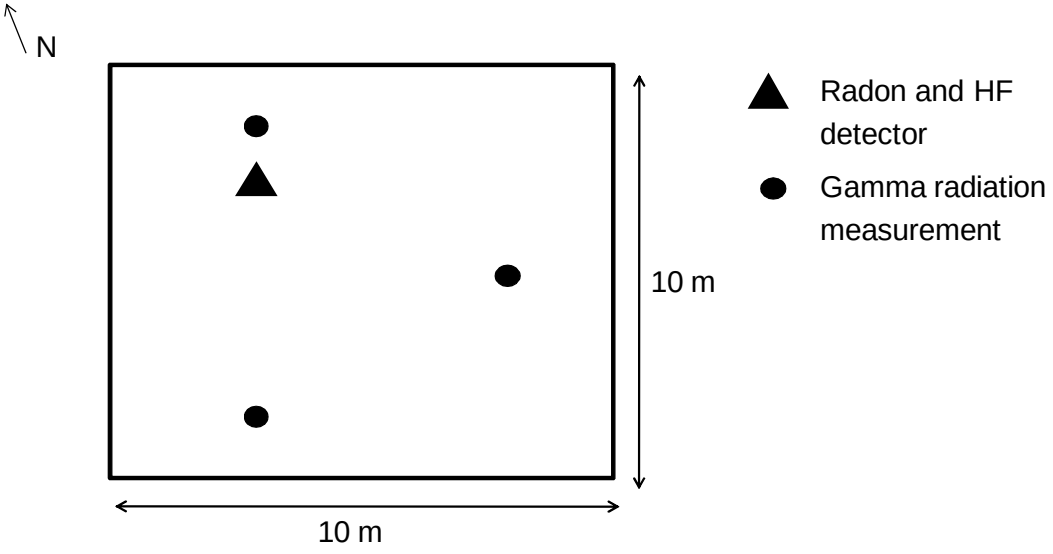

Figure 4.5. Location of radon detectors, HF detectors and gamma radiation readings on *Agropyron trachycaulum* treatments at Agrium Fort Saskatchewan, Alberta.

Figure 4.6. Detected radon emissions around the Agrium Fort Saskatchewan site perimeter.

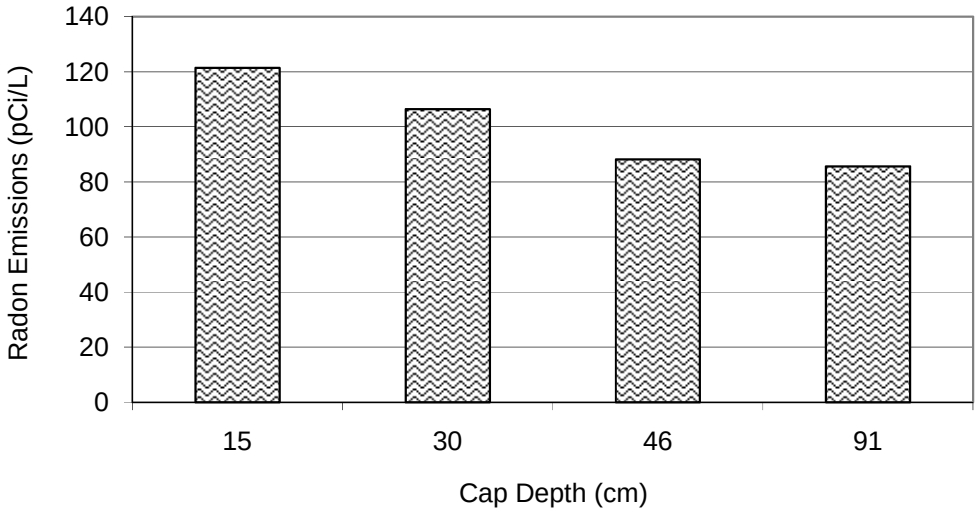

Figure 4.7. Radon gas emissions from 15, 30, 46 and 91 cm cap plots at Agrium Redwater, Alberta. Data are not replicated. Emissions on 0 cm caps exceeded upper detectable limits (140,000 piC/L-day). $r^2 = 0.93$.

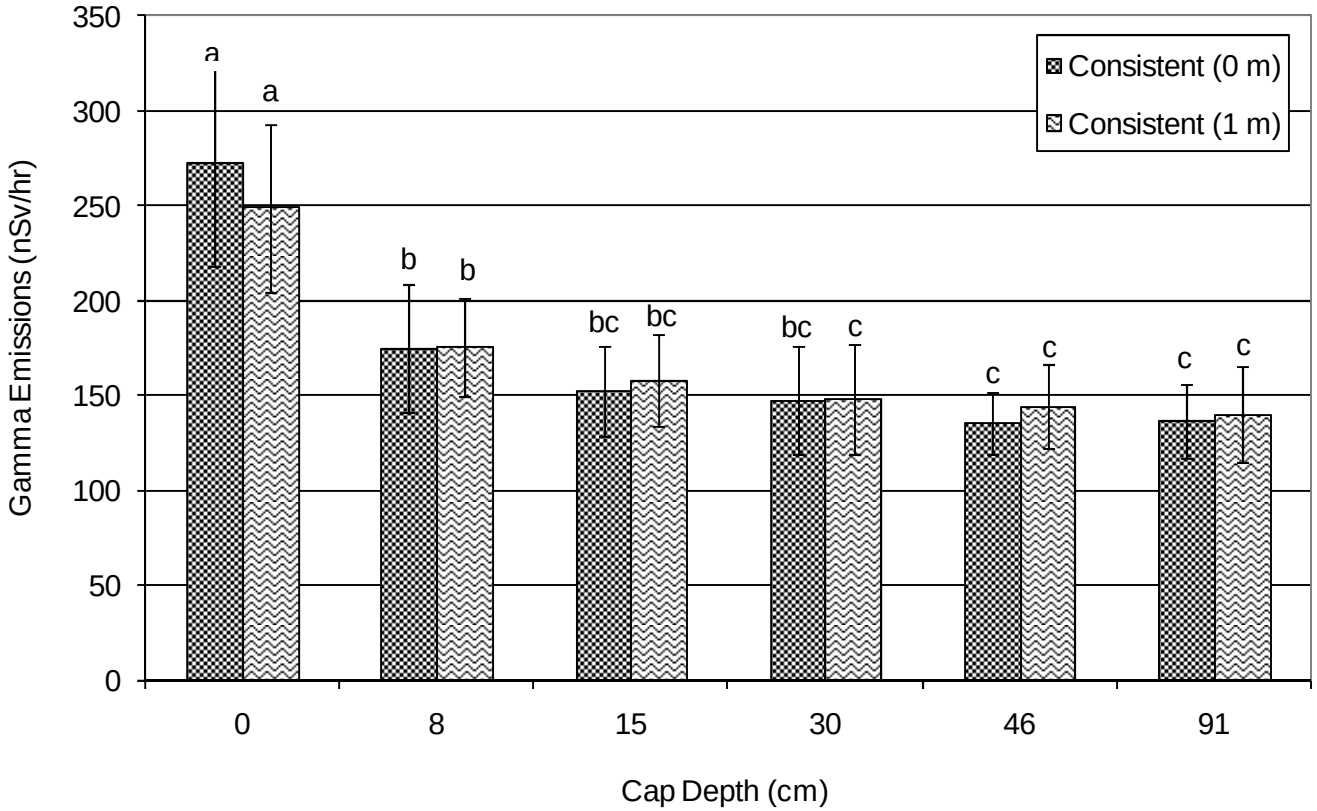

Figure 4.8. Mean (consistent) gamma emissions from capping depth plots at 0 m and 1 m above the ground surface at Agrium Fort Saskatchewan, Alberta. Error bars are standard deviation. Different letters denote statistically significant differences between cap depths at $p < 0.05$.

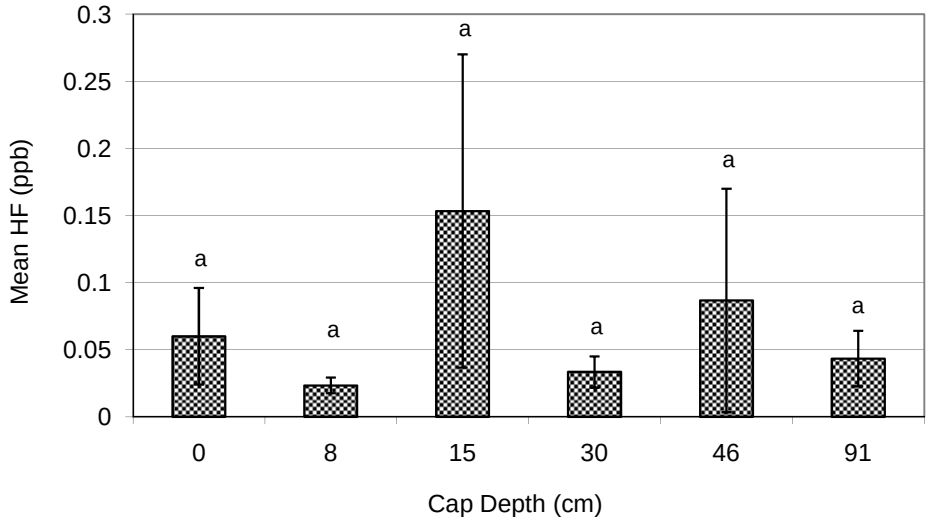

Figure 4.9. Mean hydrogen fluoride emissions from capping depth plots at Agrium Fort Saskatchewan, Alberta. Error bars are standard deviation. Different letters denote statistically significant differences between cap depths at $p < 0.05$.

Table 4.1. Capping depth for research plots at Agrium Fort Saskatchewan, Alberta.

Target Cap Depth (cm)	Cap Depth (cm)
8	11.3 (3.4)
15	19.3 (3.3)
30	28.4 (5.5)
46	46.7 (8.9)
91	96.9 (8.7)

Data are means with standard deviations in brackets.
n = 27.

Table 4.2. Capping soil properties for experimental research plots at Agrium Fort Saskatchewan, Alberta.

	Capping Depth (cm)				
	8	15	30	46	91
Cation Exchange Capacity (meq/100 g)	17.8 (2.2)	20.5 (4.0)	19.7 (3.4)	16.0 (0.1)	16.6 (1.5)
Electrical Conductivity (dS/m)	2.8 (0.4)	1.2 (0.8)	2.4 (0.5)	2.6 (0.1)	2.5 (0.1)
Saturation (%)	33.7 (1.5)	38.3 (4.5)	37.0 (1.0)	32.7 (0.6)	34.0 (1.0)
pH	6.3 (1.3)	7.1 (0.8)	6.7 (0.8)	6.1 (0.6)	6.8 (0.8)
Sand (%)	79.00 (1.00)	80.67 (0.58)	81.00 (1.00)	81.67 (2.52)	80.67 (2.31)
Silt (%)	9.33 (1.15)	9.67 (0.58)	9.33 (1.15)	9.00 (1.73)	7.00 (2.65)
Clay (%)	11.67 (0.58)	9.67 (0.58)	10.00 (1.00)	9.67 (0.58)	12.00 (2.65)
Texture	SL	SL/LS	LS/SL	SL/LS	SL/LS
Available Nitrate - N (mg/kg)	23.5 (17.8)	9.5 (4.2)	10.5 (3.4)	5.7 (3.7)	3.97 (1.7)
Available Phosphate - P (mg/kg)	55.0 (28.2)	22.0 (11.1)	30.7 (9.1)	31.3 (6.5)	18.0 (10.4)
Available Potassium (mg/kg)	63.3 (14.2)	83.3 (52.2)	106.3 (16.3)	83.0 (45.9)	54.0 (19.1)
Available Sulphate - S (mg/kg)	802.3 (55.7)	63.0 (56.4)	273.0 (184.7)	710.0 (234.2)	384.7 (238.2)
Sodium (Na) (meq/100 g)	0.4 (0.2)	*	*	0.3 (0.1)	0.3 (0.1)
Potassium (K) (meq/100 g)	*	0.6 (0.2)	0.6 (0.1)	0.3 (0.1)	0.5 (0.1)
Calcium (Ca) (meq/100 g)	19.1 (6.5)	19.1 (4.6)	21.2 (5.9)	15.6 (2.5)	20.3 (5.1)
Magnesium (Mg) (meq/100 g)	1.2 (0.2)	1.4 (0.5)	1.5 (0.1)	1.4 (0.3)	1.4 (0.1)
ESP (%)	2.5 (1.3)	*	*	1.7 (0.7)	1.8 (0.8)
SAR	0.4 (0.2)	*	*	0.3 (0.1)	0.3 (0.1)
Total Organic Carbon (%)	1.9 (0.2)	2.4 (0.6)	2.4 (0.3)	1.7 (0.2)	2.0 (0.2)
Total Carbon by Combustion (%)	2.0 (0.2)	2.4 (0.6)	2.4 (0.3)	1.7 (0.2)	2.0 (0.2)
Available Ammonium - N (mg/kg)	8.4 (8.6)	2.1 (0.3)	2.3 (0.3)	2.5 (0.4)	2.2 (0.3)
Copper (Cu) (mg/kg)	0.4 (0.1)	0.4 (0.1)	0.4 (0.0)	0.4 (0.1)	0.4 (0.1)
Iron (Fe) (mg/kg)	55.7 (30.4)	57.3 (15.5)	58.3 (31.3)	58.3 (15.2)	60.3 (35.0)
Manganese (Mn) (mg/kg)	9.9 (10.7)	4.4 (1.3)	4.9 (1.8)	6.4 (2.4)	4.0 (1.3)
Zinc (Zn) (mg/kg)	3.2 (1.6)	3.8 (2.2)	3.7 (1.4)	2.7 (0.7)	2.8 (1.6)

Data are means with standard deviations in brackets.
n = 3.
*Incomplete data set available for calculation of mean.
SL = sandy loam, LS = loamy sand.
Inorganic carbon and $CaCO_3$ equivalent were not included due to incomplete data set available for calculation of mean.

Table 4.3. Radon emissions for capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Radon Emissions (piC/L-day)		
	Replicate A	Replicate B	Replicate C
0	> UDL	> UDL	> UDL
8	> UDL	> UDL	> UDL
15	> UDL	> UDL	> UDL
30	> UDL	984	> UDL
46	> UDL	> UDL	1107
91	659	583	326

UDL = Upper detectable limit (140,000 piC/L-day).

Table 4.4. Maximum, minimum and consistent gamma emissions (nSv/hr) on capping depth plots at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Position	Maximum	Minimum	Consistent
0	0 m	278.9 (56.0)	269.6 (53.8)	272.9 (54.4)
	1 m	254.5 (45.3)	244.2 (42.7)	248.8 (44.1)
8	0 m	177.8 (33.3)	172.6 (32.8)	174.9 (33.3)
	1 m	179.7 (25.7)	172.2 (25.1)	175.4 (25.8)
15	0 m	155.3 (24.4)	148.8 (24.4)	152.4 (23.8)
	1 m	160.7 (24.3)	155.7 (24.0)	158.0 (24.0)
30	0 m	150.8 (29.0)	145.0 (28.3)	147.6 (28.6)
	1 m	150.5 (29.3)	144.5 (28.8)	147.9 (28.8)
46	0 m	138.4 (17.3)	132.0 (15.8)	135.0 (16.4)
	1 m	147.7 (22.5)	142.1 (22.3)	144.4 (22.4)
91	0 m	138.8 (19.6)	133.0 (19.8)	136.2 (19.5)
	1 m	143.2 (25.6)	137.1 (25.7)	140.2 (25.2)
Background[†]	1 m	93.7 (16.0)	85.8 (17.0)	89.2 (16.0)

Data are means with standard deviations in brackets.
n = 27.
[†]n = 9.
Maximum, minimum and consistent (most common value) readings were recorded during a one minute interval with a digital survey reader.

5.0 EFFECT OF AMENDED PHOSPHOGYPSUM ON VEGETATION ESTABLISHMENT: A GREENHOUSE STUDY

5.1 Introduction

Phosphogypsum (PG) is an acidic by product of phosphoric acid production (Richardson et al. 1995, Rutherford et al. 1994). The fertilizer industry generates approximately five tonnes of PG per tonne of phosphoric acid, the latter being required for phosphorus fertilizer production (Rutherford et al. 1995a, Rutherford et al. 1994, Ferguson 1988). PG is commonly wet stacked on land adjacent to fertilizer production facilities (Luther and Dudas 1993) where they can span hundreds of hectares and tens of meters in height (Rutherford et al. 1995b). The main environmental concerns associated with PG stacks are chemical impurities such as residual acidity, silica, unreacted phosphate rock, radon, uranium and trace elements including fluoride, cadmium, arsenic, lead and silver; their presence and concentration dictated mainly by composition of the source rock (Wissa 2002). The most common PG stack reclamation method is to cap with soil. A cap can prevent wind and water erosion, limit percolation, provide a plant substrate, prevent contaminated water from running off stacks and provide a landscape conducive to the desired end land use (Richardson et al. 1995).

PG alone is not an effective plant growth substrate as it lacks organic matter and many nutrients required by plants, with the exception of calcium and sulphur. If soil is unavailable or available in insufficient quantities required for large scale revegetation projects, locally available sources of organic materials may be used to create a suitable medium. Incorporation of amendments into deficient or unsuitable substrates is common practice in land reclamation to improve water holding capacity and aeration, provide a source of organic matter and reduce surface crusting (Land Resources Network Ltd. 1993), an inherent property of exposed PG. Amendments such as manures, composts and wood wastes can provide large inputs of carbon and nitrogen to deficient soils or substrates.

In 1990 Thorne identified key issues associated with successful reclamation of a PG tailings pond in Calgary, Alberta with a specific focus on the use of

amendments to overcome chemical and physical limitations of PG required for successful revegetation. In greenhouse studies, the addition of soil or lime to PG tailings was effective at overcoming many limitations associated with PG and establishing vegetation. In a field study in Florida, dolomite, composted garbage, sand tailings and overburden were incorporated into the surface of a weathered PG stack and effects on establishment of grasses was investigated (Richardson et al. 1995). Above ground biomass was initially highest on overburden amended plots and lowest on plots with composted garbage, relative to the PG control. Biomass did not differ significantly among treatments two years later but was generally higher on amended plots than on the control, with the exception of overburden plots. Incorporation of amendments into PG using locally available amendments and plant species common to the climatic region may be an effective option for large scale or site specific revegetation of PG stacks.

5.2 Research Objectives and Hypotheses

5.2.1 Research objectives

The objective of this experiment was to evaluate plant establishment, health and vigour using PG mixed with amendments in a greenhouse experiment. Specific objectives were to determine the effect of the following treatments on plant emergence, height, health, stage of physiological development and seed germination. Treatments included a PG control; PG + soil (S); PG + manure (M); PG + wood shavings (WS); PG + soil + manure; and PG + soil + wood shavings.

5.2.2 Research hypotheses

- Emergence and establishment will be highest for treatments with more than one amendment mixed with PG and lowest on the PG treatment.
- Treatments with PG + soil will provide a suitable growth medium, but will not be as effective as for treatments with more than one amendment.
- Emergence and growth in the manure treatments may be negatively impacted by the elevated salt content of the amendment.

5.3 Methods and Materials

5.3.1 Experimental design and monitoring

5.3.1.1 Pot experiment

The experiment was established in winter 2008 in a greenhouse at the University of Alberta and ran for 13 weeks. PG, soil, manure and wood shavings were mixed by hand in equal volumes depending on treatment to fill 15 cm round plastic pots. PG and sandy loam soil were obtained from Agrium Fort Saskatchewan. Soil was collected from random locations on the surface of a soil stockpile. Manure compost and wood shavings were obtained from the University of Alberta research farm and selected for their high nitrogen and carbon contents, respectively. To determine the effect of PG amendments on plant growth and survival, three categories of plants were chosen; forb, *Gaillardia aristata* Pursch (brown eyed susan), cereal crop, *Hordeum vulgare* L. (barley) and grass, *Koeleria macrantha* (Ledeb.) Schult. (june grass). Each of the six randomized treatments were replicated four times, for a total of 72 pots.

Pots were saturated with distilled water one day in advance of seeding. *Gaillardia aristata* seeds were placed on the surface and lightly sprinkled with substrate; *Hordeum vulgare* was placed in rows made with a fork in the substrate. *Koeleria macrantha* seeds were pressed gently into the substrate to a depth of approximately 0.6 cm. Each pot was seeded with 20 seeds of a single species then watered lightly. Greenhouse temperature was maintained at 21 ℃ with a photoperiod of 16 hours daylight and 8 hours darkness. Pots were randomized one week after seeding and then once every two weeks.

Pots were watered daily for the first three weeks then as required to keep the substrates moist. The number of plants present in each pot was recorded weekly following seeding. Plant height and health were measured at the midpoint and end of the experiment. Plant height (cm) was measured with a ruler from the substrate base to the top of the stretched out stem on tallest, shortest and average height plants, if available. Species health was evaluated using a 3 point scale. A value of 1 was assigned to necrotic plants (< 25 % live material), 2

indicated the plant was exhibiting some unhealthy symptoms (chlorosis or wilting) (25 to 75 % live material) and 3 indicated a healthy plant (> 75 % live material). Each pot was assigned a plant heath index value representative of all plants in the pot. Percent dead material on *Hordeum vulgare* plants was estimated at the end of the experiment and each tiller of each plant assigned a stage of physiological development based on Zadoks growth stages (Zadoks et al. 1974).

5.3.1.2 Petri dish experiment

Using the same treatments as in the pot experiment, materials were mixed in equal proportions to cover the bottom of petri dishes and replicated three times. Ten seeds per dish of *Hordeum vulgare* and *Koeleria macrantha* were used for the petri dish experiment in March 2008 and it was repeated in June 2008 using *Agropyron trachycaulum* (Link) Malte ex H. F. Lewis (slender wheatgrass) and *Koeleria macrantha* seeds. Dishes were kept in the greenhouse and moistened with distilled water as required to prevent the substrate from drying out. The number of seeds exhibiting radicle development were recorded daily and removed until germination ceased after approximately 4 weeks.

5.3.2 Germination tests

Germination tests were conducted for *Hordeum vulgare* prior to experiment initiation. One hundred seeds were used; ten per petri dish for a total of ten dishes. Seeds were placed on paper towel moistened with distilled water in a petri dish and the lid replaced. Dishes were placed on a counter in front of a west facing window at room temperature until most seeds germinated, approximately one week. Distilled water was added as required to prevent paper towels from drying out. Seeds exhibiting radicle development were counted and recorded daily and removed. The number of seeds which germinated was converted to a percentage. *Gaillardia aristata* and *Koeleria macrantha* had known germination rates of 70 % (Bashforth 2007) and 67 % (Naeth Seed Inventory 2007), respectively. Germination tests were conducted for *Koeleria macrantha* seeds and repeated for *Hordeum vulgare* prior to initiating the petri dish experiment in March following the protocol outlined above. *Agropyron trachycaulum* had a known germination of 36 % (Naeth Seed Inventory 2007) (Table 5.1).

5.3.3 Characterization of PG and amendments

Electrical conductivity (EC) (dS/m) and pH for phosphogypsum, wood shavings and manure were obtained from various sources (Desserud 2009, Hao et al. 2005, Agrium Inc. 2004, Ye et al. 2000). Soil was sent to ALS Laboratory in Edmonton to be analyzed for pH in a 1:2 water extract (Carter and Gregorich 2008) and EC by saturated paste (Carter 1993).

5.3.4 Statistical analyses

Data were compiled in Microsoft Excel and means and standard deviations calculated. To determine whether the number of plants present at week 12 for each species differed among treatments, one way analyses of variance (ANOVA) were conducted in SigmaPlot 11.0 at the 5 % level of significance. *Hordeum vulgare* height, stage of physiological development and percent germination were similarly tested for treatment differences. If data failed to pass the tests for normality or homogeneity of variance, a Kruskal-Wallis one way ANOVA on ranks was performed. Tukey's multiple comparison test or Dunn's method were used to detect which means differed from one another.

5.4 Results and Discussion

5.4.1 Characterization of PG and amendments

Phosphogypsum EC and pH were relatively high and low, respectively, typical of the material (Hao et al. 2005) (Table 5.2). Soil pH was approximately neutral and EC relatively low. The manure had a relatively high EC and slightly alkaline pH (Ye et al. 2000). Data for pine sawdust were used to approximate the wood shavings used in the experiment (Desserud 2009). EC was relatively low and pH was slightly alkaline. While it is recognized that values for pH and EC of the manure and wood shavings were obtained from other sources, they are considered general approximations for materials used in the experiment. Values cannot be directly compared since they were analyzed using different extract ratios but are considered general approximations.

5.4.2 Vegetation response to amendments

5.4.2.1 General plant response

Species generally responded positively to treatments containing wood shavings in the pot experiment (Tables 5.3, 5.4, 5.5). Relative to *Hordeum vulgare*, relatively few *Gaillardia aristata* and *Koeleria macrantha* plants were present regardless of treatment with the exception of the PG + WS and PG + S + WS treatments. In the petri dish experiment mean germination of all species was highest for treatments containing soil and lowest for unamended PG, although germination did not differ significantly among treatment (Table 5.6). PG amended with soil may provide a suitable growth medium for initial seedling germination while incorporation of wood shavings into a substrate may provide aeration, a carbon source and create surface microsites for establishment.

5.4.2.2 Individual species responses

Hordeum vulgare performed as expected, establishing quickly and vigourously in pots. Emergence was significantly higher on PG + WS than on PG + S and PG at conclusion of the experiment. Emergence on PG + S + WS was significantly higher than on PG (Table 5.3). Emergence at week 13 was the same for PG + WS and PG + S + WS. Number of plants per treatment at the end of the experiment ranged from 0.25 (0.50) to 8.75 (1.71) (standard deviation). The low plant number relative to seed number may be partly due to seed incorporation too deep in pots after watering. In several pots seeds were observed as having germinated at depth but died from insufficient energy to reach the surface.

Hordeum vulgare plant height measured at the halfway point (week 7) were significantly greater on PG + S + WS than on PG + S treatments (Table 5.7). Heights at the end of the experiment did not differ significantly among treatment and were generally between 70 and 76 cm with tallest plants on the PG + S + WS treatment. Plants were healthy at the halfway point with the exception of those on PG + S. At the conclusion of the experiment plants in most treatments were exhibiting signs of necrosis. The high above and below ground biomass production may have depleted available substrate nutrients and caused roots to

become bound in pots, leading to necrosis of above ground material. Growth stages for *Hordeum vulgare* plants did not differ significantly among treatments and were between stages 4 (booting) and 5 (heading) (Zadoks et al. 1974) (Table 5.8). All seed heads appeared healthy and plump. Necrotic above ground biomass varied with treatment but necrosis was generally exhibited on lower portions of plants. Germination of *Hordeum vulgare* seeds in the petri dish experiment was significantly higher for PG + S + M and PG + S treatments than PG alone (Table 5.6). Germination was highest on treatments containing soil. Generally, *Hordeum vulgare* responded well when soil and wood shavings were incorporated. Wood shavings likely provided aeration to the substrate and increased the C:N ratio. The unintentional concentration of wood shavings on the pot surface likely provided microsites, promoting seedling establishment.

Gaillardia aristata performed poorly on all treatments and number of plants per pot did not exceed 5 during the experiment (Table 5.4). Emergence was most consistent on PG + S + WS and PG + WS treatments. Insufficient plants were available for height measurements and health classification (Table 5.9). Germination and emergence may have been affected by elevated salt concentrations in manure. *Gaillardia's* slow growing nature and competition from unseeded species (from seed bank) may have contributed to low emergence.

Koeleria macrantha performed similarly to *Gaillardia aristata.* Emergence was highest on PG + WS and PG + S + WS but did not differ significantly (Table 5.5). Plant height was 9.42 (standard deviation 3.16) cm for PG + WS and plants were healthy (Table 5.10). Germination and emergence in pots may have been reduced by elevated salt concentrations in manure. Germination was highest for PG + S + M treatments and differed significantly from PG alone, PG + S and PG + WS treatments in March 2008 (Table 5.6). PG + S + WS had significantly higher germination than PG alone and PG + M treatments. PG + S + M and PG + S + WS treatments did not differ significantly. In June 2008, germination was highest for PG + S + M but did not differ significantly with treatment.

Percent germination of *Agropyron trachycaulum* was highest on PG + S + WS treatments in the petri dish experiment but did not differ significantly among treatments (Table 5.6).

5.4.3 Practical applications

Results indicate amendments incorporated into PG may be effective for revegetation of PG stacks, either large scale or for site specific locations, such as steep slopes. Vegetation could be anchored directly into PG providing erosion control while maintaining cover. By ameliorating PG with materials such as manure compost, wood shavings, soil or combinations of amendments, the inhospitable chemical and physical properties of PG can potentially be overcome, as found in studies by Thorne (1990) and Richardson et al. (1995). Use of locally available organic materials incorporated into PG may provide a suitable plant growth medium while being cost effective. Further research to determine an appropriate depth of amendment incorporation into PG on a field scale, the effect of amendments on additional grass species and on amendment proportions would be useful to increase the limited knowledge base of PG stack reclamation.

5.5 Conclusions

- Generally, species response was highest on treatments where soil and wood shavings were incorporated with PG.
- Plant emergence and establishment on treatments containing manure may have been reduced by the elevated salt content of the manure and PG.
- The bulky nature of wood shavings was effective at aerating the PG and soil mix and promoting root development.
- Wood shavings may have provided a source of carbon to establishing plants and concentration of shavings on the pot surface likely created microsites for plant establishment.
- Incorporation of amendments into PG can be effective at establishing vegetation, provided the chemical properties of selected materials are compatible with those of PG.

5.6 References

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Table 5.1. Germination of species in greenhouse pot and petri dish experiments.

Species	Pot (%)	Petri Dish (%)
Agropyron trachycaulum	-	36
Hordeum vulgare	92	97
Gaillardia aristata	70	-
Koeleria macrantha	67	83

Table 5.2. Electrical conductivity and pH for phosphogypsum (PG), soil, manure and wood shavings used in greenhouse experiments.

Material	EC (dS/m)	pH
PG[†]	5.8 (0.2)	5.1 (0.8)
Soil[‡]	2.3 (0.7)	6.6 (0.8)
Manure[ŧ]	7.6 (0.0)	8.2 (0.0)
Wood Shavings[t]	0.5 (0.0)	8.0 (0.0)

Data are mean with standard deviation in brackets.
n = 3.
[†]Determined in 1:10 solution, PG from Agrium Fort Saskatchewan (Agrium Inc. 2004). EC data from Hao et al. 2005.
[‡]Determined in 1:2 solution and saturation paste extract, respectively.
[ŧ]Determined in 1:5 solution (Ye et al. 2000).
[t]Data are for sawdust (Desserud 2009).

Table 5.3. Number of *Hordeum vulgare* plants present weekly during the greenhouse experiment.

Week	Treatment					
	PG	PG + S	PG + M	PG + WS	PG + S + M	PG + S + WS
1	-	-	-	0.2 (0.5)	-	2.5 (2.1)
2	-	2.5 (2.1)	2.2 (3.3)	9.0 (1.2)	6.8 (4.0)	12.8 (1.7)
3	0.8 (1.0)	3.0 (2.2)	2.8 (2.2)	11.2 (1.0)	7.0 (3.9)	10.2 (1.0)
4	0.2 (0.5)	3.0 (2.2)	2.8 (2.2)	12.0 (0.8)	7.8 (4.6)	10.5 (1.3)
5	0.5 (1.0)	3.0 (2.2)	2.8 (2.2)	11.2 (0.5)	7.8 (4.6)	10.2 (1.3)
6	-	1.0 (0.8)	2.8 (2.2)	11.0 (0.8)	7.2 (4.6)	10.0 (0.8)
7	0.2 (0.5)	0.5 (1.0)	2.5 (2.4)	10.2 (1.3)	6.2 (3.8)	9.8 (1.3)
8	0.2 (0.5)	0.5 (1.0)	2.2 (1.9)	9.5 (0.6)	5.2 (3.9)	9.5 (1.3)
9	0.2 (0.5)	0.5 (1.0)	2.0 (1.4)	9.5 (1.7)	5.8 (3.6)	9.0 (1.2)
10	0.2 (0.5)	0.5 (1.0)	2.0 (1.4)	9.8 (1.0)	5.5 (3.7)	9.0 (1.8)
11	0.2 (0.5)	0.5 (1.0)	2.0 (1.4)	8.8 (1.3)	5.5 (3.4)	9.0 (2.2)
12	0.2 (0.5)[a]	0.5 (1.0)[ac]	2.0 (1.4)[ab]	8.8 (1.3)[b]	5.2 (3.5)[ab]	8.8 (1.7)[bc]
12 (Dead)	0.2 (0.5)	0.5 (1.0)	-	-	-	-
12 (Unseeded)	0.2 (0.5)	-	0.5 (1.0)	-	0.5 (0.6)	1.5 (1.7)

Data are means with standard deviations in brackets.
n = 4.
-Not present.
PG = phosphogypsum, S = soil, M = manure, WS = wood shavings.
Different letters in columns denote statistically significant differences between treatments at week 12 at $p < 0.05$.
Unseeded = from seed bank.

Table 5.4. Number of *Gaillaria aristata* plants present weekly during the greenhouse experiment.

Week	Treatment					
	PG	PG + S	PG + M	PG + WS	PG + S + M	PG + S + WS
1	-	0.5 (0.6)	-	-	0.2 (0.5)	1.0 (1.4)
2	-	-	-	0.8 (0.5)	1.2 (1.3)	4.8 (4.9)
3	-	0.2 (0.5)	-	2.0 (0.8)	-	3.5 (3.1)
4	-	0.2 (0.5)	-	2.0 (1.2)	-	3.5 (2.9)
5	-	-	-	1.2 (0.5)	-	1.8 (2.9)
6	-	-	-	1.0 (1.2)	-	0.2 (0.5)
7	-	-	-	-	-	-
8	-	-	-	-	-	0.5 (0.6)
9	-	-	-	0.2 (0.5)	-	0.5 (0.6)
10	-	-	-	0.2 (0.5)	-	0.5 (0.6)
11	-	-	-	-	-	0.5 (0.6)
12	-	-	-	-	-	0.5 (0.6)
12 (Dead)	-	-	-	-	-	-
12 (Unseeded)	-	0.2 (0.5)	1.0 (0.8)	1.8 (2.1)	2.0 (1.4)	2.5 (1.7)

Data are means with standard deviations in brackets.
n = 4.
-Not present.
PG = phosphogypsum, S = soil, M = manure, WS = wood shavings.
Unseeded = from seed bank.

Table 5.5. Number of *Koeleria macrantha* plants present weekly during the greenhouse experiment.

Week	Treatment					
	PG	PG + S	PG + M	PG + WS	PG + S + M	PG + S + WS
1	-	0.2 (0.5)	-	-	-	1.0 (0.8)
2	-	0.5 (1.0)	0.2 (0.5)	2.2 (1.3)	0.5 (1.0)	5.2 (3.0)
3	-	-	-	3.0 (1.6)	0.2 (0.5)	4.0 (4.3)
4	-	-	-	1.0 (0.8)	-	4.0 (4.3)
5	-	-	-	1.5 (0.6)	-	3.5 (4.4)
6	-	-	-	0.5 (0.6)	-	1.5 (3.0)
7	-	-	-	0.8 (0.5)	-	1.2 (2.5)
8	-	-	-	0.8 (0.5)	-	1.2 (2.5)
9	-	-	-	0.8 (0.5)	-	1.0 (2.0)
10	-	-	-	0.8 (0.5)	-	1.2 (2.5)
11	-	-	0.2 (0.5)	0.8 (0.5)	-	1.0 (2.0)
12	-	0.2 (0.5)[a]	0.2 (0.5)[a]	1.0 (0.8)[a]	-	0.8 (1.5)[a]
12 (Dead)	-	-	-	-	-	-
12 (Unseeded)	-	-	0.2 (0.5)	1.5 (0.6)	0.8 (1.0)	1.5 (1.3)

Data are means with standard deviations in brackets.
n = 4.
-Not present.
PG = phosphogypsum, S = soil, M = manure, WS = wood shavings.
Different letters in columns denote statistically significant differences between treatments at week 12 at $p < 0.05$.
Unseeded = from seed bank.

Table 5.6. Germination of *Hordeum vulgare, Koeleria macrantha* and *Agropyron trachycaulum* seeds in petri dish experiments.

Treatment	March 2008		June 2008		Mean
	Hordeum vulgare	*Koeleria macrantha*	*Agropyron trachycaulum*	*Koeleria macrantha*	
PG	26.7 (2.5)[a]	0.0 (0.0)[b]	0.0 (0.0)[a]	3.3 (0.6)[a]	7.5 (12.9)[a]
PG + S	93.3 (1.2)[b]	10.0 (1.7)[bc]	53.3 (1.5)[a]	13.3 (1.5)[a]	42.5 (39.2)[a]
PG + M	70.0 (2.6)[ab]	0.0 (0.0)[b]	16.7 (2.9)[a]	6.7 (0.6)[a]	23.3 (31.8)[a]
PG + WS	73.3 (1.5)[ab]	6.7 (1.2)[bc]	43.3 (1.5)[a]	16.7 (1.5)[a]	35.0 (29.9)[a]
PG + S + M	83.3 (2.1)[b]	50.0 (1.0)[a]	43.3 (2.3)[a]	43.3 (1.2)[a]	55.0 (19.1)[a]
PG + S + WS	76.7 (1.2)[ab]	36.7 (2.1)[ac]	60.0 (1.7)[a]	20.0 (2.6)[a]	48.3 (25.0)[a]

Data are means with standard deviations in brackets.
n = 3.
PG = phosphogypsum, S = soil, M = manure, WS = wood shavings.
Different letters in columns denote statistically significant differences between treatments at $p < 0.05$.

Table 5.7. *Hordeum vulgare* plant height and health during the greenhouse experiment.

Treatment	Height (cm)		Health (1 to 3)	
	Week 7	Week 13	Week 7	Week 13
PG	-	*	-	*
PG + S	11.0 (11.3)[a]	*	1	*
PG + M	22.1 (15.7)[ab]	70.1 (9.3)[a]	3	3
PG + WS	35.2 (3.6)[ab]	75.5 (2.1)[a]	3	2
PG + S + M	28.5 (3.8)[ab]	72.9 (10.0)[a]	3	2
PG + S + WS	38.5 (3.4)[b]	75.8 (1.6)[a]	3	2

Data are means with standard deviations in brackets.
n ≥ 3.
-Not present.
*Insufficient data available for calculation of mean.
PG = phosphogypsum, S = soil, M = manure, WS = wood shavings.
Different letters in columns denote statistically significant differences between treatments at $p < 0.05$.

Table 5.8. *Hordeum vulgare* stage of physiological development and percent dead above ground biomass at the end of the greenhouse experiment.

Treatment	Zadoks Growth Stage[†]	Above Ground Biomass	
		Dead (%)[‡]	Location
PG	*	*	*
PG + S	*	*	*
PG + M	41.2 (3.6)[a]	1.8 (2.4)	100 %
PG + WS	50.4 (2.5)[a]	33.8 (8.5)	lower 62 %
PG + S + M	45.0 (2.6)[a]	10.0 (10.8)	lower 42 %
PG + S + WS	51.1 (5.9)[a]	40.0 (8.2)	lower 69 %

Data are means with standard deviations in brackets.
[†]n ≥ 3.
[‡]n = 4.
*Insufficient data available for calculation of mean.
PG = phosphogypsum, S = soil, M = manure, WS = wood shavings.
Different letters in columns denote statistically significant differences between treatments at $p < 0.05$.

Table 5.9. *Gaillardia aristata* plant height and health during the greenhouse experiment.

Treatment	Height (cm)		Health (1 to 3)	
	Week 7	Week 13	Week 7	Week 13
PG	-	-	-	-
PG + S	-	-	-	-
PG + M	-	-	-	-
PG + WS	*	-	*	-
PG + S + M	-	-	-	-
PG + S + WS	*	*	*	*

Data are means with standard deviations in brackets.
n ≥ 3.
-Not present.
*Insufficient data available for calculation of mean.
PG = phosphogypsum, S = soil, M = manure, WS = wood shavings.

Table 5.10. *Koeleria macrantha* plant height and health during the greenhouse experiment.

Treatment	Height (cm)		Health (1 to 3)	
	Week 7	Week 13	Week 7	Week 13
PG	-	-	-	-
PG + S	-	*	-	*
PG + M	-	*	-	*
PG + WS	*	9.4 (3.2)	*	3
PG + S + M	-	-	-	-
PG + S + WS	*	*	*	*

Data are means with standard deviations in brackets.
n ≥ 3.
-Not present.
*Insufficient data available for calculation of mean.
PG = phosphogypsum, S = soil, M = manure, WS = wood shavings.

6.0 SYNTHESIS AND FUTURE RESEARCH

6.1 Summary

Reclamation of large scale waste piles, such as phosphogypsum, is commonly achieved by soil capping. Caps can provide a suitable plant growth medium, act as a barrier between waste and the surrounding environment and provide a landscape conducive to the desired end land use. It was hypothesized that the 1 m soil cap required by Alberta Environment (2008) for PG stack reclamation could be reduced.

This research evaluated the effect of soil cap depth on vegetation establishment, health and vigour, radon gas, gamma radiation, hydrogen fluoride emissions and water quality and quantity in PG. Eighteen experimental research plots with varying capping depths in a complete randomized design were used to evaluate these parameters on an inactive PG stack at Agrium Fort Saskatchewan, Alberta.

Vegetation cover, height, health, physiological development stage and biovolume were assessed. Vegetation treatments performed as expected but establishment was hindered by the presence of unseeded species from the soil seed bank at the early stage of plant community development. Most species responded well to soil depths between 8 and 15 cm with no adverse effects apparent from rooting into PG. Seeding to a mix of grass and legume species is recommended for initiating a trajectory toward a desirable and self sustaining plant community.

Water movement at the soil / PG interface was not greatly affected by magnitude of storm event or antecedent precipitation index. Changes in water content below the interface were small during storm events. Subsurface water quality (at 30 cm) was not influenced by cap depth ≤ 30 cm. Little water was collected in lysimeters at 30 cm for caps > 30 cm. Almost all measured parameters were in exceedance of water quality of the North Saskatchewan River in the vicinity of Agrium Fort Saskatchewan and many parameters exceeded provincial and federal guidelines.

Radon gas, gamma radiation and hydrogen fluoride emissions, inherent to PG, were measured to determine if depth of soil influenced concentration. A trend

between soil depth and radon concentration may be present; additional research is required to investigate this. Gamma radiation decreased with an increase in soil depth. Emissions exceeded background levels for the Fort Saskatchewan area but were not present at levels considered hazardous to humans. Hydrogen fluoride emissions, originating primarily from PG dust on inactive stacks (Wissa 2002), were not influenced by soil cap depth. Detected HF emissions did not exceed levels generally found in the vicinity of emissions sources.

In a greenhouse study the effect of amendment and PG mixtures on plant establishment, health and vigour were evaluated. Wood shaving treatments had the best plant response, likely due to the bulky nature of the shavings and its ability to provide aeration and a carbon source to the substrate. Results indicated amendments directly incorporated into PG may be an effective technique for large scale or site specific revegetation where soil is unavailable or limited.

6.2 Practical Applications

Results from this study indicate that shallow caps may be as effective as thick caps for reclamation of PG stacks in Alberta. Shallow depths, as low as 8 cm, can support a plant community and minimize radiation emissions and percolation of rain water into phosphogypsum, critical to the long term stability and aesthetics of PG stacks. Implementation of these findings into a reclamation program in Alberta will be important for designing a suitable and cost effective cover system.

6.3 Future Research

All interpretations and conclusions from this research have been based on one year of data. As the PG stack cover system continues to develop, changes may occur, such as plant rooting into PG. These changes may bring about different responses in the variables measured. For example, rooting into the PG may cause channels for more water movement; denser plant cover may affect radon gas emissions. Thus longer term monitoring is needed before making more firm conclusions.

This research has provided important information on the influence of soil cap depth on vegetation establishment, radioactivity and gaseous emissions and water quality and quantity in PG, building upon the research of Hallin (2009). The combined work has addressed broad aspects of PG stack reclamation necessary for closure. To build on these findings and provide a more comprehensive knowledge base for PG stack reclamation in Alberta, additional studies are required. Specific areas for further studies may include the following.

- Influence of soil cap depth on radon gas emissions.
- Effect of a compacted clay layer on radon gas emissions.
- Effect of PG dust on hydrogen fluoride emissions for partially reclaimed stacks.
- Characterization of micro and mesofauna present on reclaimed PG stacks as indicators of ecological success.
- Detailed investigation of hydrologic balance for various soil cap depths. Installation of reflectometry probes at the surface and above the soil / PG interface would provide important information on the water balance.
- Effect of high magnitude and extreme storm events on water movement at the soil / PG interface.
- Amount of evapotranspiration occurring and its influence on water balance.
- Effect of organic amendments incorporated into a reclamation cap on vegetation development, hydrology and radiation.
- Cover system development for PG side slopes with varied slope and aspect.
- The effect of taprooting species for PG stack reclamation.

6.4 References

Alberta Environment. 2008. Construction, operation and reclamation of the Redwater fertilizer manufacturing plant. Approval No. 210-02-00. Edmonton, AB. 42 pp.

Hallin, I.L. 2009. Evaluation of a substrate and vegetation cover system for reclaimed phosphogypsum stacks at Fort Saskatchewan, Alberta. M.Sc. Thesis. University of Alberta, Department of Renewable Resources. Edmonton, AB. 107 pp.

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APPENDIX

Table A1. Revegetation species selection matrix for Agrium Fort Saskatchewan, Alberta.

Recommended Species	Origin	Germination	Establishment	Erosion Control	Persistence	Nutrient Requirements	Acidic Soils	Moisture	Palatability
Agrostis stolonifera (Redtop)	I	M-H	H	M	H	L	H	M-W	H
Agropyron trachycaulum (Slender wheatgrass)	N	H	H	H	M	L-M	M	D-M	M
Deschampsia caespitosa (Tufted hairgrass)	N	H	H	H	M	L-M	H	D-M	M
Sheep fescue (*Festuca ovina*)	I/N	H	M-H	H	H	L	H	D-M	H

I = Introduced, N = Native, M = Moderate, H = High, L = Low, W =Well and D = Dry.

Table A2. Plant species on research plots at Agrium Fort Saskatchewan, Alberta.

Scientific Name	Common Name
Agropyron repens (L.) Beauv.	Quackgrass
Agropyron trachycaulum (Link) Malte ex. H.F. Lewis	Slender wheatgrass
Agrostis scabra Willd.	Rough bentgrass
Agrostis stolonifera L.	Redtop
Bromus inermis Leyss.	Smooth brome
Deschampsia caespitosa (L.) P. Beauv.	Tufted hairgrass
Festuca ovina L.	Sheep fescue
Poa palustris L.	Fowl bluegrass
Poa pratensis L.	Kentucky bluegrass
Puccinellia nuttalliana (Schult.) Hitchc.	Nuttal's alkali grass
Achillea millefolium L.	Yarrow
Amaranthus retroflexus L.	Redroot pigweed
Artemisia absinthium L.	Absinthe
Capsella bursa-pastoris (L.) Medic.	Shepard's purse
Chenopodium album L.	Lamb's quarters
Cirsium arvense (L.) Scop.	Canada thistle
Crepis tectorum L.	Narrow leaved hawk's beard
Descurainia sophia (L.) Webb.	Flixweed
Dracocephalum parviflorum Nutt.	American dragonhead
Epilobium angustifolium L.	Fireweed
Erucastrum gallicum (Willd.) Schulz	Dog mustard
Fagopyrum tataricum (L.) Gaertn.	Tartary buckwheat
Hordeum jubatum L.	Foxtail barley
Kochia scoparia (L.) Schrad.	Kochia
Lepidium densiflorum Schrad.	Common peppergrass
Linaria vulgaris Hill.	Toadflax
Lotus corniculatus L.	Birdsfoot trefoil
Medicago sativa L.	Alfalfa
Melilotus alba Desr.	White sweet clover
Plantago spp.	Plaintain
Polygonum arenastrum Jord. ex Bor.	Common knotweed
Polygonum aviculare L.	Prostrate knotweed
Polygonum convolvulus L.	Wild buckwheat
Potentilla norvegica L.	Rough cinquefoil
Setaria viridis (L.) Beauv.	Green foxtail
Silene pratensis (Rafn) Godron & Gren.	White cockle
Sonchus arvensis L.	Perennial sow thistle
Solidago canadensis L.	Canada goldenrod
Taraxacum officinale Weber	Dandelion
Thlapsi arvense L.	Stinkweed
Trifolium hybridum L.	Alsike clover
Urtica dioica L.	Stinging nettle
**Populus tremuloides* Michx.	Trembling aspen

*Found in basin outside plots growing directly in PG.
[1]Unidentified forb was found.

Table A3. Survival of seeded species in July and August 2007 at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	*Agrostis stolonifera*		*Agropyron trachycaulum*		*Deschampsia caespitosa*		*Festuca ovina*		Mix	
	July	August	July	August	July	August	July	August	July	August
0	6 (12)	5 (12)	6 (7)	0 (0)	10 (9)	4 (8)	2 (4)	0 (1)	3 (4)	1 (2)
8	40 (19)	48 (21)	40 (10)	60 (11)	12 (9)	13 (11)	19 (14)	19 (12)	24 (6)	38 (15)
15	52 (12)	48 (18)	46 (8)	61 (13)	19 (14)	8 (8)	33 (12)	26 (10)	27 (11)	35 (10)
30	56 (19)	34 (24)	46 (9)	35 (14)	10 (8)	3 (4)	34 (14)	18 (14)	30 (19)	21 (15)
46	45 (20)	50 (28)	50 (11)	56 (15)	29 (14)	16 (12)	38 (14)	23 (13)	47 (27)	44 (27)
91	56 (17)	37 (24)	50 (14)	44 (23)	50 (19)	25 (16)	53 (11)	24 (13)	42 (17)	29 (14)

Data are means with standard deviations in brackets.
n = 9.

Table A4. Canopy cover of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Treatment	Vegetation Type					
		Agrostis stolonifera	*Agropyron trachycaulum*	*Deschampsia caespitosa*	*Festuca ovina*	*Trifolium hybridum*	Unseeded
0	*Agrostis stolonifera*	0.1 (0.3)	-	-	-	-	7.6 (22.7)
	Agropyron trachycaulum	-	-	-	-	-	-
	Deschampsia caespitosa	-	-	-	-	-	-
	Festuca ovina	-	-	-	-	-	-
	Mix	0.6 (1.7)	-	-	-	-	1.3 (2.4)
8	*Agrostis stolonifera*	16.1 (27.4)	5.2 (14.4)	-	0.0 (0.0)	-	20.7 (18.3)
	Agropyron trachycaulum	-	28.2 (14.7)	-	0.1 (0.3)	-	7.1 (9.1)
	Deschampsia caespitosa	5.7 (7.5)	0.1 (0.5)	2.1 (3.8)	1.6 (5.9)	-	28.4 (24.8)
	Festuca ovina	4.0 (10.6)	0.2 (0.8)	0.1 (0.4)	20.4 (17.9)	-	29.7 (25.0)
	Mix	0.7 (1.6)	16.4 (18.8)	0.0 (0.0)	2.2 (5.5)	0.2 (0.5)	10.0 (5.2)
15	*Agrostis stolonifera*	6.0 (7.2)	-	-	-	-	38.3 (17.9)
	Agropyron trachycaulum	-	37.1 (33.5)	-	-	-	6.8 (7.8)
	Deschampsia caespitosa	2.8 (5.0)	0.7 (2.0)	0.9 (1.8)	0.2 (0.5)	-	49.4 (21.5)
	Festuca ovina	1.3 (2.4)	-	-	20.3 (26.8)	-	33.7 (25.7)
	Mix	0.0 (0.0)	21.1 (23.0)	-	0.7 (1.0)	0.0 (0.0)	14.0 (28.7)
30	*Agrostis stolonifera*	4.2 (5.6)	0.7 (2.0)	-	-	-	38.8 (20.0)
	Agropyron trachycaulum	-	38.2 (29.2)	-	0.2 (0.7)	0.3 (1.0)	9.9 (6.8)
	Deschampsia caespitosa	0.9 (2.7)	-	0.0 (0.0)	0.7 (2.0)	-	36.4 (14.5)
	Festuca ovina	-	0.8 (2.3)	-	9.1 (8.8)	-	43.2 (36.0)
	Mix	1.0 (1.7)	9.8 (6.9)	-	2.0 (2.1)	0.1 (0.3)	14.3 (6.7)
46	*Agrostis stolonifera*	6.9 (5.9)	1.3 (2.7)	-	1.2 (3.0)	-	31.4 (20.5)
	Agropyron trachycaulum	-	21.7 (14.8)	-	-	-	2.9 (3.7)
	Deschampsia caespitosa	1.6 (2.6)	-	13.8 (18.8)	-	-	11.8 (6.4)
	Festuca ovina	0.1 (0.3)	-	-	21.0 (12.1)	-	17.9 (11.4)
	Mix	0.6 (1.3)	13.8 (11.1)	-	1.6 (2.3)	1.7 (3.9)	16.3 (15.6)
91	*Agrostis stolonifera*	8.7 (8.6)	0.7 (1.7)	-	0.6 (1.8)	-	12.2 (8.1)
	Agropyron trachycaulum	-	16.2 (7.8)	-	-	-	4.5 (4.3)
	Deschampsia caespitosa	0.5 (0.8)	0.1 (0.3)	7.7 (13.2)	0.2 (0.7)	-	18.2 (9.1)
	Festuca ovina	0.0 (0.0)	-	-	7.6 (3.9)	-	13.4 (4.6)
	Mix	0.4 (0.6)	7.2 (5.7)	-	0.9 (1.4)	0.4 (0.7)	17.6 (14.2)

Data are means with standard deviations in brackets.
n = 9 for 0, 15, 30, 46, 91 cm, n = 15 for 8 cm.
-Data not available.

Table A5. Biovolume of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Treatment†	Vegetation Type					
		Agrostis stolonifera	*Agropyron trachycaulum*	*Deschampsia caespitosa*	*Festuca ovina*	*Trifolium hybridum*	Unseeded
0	*Agrostis stolonifera*	-	-	-	-	-	*
	Agropyron trachycaulum	-	-	-	-	-	-
	Deschampsia caespitosa	-	-	-	-	-	-
	Festuca ovina	-	-	-	-	-	-
	Mix	*	-	-	-	-	0.1 (0.1)
8	*Agrostis stolonifera*	0.5 (0.5)	*	-	*	-	0.7 (0.5)
	Agropyron trachycaulum	-	1.0 (1.0)	-	-	-	0.3 (0.8)
	Deschampsia caespitosa	0.1 (0.2)	*	0.0 (0.1)	*	-	0.8 (0.8)
	Festuca ovina	*	*	*	0.3 (0.4)	-	1.0 (0.8)
	Mix	*	0.6 (0.5)	T (0.0)	*	*	0.4 (0.4)
15	*Agrostis stolonifera*	0.2 (0.3)	-	-	-	-	1.1 (0.4)
	Agropyron trachycaulum	-	1.1 (0.7)	-	-	-	0.1 (0.2)
	Deschampsia caespitosa	0.1 (0.1)	*	0.0 (0.1)	*	-	1.2 (0.7)
	Festuca ovina	T (0.0)	-	-	0.5 (0.6)	-	1.7 (2.3)
	Mix	*	0.8 (0.4)	-	T (0.0)	T (0.0)	0.3 (0.8)
30	*Agrostis stolonifera*	0.2 (0.2)	*	-	-	-	1.4 (1.1)
	Agropyron trachycaulum	-	0.9 (0.7)	-	*	*	0.2 (0.2)
	Deschampsia caespitosa	*	-	*	*	-	1.0 (0.5)
	Festuca ovina	-	*	-	0.2 (0.2)	-	1.5 (1.4)
	Mix	0.0 (0.1)	0.3 (0.2)	-	0.0 (0.0)	*	0.5 (0.5)
46	*Agrostis stolonifera*	0.2 (0.1)	*	-	*	-	0.8 (0.6)
	Agropyron trachycaulum	-	0.9 (0.3)	-	-	-	0.1 (0.2)
	Deschampsia caespitosa	0.2 (0.3)	-	0.3 (0.4)	-	-	0.6 (0.5)
	Festuca ovina	*	-	-	0.4 (0.2)	-	0.7 (0.4)
	Mix	0.1 (0.2)	0.5 (0.4)	-	0.0 (0.0)	0.1 (0.1)	0.4 (0.3)
91	*Agrostis stolonifera*	0.4 (0.4)	*	-	*	-	0.3 (0.4)
	Agropyron trachycaulum	-	0.7 (0.3)	-	-	-	0.1 (0.1)
	Deschampsia caespitosa	T (0.0)	*	0.1 (0.2)	*	-	0.4 (0.3)
	Festuca ovina	*	-	-	0.2 (0.1)	-	0.5 (0.3)
	Mix	T (0.0)	0.2 (0.1)	-	T (0.0)	T (0.0)	0.4 (0.4)

Data are means with standard deviations in brackets. $3 \leq n \leq 9$.
T = trace (0.0001 L).
–Data not available; *incomplete data set available for calculation of mean.

Table A6. Height of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Treatment	Vegetation Type					
		Agrostis stolonifera	*Agropyron trachycaulum*	*Deschampsia caespitosa*	*Festuca ovina*	*Trifolium. hybridum*	Unseeded
0	*Agrostis stolonifera*	*	-	-	-	-	*
	Agropyron trachycaulum	-	-	-	-	-	-
	Deschampsia caespitosa	-	-	-	-	-	-
	Festuca ovina	-	-	-	-	-	-
	Mix	*	-	-	-	-	28.6 (0.8)
8	*Agrostis stolonifera*	63.6 (26.3)	*	-	*	-	40.1 (18.6)
	Agropyron trachycaulum	-	72.2 (34.0)	-	*	-	31.1 (24.3)
	Deschampsia caespitosa	62.1 (22.3)	*	19.8 (14.6)	*	-	44.0 (30.0)
	Festuca ovina	*	*	*	34.1 (15.0)	-	47.7 (18.7)
	Mix	*	78.6 (27.0)	22.0 (13.2)	*	*	32.5 (15.7)
15	*Agrostis stolonifera*	62.3 (18.1)	-	-	-	-	71.4 (39.3)
	Agropyron trachycaulum	-	79.1 (12.4)	-	-	-	35.3 (18.6)
	Deschampsia caespitosa	63.7 (2.7)	*	44.9 (9.7)	*	-	61.1 (22.4)
	Festuca ovina	55.9 (19.0)	-	-	34.7 (8.3)	-	63.2 (40.9)
	Mix	*	92.5 (16.8)	-	23.9 (4.6)	24.1 (26.9)	40.4 (33.1)
30	*Agrostis stolonifera*	46.7 (9.6)	*	-	-	-	51.4 (34.4)
	Agropyron trachycaulum	-	66.3 (15.1)	-	*	*	26.9 (9.4)
	Deschampsia caespitosa	*	-	*	*	-	35.4 (5.7)
	Festuca ovina	-	*	-	26.3 (7.9)	-	51.0 (35.4)
	Mix	48.4 (8.5)	71.7 (12.1)	-	20.1 (6.0)	*	33.8 (11.9)
46	*Agrostis stolonifera*	48.3 (9.0)	*	-	*	-	47.2 (11.9)
	Agropyron trachycaulum	-	66.5 (6.6)	-	-	-	28.0 (9.0)
	Deschampsia caespitosa	56.0 (14.7)	-	29.0 (14.7)	-	-	42.7 (10.1)
	Festuca ovina	*	-	-	26.0 (7.3)	-	39.1 (12.1)
	Mix	43.3 (18.8)	74.7 (12.0)	-	23.0 (9.7)	22.8 (15.8)	39.7 (10.2)
91	*Agrostis stolonifera*	48.0 (5.9)	*	-	*	-	33.5 (8.0)
	Agropyron trachycaulum	-	59.1 (5.0)	-	-	-	20.6 (7.6)
	Deschampsia caespitosa	51.1 (17.1)	*	23.9 (16.8)	*	-	38.0 (10.2)
	Festuca ovina	*	-	-	25.8 (5.1)	-	39.0 (4.0)
	Mix	45.4 (7.9)	67.1 (9.7)	-	18.1 (4.8)	8.4 (2.0)	33.8 (8.0)

Data are means with standard deviations in brackets.
$3 \leq n \leq 9$.
–Data not available; *incomplete data set available for calculation of mean.

Table A7. Health of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Treatment	Health Index (% of Plants)					
		1		2		3	
		Seeded	Unseeded	Seeded	Unseeded	Seeded	Unseeded
0	*Agrostis stolonifera*	*	0	*	0	*	100
	Agropyron trachycaulum	-	-	-	-	-	-
	Deschampsia caespitosa	-	-	-	-	-	-
	Festuca ovina	-	-	-	-	-	-
	Mix	*	0	*	0	*	100
8	*Agrostis stolonifera*	0	19	0	23	100	58
	Agropyron trachycaulum	0	26	0	13	100	61
	Deschampsia caespitosa	14	11	29	44	57	44
	Festuca ovina	0	9	22	17	78	74
	Mix	0	19	25	42	75	38
15	*Agrostis stolonifera*	12	4	25	19	62	77
	Agropyron trachycaulum	0	6	0	33	100	61
	Deschampsia caespitosa	0	13	67	13	33	73
	Festuca ovina	0	12	17	19	83	69
	Mix	5	16	0	0	95	84
30	*Agrostis stolonifera*	0	6	40	3	60	91
	Agropyron trachycaulum	0	8	11	29	89	62
	Deschampsia caespitosa	*	13	*	6	*	81
	Festuca ovina	11	4	33	7	56	89
	Mix	0	20	20	13	80	67

$3 \leq n \leq 9$ on all treatments except mix where $3 \leq n \leq 45$.
-Data not available.
*Incomplete data set available.
Data are % of plants. Health categories: 1 = < 25 % live green material, 2 = 25 to 75 % live green material, 3 = > 75 % live green material.

Table A7. Health of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta (continued).

Cap Depth (cm)	Treatment	Health Index (% of Plants)					
		1		2		3	
		Seeded	Unseeded	Seeded	Unseeded	Seeded	Unseeded
46	*Agrostis stolonifera*	0	9	12	17	88	74
	Agropyron trachycaulum	0	14	0	24	100	62
	Deschampsia caespitosa	17	11	33	15	50	74
	Festuca ovina	0	4	0	19	100	78
	Mix	9	11	13	42	78	47
91	*Agrostis stolonifera*	0	13	14	40	86	47
	Agropyron trachycaulum	0	8	0	12	100	79
	Deschampsia caespitosa	14	12	0	41	86	47
	Festuca ovina	0	11	38	7	62	82
	Mix	0	9	21	32	79	59

$3 \leq n \leq 9$ on all treatments except mix where $3 \leq n \leq 45$.
-Data not available.
*Incomplete data set available.
Data are % of plants. Health categories: 1 = < 25 % live green material, 2 = 25 to 75 % live green material, 3 = > 75 % live green material.

Table A8. Stage of physiological development of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta.

Cap Depth (cm)	Treatment	Development Index (% of plants)					
		1		2		3	
		Seeded	Unseeded	Seeded	Unseeded	Seeded	Unseeded
0	*Agrostis stolonifera*	*	0	*	25	*	75
	Agropyron trachycaulum	-	-	-	-	-	-
	Deschampsia caespitosa	-	-	-	-	-	-
	Festuca ovina	-	-	-	-	-	-
	Mix	*	0	*	0	*	100
8	*Agrostis stolonifera*	0	0	29	35	71	65
	Agropyron trachycaulum	11	22	0	22	89	57
	Deschampsia caespitosa	57	15	14	7	29	78
	Festuca ovina	0	4	78	30	22	65
	Mix	19	8	6	19	75	73
15	*Agrostis stolonifera*	12	4	0	4	88	92
	Agropyron trachycaulum	0	11	0	33	100	56
	Deschampsia caespitosa	0	3	67	7	33	90
	Festuca ovina	0	0	50	19	50	81
	Mix	21	21	16	21	63	58
30	*Agrostis stolonifera*	0	6	20	22	80	72
	Agropyron trachycaulum	0	21	11	33	89	46
	Deschampsia caespitosa	*	10	*	10	*	81
	Festuca ovina	67	7	33	11	0	82
	Mix	40	7	0	20	60	73

$3 \leq n \leq 9$ on all treatments except mix where $3 \leq n \leq 45$.
-Data not available.
*Incomplete data set available.
Data are % of plants. Development categories: 1 = rosette or immature plant, 2 = plant close to flowering or flowering, 3 = plant has set seed.

Table A8. Stage of physiological development of seeded and unseeded species at Agrium Fort Saskatchewan, Alberta (continued).

Cap Depth (cm)	Treatment	Development Index (% of plants)					
		1		2		3	
		Seeded	Unseeded	Seeded	Unseeded	Seeded	Unseeded
46	*Agrostis stolonifera*	0	4	12	30	88	65
	Agropyron trachycaulum	0	14	0	33	100	52
	Deschampsia caespitosa	17	0	67	15	17	85
	Festuca ovina	22	11	67	7	11	81
	Mix	30	5	13	26	57	68
91	*Agrostis stolonifera*	0	17	0	13	100	70
	Agropyron trachycaulum	0	21	0	25	100	54
	Deschampsia caespitosa	43	12	14	12	43	76
	Festuca ovina	0	14	100	11	0	75
	Mix	33	6	12	38	54	56

$3 \leq n \leq 9$ on all treatments except mix where $3 \leq n \leq 45$.
-Data not available.
*Incomplete data set available.
Data are % of plants. Development categories: 1 = rosette or immature plant, 2 = plant close to flowering or flowering, 3 = plant has set seed.

Table A9. TDR probe model and calibration equation for research plots at Agrium Fort Saskatchewan, Alberta.

Plot	TDR Probe Model	Lead Length (m)	Response Time	Calibration Equation[†]
A1	CS616	55	µsec	$y = 9 \times 10^{-5}x^2 + 0.0042x - 0.0866$
A2	CS616	43		$y = 0.0002x^2 - 0.0038x + 0.0179$
A3	CS616	77		$y = 0.0002x^2 - 0.0003x - 0.0335$
A4	CS616	55		$y = 0.0001x^2 + 0.0013x - 0.0514$
A5	CS616	89		$y = 0.0001x^2 + 0.0017x - 0.0469$
A6	CS616	66		$y = 0.0004x^2 - 0.0143x + 0.1983$
C1	CS616	89		$y = - 9 \times 10^{-5}x^2 + 0.014x - 0.1999$
C2	CS616	43		$y = 0.0002x^2 - 0.0013x - 0.0194$
C3	CS616	77		$y = 0.0002x^2 - 0.0028x - 0.0109$
C4	CS616	89		$y = 8 \times 10^{-5}x^2 + 0.0053x - 0.1069$
C5	CS616	43		$y = 0.0001x^2 + 0.002x - 0.0659$
C6	CS616	66		$y = 0.0002x^2 + 0.0002x - 0.029$
B1	CS615	30	msec	$y = - 0.0344x^2 + 0.2795x - 0.1715$
B2	CS615	30		$y = - 0.0102x^2 + 0.1917x - 0.1183$
B3	CS615	30		$y = 0.0218x^2 + 0.1094x - 0.0796$
B4	CS615	30		$y = - 0.0352x^2 + 0.266x - 0.1557$
B5	CS615	30		$y = - 0.0425x^2 + 0.2875x - 0.1853$
B6	CS615	30		$y = - 0.043x^2 + 0.2956x - 0.1808$

[†]x = response time (µsec or msec).
[†]y = volumetric water content (m^3 water/m^3 PG).

Snow Density (Mg/m^3)

Equation 1A

Density (snow sample) = Mass (snow) / Volume (snow)

Mass of snow sample (Mg)
Mass (snow) = Mass (snow + bag) – Mass (bag)

Volume of snow sample (m^3)
Radius (r) of snow core = 3.785 cm = 0.0379 m
Height (h) = measured depth of snow sample (m)
Volume (snow) = $\pi r^2 h$

Snow Water Equivalent (SWE) (mm)

Equation 2A

$$\text{SWE (mm)} = \text{measured depth of snow (cm)} \times \frac{\text{calculated snow density } (Mg/m^3)}{\text{density of water } (Mg/m^3)} \times \frac{10 \text{ mm}}{1 \text{ cm}}$$

Percent Exceedance

Equation 3A

$$\text{Percent exceedance} = \frac{\text{concentration in sample} - \text{concentration in control}}{\text{concentration in control}} \times 100$$