University of Alberta

Soil Moisture and Nutrient Regimes of Reclaimed Upland Slopes in the Oil Sands Region of Alberta

by

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ABSTRACT

Research objectives were to quantify soil moisture and nutrient regimes on reclaimed upland slopes of various reclamation prescriptions and to determine how these parameters were affected by slope position. Slope position did not have a consistent effect on either soil moisture or nutrient status. Spatial variability in soil characteristics and vegetation distribution likely had a greater influence on moisture and nutrient distribution than did slope position. The upper soil profiles had highly dynamic moisture regimes and a greater response to precipitation events than the lower soil profiles. Available water increased with increasing moisture content and a site that had a greater fraction of coarse textured material within its upper peat mineral mix horizon experienced percolation. Soil nutrient availability was more affected by season than by reclamation prescription. An unvegetated site exhibited lower seasonal variability in soil moisture and nutrient regimes than those of the vegetated sites.

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ABBREVIATIONS

2^0	Secondary material
ASOR	Athabasca Oil Sands Region
AWHC	Available water holding capacity
B	Boron
BDL	Below detectable limit
Ca	Calcium
CCN	Canadian climate normals
CECe	Effective cation exchange capacity
CH_2Cl_2	Dichloromethane
C/N	Carbon to nitrogen ratio
Cu	Copper
CV	Coefficient of variation
FC	Field capacity
Fe	Iron
HCl	Hydrochloric acid
H_2O_2	Hydrogen peroxide
IER	Ion exchange resin
K	Potassium
LOS	Lean oil sand
LS	Lower subsoil
MFT	Mature fine tailings
Mg	Magnesium
Mn	Manganese
MPa	Megapascal
MRPP	Multiresponse permutation procedure
Na	Sodium
NH_4-N	Ammonium
NMS	Non-metric multidimensional scaling
NO_3-N	Nitrogen

N-P-K	Nitrogen-Phosphorus-Potassium
OB	Overburden
PET	Potential evapotranspiration
pH	$-\log[H^+]$
PMM	Peat mineral mix
PO_4	Phosphorus
PRS	Plant-Root-Simulator
PVC	Polyvinyl chloride
SiO_2	Silicon dioxide
SO_4	Sulphur
TC	Total carbon
TN	Total nitrogen
TOC	Total organic carbon
TS	Top soil
TSW	Total soil water for a given depth or interval
US	Upper subsoil
VMC	Volumetric moisture content
WP	Wilting point
Zn	Zinc

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CHAPTER I: INTRODUCTION

1.0 Background

The boreal forest is one of the world's largest intact terrestrial ecosystems covering 12,000,000 km^2 of the earth's surface (Kimmins and Wein 1986; Canadian Boreal Initiative 2003). This large ecological biome, with a northern circumpolar distribution of variable latitudinal width, is diverse in floral and faunal species structure and composition. In Alberta, the boreal forest covers a total of 346,964 km^2, approximately 52% of the province's land base and accounting for 11% of the total area of the Canadian boreal forest (Alberta Environmental Protection 1998).

This diverse ecosystem supports an array of flora and fauna, filters and stores water, mitigates flooding and releases fresh water into rivers and streams. The forest acts as a carbon sink, which produces oxygen, builds soil, cycles nutrients and provides food and shelter for human and animal use. The boreal forest represents one of the few remaining intact ecosystems that has the ability to buffer some of the ecological changes that can arise from global climate change (Canadian Boreal Initiative 2003; 2005). This forest ecosystem also provides key economic resources including wood products, oil and gas and agricultural land (Canadian Boreal Initiative 2005). Collectively these industrial activities contribute thousands of jobs and billions of dollars to Alberta's economy.

The oil sands which lie within Alberta's boreal forest are recognized as the second leading source of oil in the world (Fung and Macyk 2000; Canadian Boreal Initiative 2005). There are four significant oil reserves in Alberta: the Athabasca, Cold Lake, Peace River and Wabasca deposits. Of these four, the Athabasca deposit, in the Athabasca Oil Sands Region (AOSR), is the largest with an estimated volume of 700 billion barrels of in-place bitumen and it is the only reserve that is accessible through surface mining (Fung and Macyk 2000). Surface mining operations to extract the bitumen laden sand, result in a large scale disturbance that removes vegetation, soil and subsoil from the earth's surface, which disrupts the natural hydrologic and nutrient cycles at a landscape scale. The extent of the current disturbance from surface mining in the AOSR is 430 km^2 and with current technologies, is projected to increase to 1,767 km^2 (Alberta Environment 2006).

To maintain the structure and function of the boreal forest ecosystem, industry must have the decision making tools to implement successful reclamation strategies. The fundamental goal in land reclamation is to re-establish land capability that is equivalent to pre-disturbance conditions. This requires the reconstruction of soil profiles such that soil physical and chemical properties couple with microbiological properties to produce a favourable biogeochemical soil environment for the growth of the desired vegetation (Naeth et al. 1991).

1.1 General Research Objectives

There is a lack of information on soil moisture and nutrient regimes of soil profiles on reclaimed upland slopes in the AOSR. This research quantifies the soil moisture and nutrient regimes of the soil profiles created at the reclaimed upland slopes of various reclamation prescriptions and ages. Specific objectives related to soil moisture were: 1) to determine how soil moisture was affected by slope position and 2) to characterize the temporal variability of soil moisture at the slope level. Specific objectives related to nutrient regimes were: 1) to determine how soil nutrient availability was affected by topographical position and 2) to characterize the temporal variability of soil nutrients at the slope level.

1.2 Study Sites

1.2.1 Study Area

The five study sites are located approximately 50-80 km north of Fort McMurray in north-eastern Alberta (Figure 1.1). Sites 1 and 4 are located at Suncor Energy, Site 3 is located at Albian Sands and Site 2 and 5 are located at Syncrude Canada Ltd. These study areas are within the boreal forest, which is dominated by a continental climate with short summers and long cold winters (Strong and Leggat 1981; Natural Regions Committee 2006). The mean annual temperature is 0.7°C, where January is the coldest month with a mean temperature of -18.8 °C and July is the warmest with a mean temperature of 16.8°C (Environment Canada 2004). The mean annual precipitation is 455.7 mm, where an average of 342.2 mm occurs as rainfall and 155.8 cm occurs as snowfall. The average annual evapotranspiration is 450 to 500 mm (Fung and Macyk 2000). The boreal forest in northern Alberta consists of upland forests and extensive wetlands in low-lying areas (Natural Regions Committee 2006). The dominant upland mixed forest vegetation is aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) and white spruce (*Picea glauca (Moench)*Voss). Jack pine (*Pinus banksiana* Lamb.) stands occur on well drained, sandy soils. Low lying poorly drained areas consist of treed fens dominated with black spruce (*Picea mariana* Mill.), shrubby fens and sedge fens (Fung and Macyk 2000).

Luvisolic soils develop on well to imperfectly drained sites under upland mixedwood forest vegetation (Natural Regions Committee 2006; Strong and Leggat 1981). The thick forest floor litter layers and clay translocation in the upper mineral soil are a result of climatic conditions, where precipitation exceeds evapotranspiration and the cool temperatures keep forest floor biological activity low. Brunisols develop on well to rapidly drained fluvial and eolian materials, while Gleysols and Organic soils develop within poorly drained wetland areas.

1.2.2 Site 1 (Suncor Energy Ltd. 11A)

This site is located on a west facing slope of a tailings pond and was reclaimed in 2003. The reclamation prescription is 20 cm of a directly placed peat mineral mix (humic) overlaying 80 cm of subsoil material overlaying a lean oil sand overburden mixture. The site was seeded with barley and planted with tree and shrub species in 2003. Tree and shrub species planted on site included white spruce, aspen, paper birch (*Betula papyrifera* Marsh.) and lowbush cranberry (*Vaccinium vitis-idaea* L.). Rose and alder were planted on site but the reclamation report does not state which species. The site was fertilized with nitrogen-phosphorus-potassium (N-P-K) fertilizer once in 2003 with 23-25-8 at 300 kg ha^{-1}, once in 2005 with 31-16-5 at 250 kg ha^{-1} and once in 2006 with 31-16-5 at 250 kg ha^{-1}.

The overall size of the reclaimed dyke is 9.5 ha; however, the study area encompasses approximately a 35 m wide by 200 m long (1 ha) section of the total area. This site was instrumented at 6 slope positions with slope position 1 near the top of the dyke and slope position 6 near the toe of the slope; Diviner 2000® access tubes were placed approximately 50 m apart up the slope and 25 m apart across the slope (Figure 1.2

a and b). Slope positions 1 through 6 had Diviner 2000® access tubes replicated three times across each slope position. Slope positions 2, 4 and 6 had PRS probes replicated 3 times across each slope position.

1.2.3 Site 2 (Syncrude Canada Ltd. - 30D)

This site was a test cover, constructed in 1999 on a saline/sodic shale overburden dump. The D3 site was one of three covers constructed to test the effect of different cover depths (thicknesses) on saline/sodic shale overburden dumps. This study focused on the D3 cover, which is a 20 % north facing slope. The reclamation prescription was 20 cm of peat (mesic) mineral mix overlaying 80 cm of subsoil material overlaying saline/sodic overburden. This site was planted with aspen and white spruce in 2000.

The overall size of the site was approximately 50 m wide by 200 m long (1 ha). This site was instrumented at 3 slope positions with slope position 1 near the top of the site and slope position 3 near the toe of the slope; tubes were installed approximately 25 m apart (Figure 1.3 a and b). Slope positions 1 through 3 have Diviner 2000® access tubes and PRS probes replicated three times at each slope position.

1.2.4 Site 3 (Albian Sands - Trial Slope)

This site was a north facing 25 % slope which was designed as a reclamation trial for lean oil sand waste material and constructed in 2003. The reclamation prescription was 50 cm of a peat (mesic) mineral mix overlaying 50 cm of tailings sand overlaying lean oil sand. This site had not been vegetated or fertilized previous to or during the study time period and was void of vegetation during the study. The overall size of the reclaimed slope was 100 m wide by 50 m long (0.5 ha). This site was instrumented at 3 slope positions with slope position 1 near the top of the structure and slope position 3 near the toe of the slope; tubes were approximately 15 m apart up the slope and 20 m apart across the slope (Figure 1.4 a and b). Slope positions 1 through 3 had Diviner 2000® access tubes and PRS probes replicated three times at each slope position.

1.2.5 Site 4 (Suncor Energy Ltd. - 2W)

Site 4 was a south facing slope of a tailings sand holding facility, which was reclaimed in 1988. The reclamation prescription was 20 cm of stockpiled peat (mesic) mineral mix overlaying a tailings sand substrate. The site was seeded with a barley/grass/legume seed mix and planted with tree species in 1988. The seed mix included Jackson barley (*Hordeum vulgare* L.), violet wheatgrass (*Agropyron violaceum* (Hornem.) Lange), sheep fescue (*Festuca ovina* L.), hairgrass (*Deschampsia caespitosa* L.), fowl bluegrass (*Poa palustris* L.), meadow foxtail (*Alopecurus pratensis* L.), red top (*Agrostis gigantea* Roth) and alsike clover (*Trifolium hybridum* L.). The tree and shrub species planted on site included white spruce, northwest poplar (*Populus* × *jackii*), dogwood (*Cornus sericea* L.) and Saskatoon berry (*Amelanchier alnifolia* Nutt.); rose and willow were planted on site but the reclamation report did not state which species. "Fill in planting" with the tree and shrub species occurred in 1989, 1992, 1994 and 1998. This site was fertilized with N-P-K fertilizer twice in 1989 with 23-25-8 at 300 kg ha^{-1} and 32-16-5 at 200 kg ha^{-1}, twice in 1989 with 6-24-24 at 100 kg ha^{-1} and 32-16-5 at 200 kg ha^{-1}, twice in 1990 with 34-17-0 at 200 kg ha^{-1} and 6-24-24 100 kg ha^{-1}, once in 1991 with 32-16-5 at 200 kg ha^{-1}, once in 1992 with 32-16-5 at 200 kg ha^{-1} and once 1993 with 34-17-0 at 200 kg ha^{-1}. The reclamation report did not state at what time of the year these fertilizer treatments were applied.

The overall size of the reclaimed dyke was 9.6 ha; however, the study area encompassed approximately a 50 m wide by 100 m long section (0.5 ha) of the total area. This site was instrumented at 6 slope positions with slope position 1 near the top of the facility and slope position 6 in the middle of the whole slope adjacent to an access road; tubes were installed approximately 20 m apart (Figure 1.5 a and b). Slope positions 1 through 6 have Diviner 2000® access tubes replicated three times at each slope position. Slope positions 2 and 5 are replicated 3 times at each slope position with PRS probes. The upper half of this slope is instrumented. Tubes from slope 4 through 6 were analyzed for the hydrology chapter and the PRS probe data were used to determine nutrient availability at this site.

1.2.6 Site 5 (Syncrude Canada Ltd. - Fibric)

This site was constructed on a north facing saline/sodic overburden dump. The reclamation prescription was 20 cm of peat (fibric) mineral mix overlaying 80 cm of subsoil material overlaying saline/sodic overburden. The overall size of the site was approximately 60 m wide by 15 m long. This site was instrumented at one slope position with PRS probe replicated three times across the slope and the data were used to determine nutrient availability at this site.

1.3 Literature Cited

Alberta Environment. 2006. Oil sands. www3.gov.ab.ca/env/land/quality/html/use/oilsands.html. Accessed August 1, 2007.

Alberta Environmental Protection. 1998. The final frontier: protecting landscape and biological diversity within Alberta's boreal forest natural region. Protected Areas Report no. 13. Alberta Environmental Protection. Edmonton, AB. 313 Pp.

Canadian Boreal Initiative. 2003. The boreal forest at risk: a progress report. Fourth anniversary of competing realities: the boreal forest at risk by the Senate committee on agriculture and forestry. 14 Pp. http://www.borealcanada.ca/pdf/cbi_2003_senate_report.pdf [Accessed online. May 10, 2005].

Canadian Boreal Initiative. 2005. The boreal in the balance: securing the future of Canada's boreal region. 72 Pp. http://www.borealcanada.ca/pdf/Boreal_in_the_Balance_Full.pdf [Accessed online. May 10, 2005].

Chaikowsky, C. L. A. 2003. Soil moisture regime and salinity on a tailings sand storage facility. M.Sc. Thesis. Department of Renewable Resources, University of Alberta. Edmonton, AB. 135 pp.

Environment Canada. 2004. Canadian Climate Normals 1971-2000. http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html [Accessed online. September 20, 2006].

Fung, M. Y. P. and Macyk, T. M. 2000. Reclamation of oil sands mining areas. In: R. I. Barmhisel, R. G. Darmody and W. L. Daniels (eds.). Reclamation of Drastically Disturbed Lands. Agronomy Monograph No. 41. American Society of Agronomy. Madison, WI. Pp. 755-774.

Kimmins, J. P. and Wein, R. W. 1986. Introduction. In: K. Van Cleve, F. S. Chapin III, P. W. Flanagan, L. A. Viereck, C. T. Dyrness (eds.). Forest Ecosystem in the Alaskan Taiga: a Synthesis of Structure and Function. Springer-Verlag. New York, NY. Pp. 3-8.

Naeth, M. A., White, D. J., Chanasyk, D. S., Macyk, T. M., Powter, C. B. and Thacker, D. J. 1991. Soil Physical Properties in Reclamation. Alberta Land Conservation and Reclamation Council Report No. RRTAC 91-4. Edmonton, AB. 216 pp.

Natural Regions Committee. 2006. Natural regions and subregions of Alberta. Compiled by D. J. Downing and W. W. Pettapiece. Government of Alberta. Pub. No. T/852. 254 pp.

Strong, W. L. and Leggat, K. R. 1981. Ecoregions of Alberta. Alberta Energy and Natural Resources. Edmonton, Alberta. 64 pp.

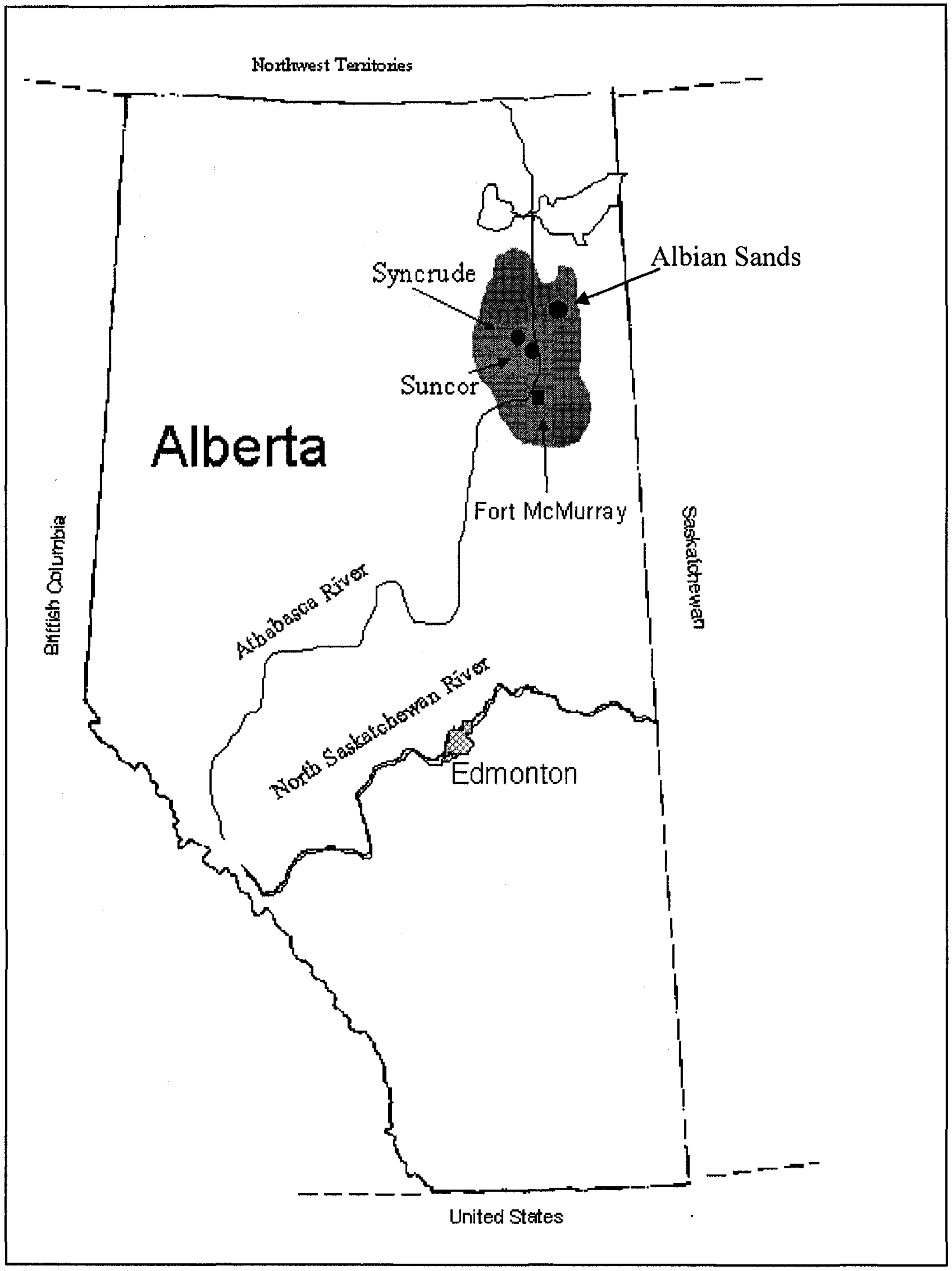


Figure 1.1 Map of Alberta indicating the locations of the study sites north of Fort McMurray (adapted from Burgers 2005)

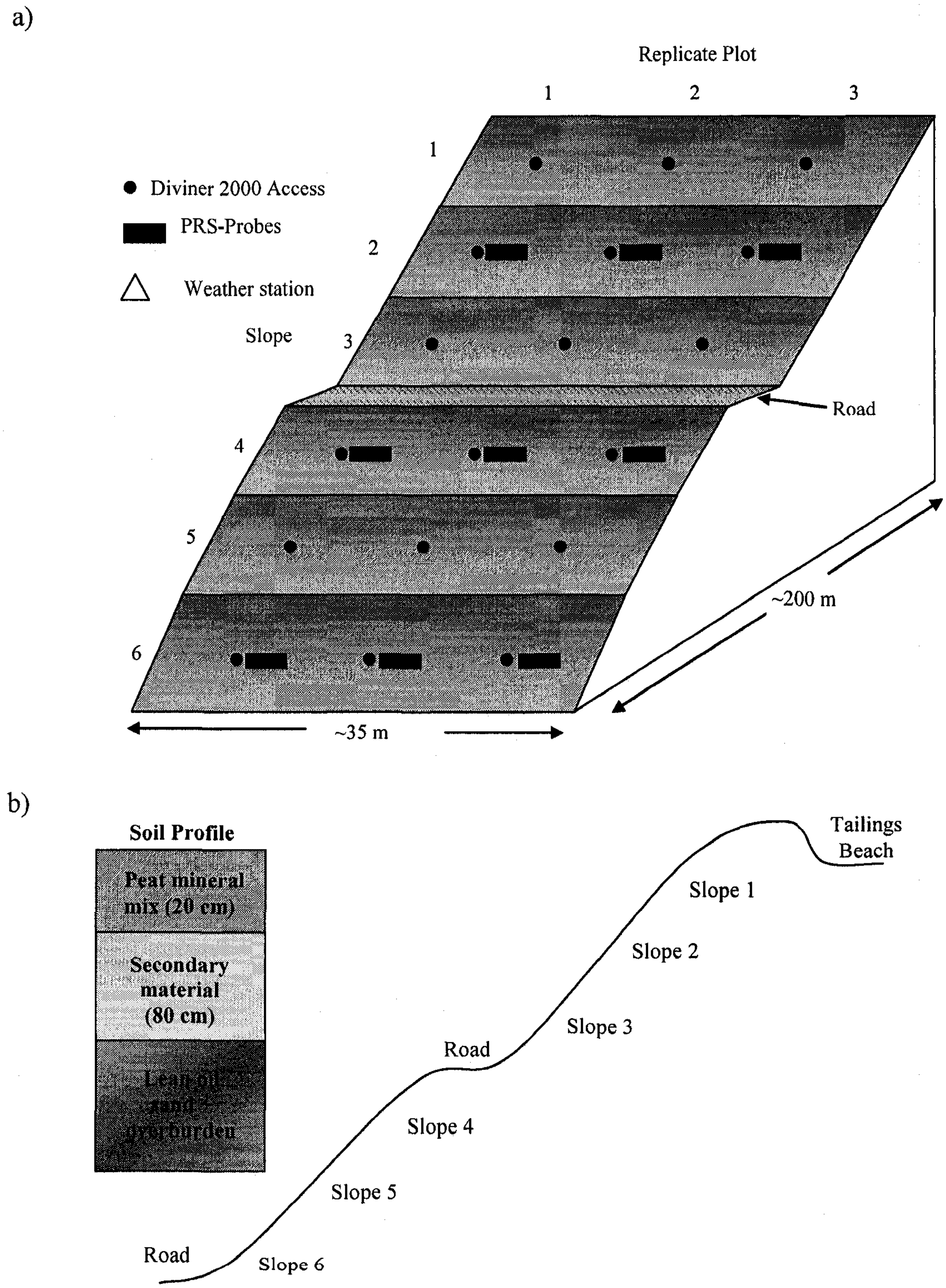
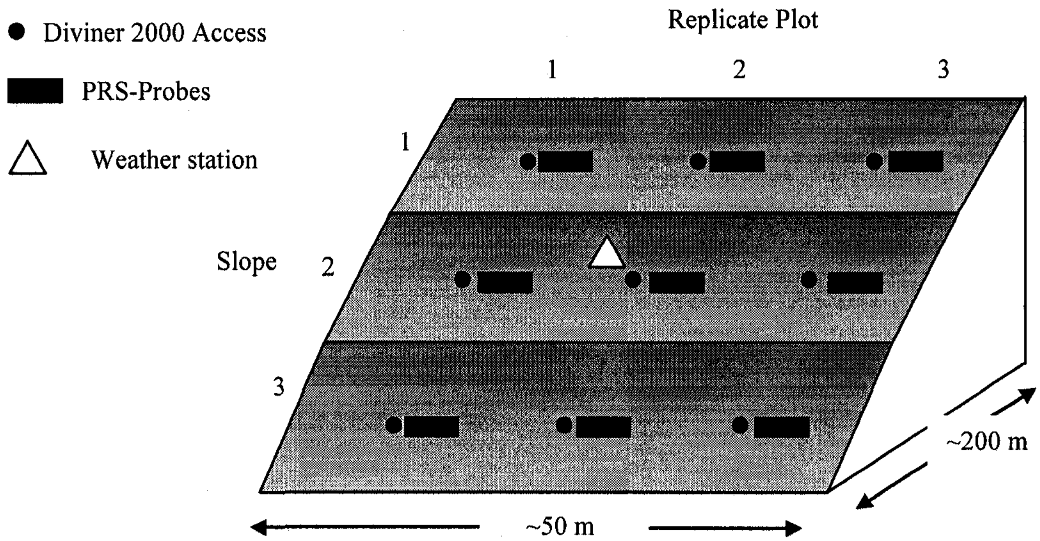


Figure 1.2 a) A schematic diagram of Site 1 with a 25% slope; b) a vertical cross-section of Site 1 (diagram adapted from Chaikowsky 2003)

a)



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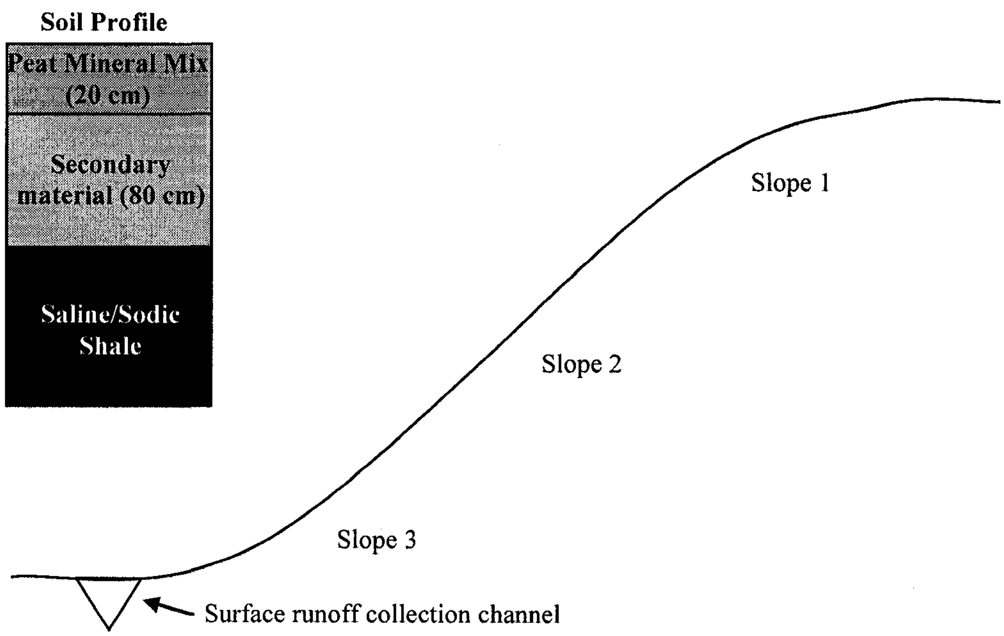


Figure 1.3 a) A schematic diagram of Site 2 with a 20% slope; b) a vertical cross-section of Site 2 (diagram adapted from Chaikowsky 2003)

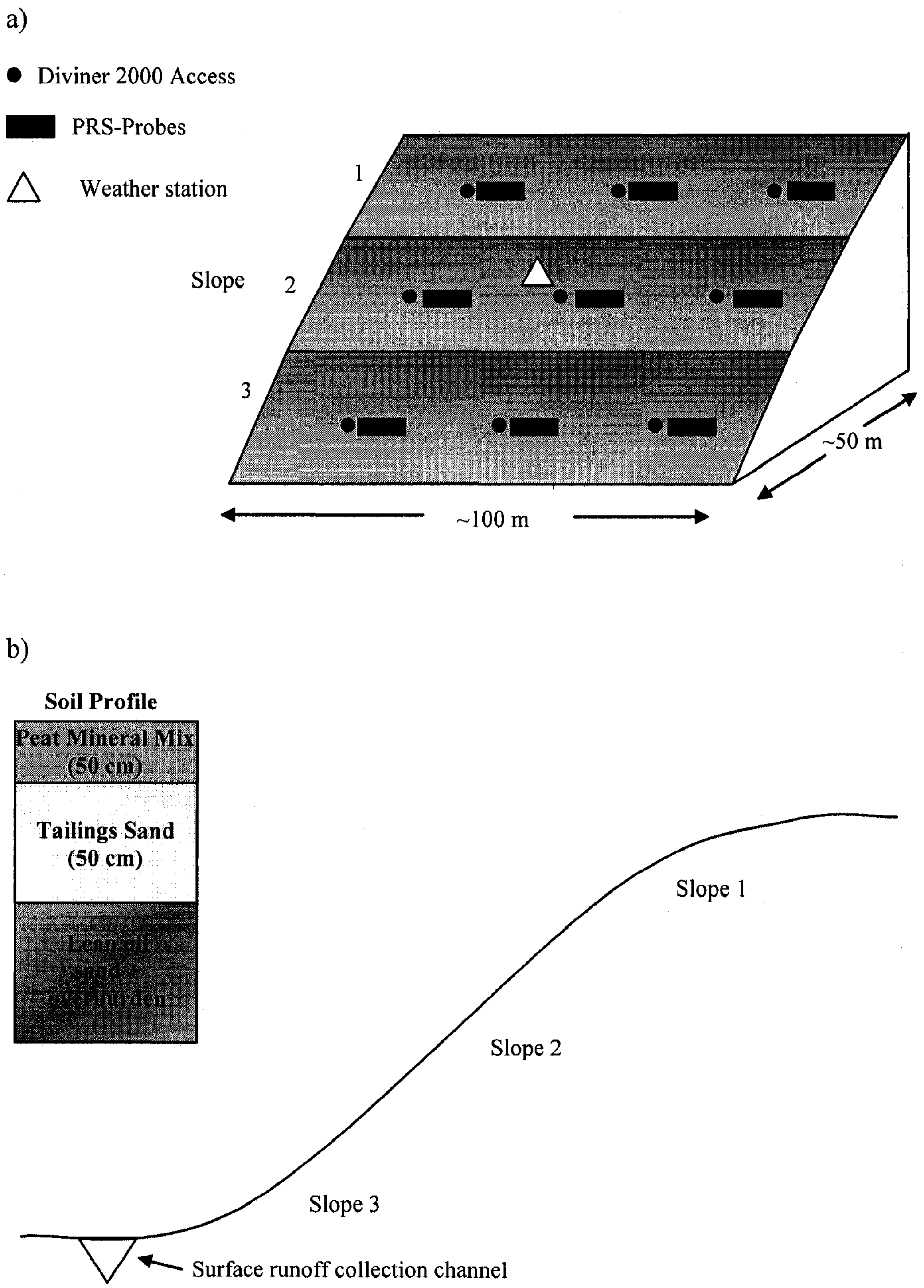


Figure 1.4 a) A schematic diagram of Site 3 with a 25% slope; b) a vertical cross-section of Site 3 (diagram adapted from Chaikowsky 2003)

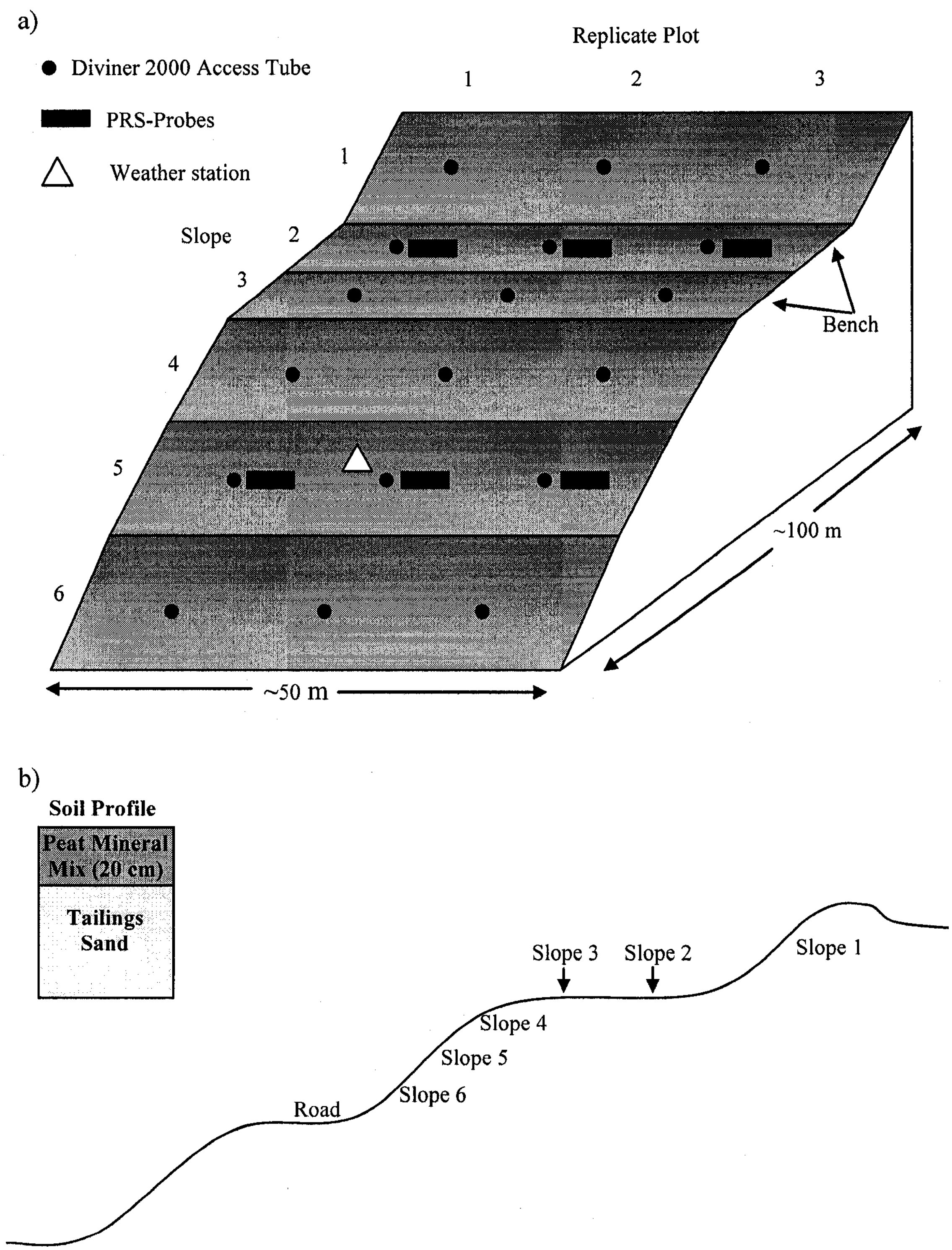


Figure 1.5 a) A schematic diagram of Site 4. Note: tubes are approximately 20 m apart and slope positions 4 through 6 were used for hydrological assessment; b) a cross-section diagram of Site 4 (diagram adapted from Chaikowsky 2003)

CHAPTER II: LITERATURE REVIEW

1.0 Surface Mining Disturbance

Surface mining can dramatically alter the physical, chemical and biological components of ecosystems over space and time (Shukla et al. 2004a). This large scale ecological disturbance imposes composition and structural changes in plant communities and disrupts the spatial organization and the functional relationships among ecosystem and soil components (Mummey et al. 2002). Surface mined areas and wastes produced from surface mining need to be reclaimed to functional ecosystems. The objective of reclamation is to restore ecological integrity to the land such that as the reclaimed ecosystem develops, its productivity will be within the range of natural variability (Mummey et al. 2002). However, reclaimed and reconstructed landforms are a function of the available reclamation material and soil amendments (Khasa et al. 2005). The material used to recreate soil profiles must have the ability to develop the hydrologic and nutrient dynamics, which are comparable to pre-disturbance conditions. Thus, a soil medium must have the ability to retain and supply moisture and nutrients to the rhizosphere, the mechanical strength to resist erosion and the biological and chemical activity to buffer the effects of a changing soil environment.

Reclaimed soils are dramatically altered from pre-mine conditions due to removing, stockpiling and replacing of the original soil or amendment material (Chong and Cowsert 1997; Guebert and Gardner 2001; Shukla et al. 2004b; Ussiri et al. 2006). This disturbance often creates plant limiting characteristics of reclaimed soils including poor soil structure and aggregation, increased bulk density and reduced near surface porosity, soil fertility and microbial activity. These limiting soil conditions create a challenge when returning a disturbed ecosystem to a productive ecosystem.

Several studies have investigated possible implications of, and solutions for, the limiting characteristics of reclaimed soils. Reclaimed watersheds in western Maryland had increased stormflow responses, including increased peak runoff and total storm runoff (Negley and Eshleman 2006). Guebert and Gardner (2001) found that newly reclaimed minesoils in Pennsylvania had low infiltration rates, which resulted in runoff. However, as the mine soils became older, the infiltration rate increased and was similar to pre-disturbance rates, which was attributed to development of macropore networks within the reconstructed soil. Soil amendments have been used to ameliorate limiting soil physical conditions and to increase soil available nutrients and water for vegetation. Chong and Cowsert (1997), studying infiltration rates of reclaimed surface mine soils with various deep tillage treatments in Illinois found that soils with deeper tillage tended to have higher water infiltration rates. In contrast, Yarmuch (2003) found that soil was not compacted at reclaimed oil sands sites in northern Alberta, likely because peat mineral mix was placed during the winter, while still frozen. Shukla et al. (2004b) found fertilizer application improved soil structure and water transmission by increasing soil organic matter thereby decreasing soil bulk density.

Coyne et al. (1998) investigated the effects of the addition of organic waste material to stimulate microbial activity and thereby increase available nitrogen at a reclaimed surface mine site in Kentucky. Waste amended soil had similar bulk densities and water holding capacity as un-amended soil, and microbial biomass and gross mineralization rates were greater in the waste amended soil. Stehouwer et al. (2006) found that the addition of biosolids to reclaimed mine land in Pennsylvania, USA, increased plant available nutrients, organic carbon and vegetation development but had adverse impacts on ground water quality by increasing water acidity and nitrate concentrations. Grigg et al. (2006) studying reclamation of saline/sodic overburden in Australia, found that the incorporation of mulch amendments (straw and sawdust) increased infiltration and reduced evaporation and surface crust and improved revegetation success. It is evident that reclamation strategies are a function of the materials to be reclaimed and reclamation objectives (Fung and Macyk 2000).

End land use of reclaimed land is dependent upon the region, the surrounding ecosystems and active industry or projected end land use. Revegetation of reclaimed land has had varying degrees of success in achieving end land use. In the Appalachian region of the United States, commercial forestry is the end land use for reclaimed lands (Rodrigue et al. 2004). Rodrigue et al. (2002) studied forest productivity of reclaimed coal mines in the eastern and midwest regions of the USA. They found reclaimed forests to be equally productive as non-mined forests. Rodrigue and Burger (2004) investigated the forest productivity of reclaimed mine sites and determined the soil properties that influenced long-term tree productivity in the eastern United States. Forests on reclaimed land were equally productive as adjacent natural forests and that the main soil factors influencing site productivity were base saturation and electrical conductivity, total coarse fragments, total available water and total porosity of the C horizon. Conversely, Craw et al. (2007) studying natural vegetation recovery on coal mine waste rock dump in south-eastern New Zealand, found strong geological controls on natural revegetation. Reclaimed soils with greater than 35% quartz pebbles were less vegetated than reclaimed soils with 5 - 15% quartz pebbles, which they attributed to limited physical properties thereby reducing vegetation productivity. Leavitt et al. (2000) studied waste rock dumps at a gold mine in Nevada, USA. They found that revegetation of the dumps was limited by coarse textured soils on steep slopes.

1.1 Reclamation Approach in the Athabasca Oil Sands Region (AOSR)

Three waste stream materials are generated from the bitumen extraction and production processes: 1) overburden material, 2) tailings sand and 3) fine tailings (Fung and Macyk 2000). Overburden is the material which overlies the economically extractable bitumen deposits and may consist of low grade oil sand, glacial till, glacial-fluvial, glacio-lacustrine and peat material. Overburden is inadequate as a revegetation material in itself because it has low available water holding capacity, microbial activity, nutrient status and organic matter (Fung and Macyk 2000). It can also be high in salinity and contain bitumen, both of which are unfavourable for plant growth.

Tailings sand is the waste product that remains after bitumen is extracted from the oil sand. It is the coarse fraction of the tailings stream and consists of 96 to 99% SiO_2 and some unrecovered bitumen (Fung and Macyk 2000). It is sluiced onto the holding ponds with fine tailings and quickly settles out from aqueous suspension to form dykes and beaches (List and Lord 1997; Li and Fung 1998). The sand has high erosion potential and low available water holding capacity, cation exchange capacity, microbial activity and organic matter and can contain high soluble sodium concentrations and be hydrophobic (Fung and Macyk 2000). The tailings sand is used to create containment facilities for the storage of fine tailings (List and Lord 1997; Li and Fung 1998).

Clays, silts and residual bitumen are the main constituents of the fine tailings waste stream (Fung and Macyk 2000). Eighty percent of the clay is kaolinite and the other 20% consists of illite, montmorillonite and chlorite. Once sluiced into holding ponds, fine tailings do not effectively dewater and consolidate to a surface that can be revegetated because of high salt and residual bitumen concentrations (Li and Fung 1998; Majid 2003). Consolidation of this material occurs until it is about 30% solids, at which time it is referred to as mature fine tailings. Mature fine tailings (MFT) results in a wet landscape that is difficult to revegetate to a self-sustaining ecosystem and can have bitumen concentrations that are acutely toxic to aquatic organisms. Further consolidation of this material would require hundreds of years and would still continue to be problematic for terrestrial reclamation (Renault et al. 1998).

Renault et al. (2000) have shown that the structure and texture of oil sands tailings contribute to difficulties in establishing a sustainable boreal forest ecosystem. They attributed this to a reduction in soil porosity of fine tailings, which affects soil available water and oxygen content, alters soil chemistry and limits root growth. The challenge for the oil sands industry is to establish a soil-plant continuum with equivalent composition, function and structure as the undisturbed landscape and with no long-term toxicity (Li and Fung 1998; Li et al. 2003; Renault et al. 2003). The goal of reclamation in the AOSR is to achieve self-sustaining ecosystems with capabilities equivalent to or better than pre-disturbance conditions (Oil Sands Vegetation Reclamation Committee 1998). Thus, successful reclamation requires constructing and placing a cover soil on these upland structures to support the growth of the desired species' populations (Li and Fung 1998; Oil Sands Vegetation Reclamation Committee 1998).

In the AOSR, a soil material is created from a peat-mineral mix salvaged from the mined areas (Oil Sands Vegetation Reclamation Committee 1998). In the one-lift soil replacement technique, organic soil is over stripped such that 25 to 50%, by volume, of the subsoil material is incorporated to create a peat-mineral mix. The mix is then placed 15 to 50 cm thick on either tailings sand or overburden subsoil. In the two-lift soil replacement technique, sandy or clayey subsoil material is placed on top of the tailings sand or overburden, which is then capped with 15 to 25 cm of the peat-mineral mix.

The target end land use for these reclaimed upland areas is commercial forest and wildlife habitat (Oil Sands Vegetation Reclamation Committee 1998). To determine if reclamation is successful requires explaining and predicting patterns of productivity through spatial and temporal scales (Turner 2005). To verify whether reclaimed sites are establishing productive ecosystems within the natural range of variability requires the ability to understand and predict the effects of landscape change. Forest productivity is a function of the interactions among solar radiation, temperature, available water and nutrients, soil aeration and microbial populations (Chen et al. 1998: Han et al. 1998). These variables directly affect the structural, functional and productive development of vegetation within a forest ecosystem. In the AOSR, being able to predict soil moisture and nutrient regimes on reclaimed upland slopes will provide important information that can be used to guide the revegetation process and achieve successful reclamation.

1.2 Literature Cited

Chen, H. Y. H., Klinka, K. and Kabzems, R. D. 1998. Site index, site quality, and foliar nutrients of trembling aspen: relationships and predictions. Can. J. Forest Res. 28: 1743-1755.

Chong, S. K. and Cowsert, P. T. 1997. Infiltration in reclaimed mined land ameliorated with deep tillage treatments. Soil Tillage Res. 44: 255-264.

Coyne, M. S., Zhai, Q, Mackown, C. T. and Barnhisel, R. I. 1998. Gross nitrogen transformation rates in soil at a surface coal mine site reclaimed for prime farmland use. Soil Biol. Biochem. 30: 1099-1106.

Craw, D., Rufaut, C. G., Hammit, S., Clearwater, S. G. and Smith, C. M. 2007. Geological controls on natural ecosystem recovery on mine waste in southern New Zealand. Environ. Geol. 51: 1389-1400.

Fung, M. Y. P. and Macyk, T. M. 2000. Reclamation of oil sands mining areas. In: R. I. Barmhisel, R. G. Darmody and W. L. Daniels (eds.). Reclamation of Drastically Disturbed Lands. Agronomy Monograph No. 41. American Society of Agronomy. Madison, WI. Pp. 755-774.

Grigg, A. H., Sheridan, G. J., Pearce, A. B. and Mulligan, D. R. 2006. The effect of organic amendment on the physical and chemical properties and revegetation success of a saline-sodic minespoil from central Queensland, Australia. Aust. J. Soil Res. 44: 97-105.

Guebert, M. D. and Gardner, T. W. 2001. Macropore flow on a reclaimed surface mine: infiltration and hillslope hydrology. Geomorphology 39: 151-169.

Han, Y. H., Kinka, K. and Kabzems, R. D. 1998. Site index, site quality and foliar nutrients of trembling aspen: relationships and predictions. Can. J. Forest Res. 28: 1743-1755.

Khasa, D. P., Fung, M. and Logan, B. 2005. Early growth response of container-grown selected woody boreal seedlings in amended composite tailings and tailings sand. Bioresour. Technol. 96: 857-864.

Leavett, K. J., Fernandez, G. C. J. and Nowak, R. S. 2000. Plant establishment on angle of repose mine waste dumps. J. Range Manage. 53: 442-452.

Li, X. and Fung, M. Y. P. 1998. Creating soil-like materials for plant growth using tailings sand and fine tails. J. Can. Petrol. Tech. 37 (11): 44-47.

Li, X., Feng, Y., Slaski, J. J. and Fung, M. 2003. Evaluation of the capability of aggregated oil sands and mine tailings: biological indicators. J. Can. Petrol. Tech. 42 (9): 47-50.

List, B. R. and Lord, E. R. F. 1997. Syncrude's tailings management practices from research to implementation. Can. Min. Metall. Bull. 90 (1010): 39-44.

Majid, A. 2003. Consolidation of Syncrude oil sands fine tailings. J. Can. Petrol. Tech. 42 (8): 46-49.

Mummey, D. L., Stahl, P. D. and Buyer, J. S. 2002. Soil microbiological properties 20 years after surface mine reclamation: spatial analysis of reclaimed and undisturbed sites. Soil Biol. Biochem. 34: 1717-1725.

Negley, T. L. and Eshleman, K. N. 2006. Comparison of stormflow responses of surface-mined and forested watersheds in the Appalachian Mountains, USA. Hydrol. Process. 20: 3467-3483.

Oil Sands Vegetation Reclamation Committee. 1998. Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region. Report 99-1. Alberta Environment. Edmonton, AB. Pp. 15-32.

Renault, S., Lait, C., Zwiazek, J. J., MacKinnon, M. 1998. Effect of high salinity tailings waters produced from gypsum treatment of oil sands tailings on plants of the boreal forest. Environ. Pollut. 102: 177-184.

Renault, S., Zwiazek, J. J., Fung, M. and Tuttle, S. 2000. Germination, growth and gas exchange of selected boreal forest seedlings in soil containing oil sands tailings. Environ. Pollut. 107: 357-365

Renault, S., MacKinnon, M. and Qualizza, C. 2003. Barley, a potential species for initial reclamation of saline composite tailings of oil sand. J. Environ. Qual. 32: 2245-2253.

Rodrigue, J. A. and Burger, J. A. and Oderwald, R. G. 2002. Forest productivity and commercial value of pre-law reclaimed mined land in the eastern United States. North. J. Appl. For. 19: 106-114.

Rodrigue, J. A. and Burger, J. A. 2004. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. Soil Sci. Soc. Am. J. 68: 833-844.

Shukla, M. K., Lal, R. and Ebinger, M. 2004a. Soil quality indicators for reclaimed minesoils in southeastern Ohio. Soil Sci. 169(2): 133-142.

Shukla, M. K., Lal, R. Underwood, J. and Ebinger, M. 2004b. Physical and hydrological characteristics of reclaimed minesoils in southeastern Ohio. Soil Sci. Soc. Am. J. 68: 1352-1359.

Stehouwer, R., Day, R. L. and Macneal, K. E. Nutrient and trace element leaching following mine reclamation with biosolids. J. Environ. Qual. 35: 1118-1126.

Turner, M. G. 2005. Landscape ecology in North America: past, present and future. Ecology 86(8): 1967-1974.

Ussiri, D. A. N., Lal, R. and Jacinthe, P. A. 2006. Soil properties and carbon sequestration of afforested pastures in reclaimed minesoils of Ohio. Soil Sci. Soc. Am. J. 70: 1797-1806.

Yarmuch, M., 2003. Measurement of soil physical parameters to evaluate soil structure quality in reclaimed oil sands, Alberta, Canada. M.Sc. Thesis. University of Alberta. Department of Renewable Resources. Edmonton, AB. 70 pp.

CHAPTER III: SOIL MOISTURE REGIMES OF RECLAIMED UPLAND SLOPES IN THE OIL SANDS REGION OF ALBERTA

1.0 Introduction

Large oil sand deposits, found in the Athabasca Oil Sands Region (AOSR) of Alberta, Canada, are recovered through surface mining, creating a significant disturbance. Surface mining operations remove vegetation, soil and subsoil from the earth's surface; disrupting the natural hydrologic and nutrient cycles at a landscape scale (Fung and Macyk 2000). Mine reclamation often alters the natural landscape topography by creating hillslopes with excess overburden and other mine waste products (Carroll et al. 2000; Salazar et al. 2002). Successful mine reclamation requires artificially constructing landforms and creating a soil medium to supply sufficient moisture and nutrients for the development of the desired vegetation type (Li and Fung 1998). In the AOSR, existing landforms, generally flat and depressional areas, are replaced with upland landforms as the extraction and processing of oil sands creates overburden piles and upland slopes on the dykes surrounding the tailings sand ponds. A soil medium is developed by overstripping organic soils to include 25 to 50% mineral subsoil material to create a peat-mineral mix (PMM), which is then placed and spread on overburden or tailings sand dykes as a cover soil (Alberta Environmental Protection 1998; Fung and Macyk 2000). The fundamental goal is to re-establish maintenance-free, self-sustaining ecosystems with a land capability equivalent to pre-disturbance conditions (Alberta Environmental Protection 1998).

Research has documented that reclaimed hillslopes manufactured from surface mine disturbances have altered hydrologic responses compared to those of undisturbed areas. Negley and Eshleman (2006) found increased storm runoff coefficients, greater total storm runoff and higher peak hourly runoff rates in two watersheds that were surface mined and reclaimed in the Appalachian region (USA). They attributed the increase in runoff to soil compaction as a result of land reclamation. Nicolau et al. (2005) and Nicolau (2002), studying a reclaimed coal mine area in central-eastern Spain, found that loam overburden developed a surficial crust which reduced infiltration rate, increased runoff and created a rill network. The upper slope positions were water deficient and plants was unable to colonize, which they attributed to low water content of the soils on the hillslope. Salazar et al. (2002) investigated steep hillslopes of a reclaimed coal mine in north-eastern Spain. As slope gradients increased, runoff increased; when slopes were greater than 33%, the lower slope positions had higher moisture contents than upper slope positions. Yarmuch (2003) compared the physical properties of undisturbed and reclaimed soils in the AOSR and found that reclaimed soils did not have compaction problems and soil structure quality was not limiting plant establishment.

Hydrologic regimes of reclaimed areas appear to be more dynamic during the early reclamation years and become more constant with time. Guebert and Gardner (2001), studying a reclaimed surface coal mine in Pennsylvania (USA), found that newly reclaimed hillslopes had low infiltration rates resulting in run off. Four years following reclamation, infiltration rates increased to pre-disturbance conditions. Loch and Orange (1997) investigated the temporal change in the physical properties at a reclaimed coal mine in Australia infiltration increased and runoff decreased within the first 4 years following reclamation, which they attributed to vegetation development. Yarmuch (2003) found that soil structure quality did not change and was relatively stable with time.

Moskal (1999), Chaikowsky (2003) and Burgers (2005) studied the moisture characteristics of PMM on tailings sand storage facilities within the AOSR. Moskal (1999) established that the water holding capacity of PMM increased when organic carbon increased and that the depth of PMM significantly increased total soil moisture. Chaikowsky (2003) found that PMM held sufficient moisture and that a textural discontinuity on the storage facility influenced the hydrologic regime. Burgers (2005) investigated the interactions of soil moisture and plant community response. He found that vegetation and textural discontinuity influenced the hydrologic regime and that the PMM soils were below wilting point during the growing season. These studies focused on one type of reclamation prescription employed in the AOSR, namely, a PMM over tailings sand.

The overall objective of this research was to quantify the moisture regimes of reclaimed upland slopes of various reclamation prescriptions and ages. Specific objectives were to determine how soil moisture was affected by slope position and to characterize the temporal variability of soil moisture at the slope level.

2.0 Methods

2.1 Study Area

The study area is located approximately 50 - 80 km north of Fort McMurray in north-eastern Alberta, within the boreal forest, which is dominated by a continental climate with short summers and long cold winters (Strong and Leggat 1981; Natural Regions Committee 2006). The mean annual temperature is 0.7°C; January is the coldest month with a mean temperature of -18.8°C and July is the warmest with a mean temperature of 16.8°C (Environment Canada 2004). The mean annual precipitation is 455.7 mm; 342.2 mm occurs as rainfall and 155.8 cm occurs as snowfall. The average annual potential evapotranspiration (PET) is 450 to 500 mm (Fung and Macyk 2000). The boreal forest consists of upland mixedwood forests and extensive wetlands in low-lying areas (Natural Regions Committee 2006). The dominant upland mixed forest vegetation is aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) and white spruce (*Picea glauca* (Moench) Voss.). Jack pine (*Pinus banksiana* Lamb.) stands occur on well-drained, sandy soils. Low lying poorly drained areas consist of black spruce (*Picea mariana* Mill.) dominated treed fens, shrubby fens and sedge fens (Fung and Macyk 2000). Luvisolic soils develop on well to imperfectly drained areas under upland mixedwood forest vegetation (Strong and Leggat 1981; Natural Regions Committee 2006). Brunisols develop on well to rapidly drained fluvial and eolian materials. Gleysols and Organic soils develop in the poorly drained wetland areas.

2.2 Experimental Sites

The soil moisture regimes were quantified, at the slope scale, on four reclaimed slopes with different reclamation prescriptions in the oil sands region of Alberta (Table 3.1). Site 1 is a tailings sand storage facility with 20 cm of PMM over 80 cm of subsoil material. Site 2 is a saline/sodic overburden dump with 20 cm of PMM over 80 cm of subsoil material over Cretaceous saline/sodic overburden. Site 3 is a reclamation trial slope for lean oil sands waste material and was developed using 50 cm of PMM over 50 cm of tailings sand over lean oil sand. Site 4 is a tailings sand storage facility with 20 cm of PMM over tailings sand. Instrumentation on these slopes included weather stations, rain gauges and Diviner 2000® access tubes. Diviner 2000® access tube were replicated three times across upper, mid and lower slope positions, approximately 25 m apart, to assess the topographic and temporal effect of soil moisture on the slopes.

2.3 Meteorological Parameters

Meteorological data were collected at all four sites using instrumented weather stations. Sites 1, 2 and 3 were instrumented with a Vaisala HMP45CF probe to measure air temperature and a Texas Electronics TE525WS tipping bucket rain gauge with a Campbell Scientific Inc. CS705 snowfall adapter. A CSI CR10X datalogger controlled and monitored the meteorological sensors at these three sites. Site 4 was instrumented with a Texas Electronics TE525MM tipping bucket rain gauge and a 107F air temperature sensor, which were monitored with a Campbell Scientific CR510 datalogger.

Canadian Climate Normals (1971-2000) were obtained for the Fort McMurray Airport from Environment Canada (Environment Canada 2004). The 2005 and 2006 data from the Fort McMurray airport were compared to the CCNs from the same location to determine the representativeness of the 2005 and 2006 study years. The data collected from the hillslopes during 2005 and 2006 were then compared to data from the Fort McMurray airport for each of those two years.

2.4 Soil Collection and Analyses

One meter deep soil pits were dug with a shovel on Sites 1 (9 pits), 3 (9 pits) and 4 (6 pits) 1.5 m downslope and 1.5 m to the right of each Diviner 2000® access tube in August 2005. Soil samples were separated by depth increments based on the Land Capability Classification for Forest Ecosystems in the Oil Sands (Cumulative Effects Monitoring Association 2006): 0 – 20 cm, 20 – 50 cm and 50 – 100 cm, classified as topsoil (TS), upper subsoil (US) and lower subsoil (LS), respectively. In some cases the soil depths for the TS were greater than 20 cm. In these cases a second TS increment was sampled or a composite sample for the complete depth was taken if there were no major visual differences within the TS to indicate separating the TS into two intervals. If the TS were less than 20 cm in thickness, the composite sample was taken from the TS only and the depth increment was noted as being less than 20 cm.

One composite soil sample was randomly taken from each depth increment from the side of each soil pit, for physical and chemical analyses, placed in a 4.0 L bucket and taken to the University of Alberta. Prior to analysis soil samples were air dried, crushed and sieved to 2 mm. Site 2 sample collections were modified from the above method as follows: samples (9 sample locations) were collected in August 2006 using an Eijkelkamp soil auger. No soil pits were dug due to industrial facility regulations. Samples were collected 1.5 m downslope and 1.5 m to the right of each Diviner 2000® access tube. One composite sample was randomly taken from each depth interval. Three auger holes adjacent to each other were required to obtain an adequate amount of sample.

Bulk density samples were collected from the upper part of each depth interval in each soil pit. At Site 1 they were collected using an Uhland core with a length of 7.6 cm and a diameter of 7.5 cm. At the other sites, bulk density samples were taken with a hammer corer 6.7 cm in length and 7 cm in diameter. Sand became wedged between the inner sleeve and outer casing of the Uhland core causing difficulties in obtaining an intact bulk density sample; thus, the hammer core was used for the other sites. Because soil pits were not dug on Site 2, bulk density samples were collected for only the TS depth interval for this site using the hammer corer described above. All bulk density samples were oven dried at 105°C for 48 hours and bulk density was calculated by dividing the mass of the oven dried sample by the volume of the core.

Soil water characteristic curves were determined using a pressure plate apparatus (Topp et al. 1983). Gravimetric water contents were determined for 0.01, 0.033, 0.1, 0.3 and 1.5 MPa pressures; where 0.01 MPa was considered field capacity (FC) for coarse textured soils (sands, sandy loams and loamy sands) and 0.033 MPa was considered FC for finer textured soils. FC is the amount of water held in the soil matrix after excess water has drained (Hillel 1998). Internal drainage of coarse-textured soils is rapid but slows quickly because of the decreasing hydraulic conductivity with increasing matrix suction. In finer-textured soils soil water redistribution and drainage occurs over a longer time period and matrix suction does not increase as rapidly. Thus, FC for coarse-textured soils is higher than finer-textured soil. The wilting point (WP) for all soil textures was 1.5 MPa. Available water holding capacity (AWHC) is the difference between FC and WP.

Mapfumo et al. (2003) found that FC and WP values from laboratory measured crushed soil samples combined with field measured bulk density samples might not accurately reflect FC and WP values that occur in the field. Thus, an alternative laboratory method was used to calculate bulk density when determining the soil water retention properties as follows.

Bulk density was calculated for each individual sample after the oven dry weight was determined. The gravimetric moisture contents at these pressures were determined by oven drying the samples at 105°C for 48 hours. Once the sample was oven dried and weighed it was crushed and re-sieved through a 2 mm mesh sieve and then the volume of the sample was measured in a 25 mL graduated measuring cylinder. By dividing the oven dry weight by the volume of the sample, the bulk density of the sieved sample was determined. This value was used to calculate the volumetric moisture content, for a given pressure, by multiplying the gravimetric moisture content by the ratio of bulk density to water density. Both field and laboratory calculated bulk densities are reported.

Particle size distribution was determined using the hydrometer method (Sheldrick and Wang 1993). PMM samples were treated with 50 % H_2O_2 to remove organic matter and 1*M* HCl to remove carbonates. Mineral horizons were treated with 1*M* HCl to remove carbonates. An addition treatment for hydrocarbons was required for some subsoil material horizons. In these cases, the samples were rinsed with dichloromethane (15.5 *M* CH_2Cl_2) following a method obtained from a private lab (Harms 2007).

Total organic carbon (TOC) was quantified using dry combustion following leaching with 8 *M* HCl to remove the inorganic carbon, by a Costech Model 4010 Elemental Analyzer (Nelson and Summers 1996). Prior to analysis the samples were ground to < 150 μm. Organic matter (%) was calculated by multiplying TOC (%) by 1.724 (Hudson 1994).

2.5 Sentek Diviner 2000® Capacitance Sensor

The Diviner 2000®, a portable soil moisture monitoring system manufactured by Sentek Ply. Ltd., is a combination data logger and portable probe. The probe is inserted into a PVC access tube (55.5 mm outside diameter) and scaled frequency readings are taken at regular 10 cm intervals through the soil profile (Sentek Pty. Ltd. 1999). This system uses a method based on measurements of the soil matrix dielectric constant to determine the volumetric water content of a given soil (Groves and Rose 2004). This method has been accepted by researchers as a portable and cost effective alternative to the conventional neutron probe (Groves and Rose 2004 and Burgess et al. 2006). O'Kane Consultants Inc. installed Diviner 2000® access tubes on the four sites in August 2005. The holes for the access tubes were drilled with a hand auger following the methods outlined in the access tube installation guide (Sentek Pty. Ltd. 2003). They also created material specific calibration curves for the soil materials monitored within this study.

Maximum depths of individual access tubes varied because not all tubes could be installed to the maximum depth (160 cm) due to rocks interfering with installation. Soil moisture readings were collected approximately biweekly in 2006 beginning in approximately the middle of May and continuing through September. The time period from the middle of May through to September is hereinafter referred to as the 'growing season'. Diviner 2000® replicates were not installed until mid August of the 2005 growing season. Biweekly moisture readings were not collected during that growing season and only the final measurements of 2005 are used in this study.

Soil moisture was expressed as volumetric moisture content (%) and total soil water (TSW mm) to/for a given depth/depth interval. The TSW to a given depth for a given access tube was calculated by multiplying the volumetric moisture content of a given depth increment by the thickness of that increment, then summing to the desired depth (Burk et al. 2000). For example, total soil water within the upper 35 cm of soil (TSW35) was calculated using the following formula:

$$TSW35 = \left(\frac{VMC10}{100} x \ \ 150 \right) + VMC20 + VMC30$$

where:

- VMC10 is the volumetric moisture content (%) at the 10 cm depth and is assumed to represent the top 150 mm of soil.
- VMC20 and VMC30 are the volumetric moisture contents (%) at 200 and 300 mm depth intervals, and are assumed to represent the 150-250 and 250-350 mm intervals, respectively.

The depths and intervals were chosen to quantify the soil moisture regimes of the different materials within a soil profile. TSW35 represents the PMM for Sites 1, 2 and 4 while TSW40 represents the PMM for Site 3. TSW65-95 and TSW55-85 represent zones in the subsoil material at Sites 1 and 2, respectively and TSW60-100 and TSW85-135 represent zones in the tailings sand at Sites 3 and 4, respectively. Each site is unique in its reclamation prescription; as a result, the TSW depths and depth increments differ among the sites. Factors influencing the depths and increments chosen were depth of the access tubes and variability in depths of the peat mineral mix and underlying material.

Site average soil moisture was used to investigate overwinter soil moisture recharge and precipitation response at each site. Soil moisture recharge over winter was determined from the difference between the first soil moisture measurement of the 2006 growing season and the last soil moisture measurement of the 2005 growing season. During the 2006 growing season, a hot dry period was followed by a cooler wet period and soil moisture data from those time periods were used to determine soil moisture response to precipitation. These are denoted "dry day" and "wet day", respectively.

2.6 Statistical Analyses

A repeated measures design was used since there were multiple measurements of a response variable on the same experimental unit (Littell et. al. 2006). In this case, the experimental unit was the Diviner 2000® access tube and the treatment assigned to the experimental unit was slope position. Data were collected on the response variable (soil moisture) of each individual experimental unit over time. The design was considered a mixed model because it contained both random and fixed effects; thus, the data were analyzed using the MIXED procedure in SAS 9.1 (Littell et. al. 2006). The statistical model for a repeated measures design is $Y_{ijk} = \mu + \alpha_i + \gamma_k + (\alpha\gamma)_{ik} + \varepsilon_{ijk}$, where $\mu + \alpha_i + \gamma_k + (\alpha\gamma)_{ik}$ is the mean for slope position i at time k, and accounts for effects the slope position, time period and the slope position x time period interaction. The random error related to the response variable at time k on the j^{th} subject within treatment i is noted by ε_{ijk}.

2.7 Data Normality

Mixed models are linear statistical models and one of the assumptions of these models is that the response variable residuals follow a normal distribution (Littell et al. 2006). The residuals of the soil moisture data were negatively skewed when inspected visually and the skewness and kurtosis values confirmed a non-normal distribution (Quinn and Keough 2002). Because the data was negatively skewed the data were square root transformed to reduce skewness and kurtosis (Steel et al. 1997). In some cases the residuals continued to have a non-normal distribution even following data transformation (Shapiro-Wilk ≤ 0.05). Attempts were made to remove 'outliers' in the datasets but this resulted in the removal of a large number of data points. In some cases removing outliers excluded an experimental unit's entire dataset reducing the power of the statistical tests. Removing an entire experimental unit's dataset was undesirable so the entire dataset was used, including the 'outliers'. Because of the complexity of the experimental design, mixed model analysis was chosen to analyze the data (normal and non-normal) and the results appear to be consistent with graphical representation of the data; caution was used in the interpretation of the results for the non-normal data.

3.0 Results

3.1 Meteorological Parameters

The air temperature at the Fort McMurray airport was similar to the CCN for the first nine months in 2005 but was higher in 2006 (Table 3.2). During the last three months in 2005 the air temperature ranged from 1 to 8 °C higher and in 2006 the monthly temperature ranged from 0.5 to 7 °C higher than the CCN. The sites were 1 to 4 °C higher during the 2006 growing season than in 2005 with the greatest temperature differences occurring in June.

Precipitation at the Fort McMurray airport was below the CCN for all of 2005 with the exception of July which received approximately 55 mm more precipitation than the CCN (Table 3.3). Precipitation was below the CCN for January through March, June and August through December. The sites had low amounts of precipitation from October 2005 though March 2006. May 2006 through September 2006 had less precipitation than the same time for the previous year. All sites experienced a large precipitation event of 74 to 104 mm from July 5th to 11th, 2006 which accounted for 41 to 56 % of the precipitation that fell during the growing season.

3.2 Soil Moisture and Retention Dynamics

The PMM materials at Site 1, 3 and 4 have a sandy loam texture and at Site 2 has a clay loam texture (Table 3.4). Sites 1 and 3 have greater AWHCs (21.7 and 28.6%, respectively) than Sites 2 and 4 which have AWHCs of 10.5 and 13.1%, respectively. The organic matter contents of PMMs at Sites 1, 2, 3 and 4 are 23.8, 8.5, 10.7 and 6.7%, respectively.

At Site 1 TSW35 was within the available range on all dates during the 2006 growing season (Figure 4.1a), while TSW65-95 was greater than FC for all measurements in 2006 (Figure 4.1b). The results were the same for both TSW35 and TSW65-95 from early August through to late September 2006 (data not shown).

At Site 2 TSW35 was within the available range for 2006 with the exception of the final measurement date in 2006, which was below WP (Figure 4.1c). TSW55-85 was within the available range for all measurements during the 2006 growing season (Figure 4.1d). TSW35 and TSW55-85 were within AWHC for all measurements from the end of August to the end of October 2005 (data not shown).

At Site 3 TSW40 was within the available range on all dates measured during the 2006 growing season (Figure 4.2a), while TSW60-100 depth interval, which is tailings sand, was above field capacity for all measurements dates during the 2006 growing season (Figure 4.2b). The results were the same for both TSW40 and TSW60-100 from early August through to mid September 2006 (data not shown).

At Site 4 TSW35 did not reach or exceed FC during the 2006 growing season and TSW35 fell below WP 72% of the time (Figure 4.2c). TSW85-135 exceeded FC for 91% of the time in 2006 (Figure 4.2d). From late June to late September 2005 TSW35 exceeded FC 20% of the time and was within AWHC for the rest of the time and TSW85-135 was within the AWHC for all measurements (data not shown).

Soil moisture response at Sites 1, 2 and 4 closely followed major precipitation events; while Site 3 soil moisture response followed precipitation events its response was more subdued than it was at the other three sites.

3.3 Slope Position Effects

The hypothesis that lower slope positions would have higher soil moisture contents than upper slope positions was generally not supported on any of the reclaimed sites. Site 1 and 2 showed slope position effects for TSW65-95 and TSW35 during the 2006 growing season only, respectively (data not shown) while Sites 2 and 3 did not have any slope position effects during either the 2005 or 2006 growing season (data not shown). It was suspected that variability in PMM depth may be influencing soil moisture results. Peat mineral mix depth was added into the repeated measures model as a covariate but was found to be non-significant (data not shown).

3.4 Soil Moisture Overwinter Recharge (Fall 2005 - Spring 2006)

The sites were not similar in soil moisture overwinter recharge. Site 1 had a negligible average gain of 0.4 mm in the upper soil (0 - 50 cm) overwinter (Table 3.5). There was high variability among tubes ranging from a loss of 26.3 to a gain of 10.7 mm of moisture in the upper soil with almost half the monitoring locations losing moisture and half gaining moisture. This trend was also reflected in the subsoil (50 - 100) where there was a site average gain of 0.4 mm in soil moisture overwinter, and large variability among tubes ranging from a loss of 13.2 to a gain of 28.7 mm in soil moisture (Table 3.5).

Site 2 had an average overwinter soil moisture gain of 22.9 mm in the upper soil at all but one monitoring location (Table 3.5). There was high variability among tubes ranging from a loss of 8.1 to a gain of 42.2 mm. The subsoil had an average gain of 5.4 mm overwinter, and two of the nine monitoring locations lost moisture (Table 3.5). There was high variability among tubes ranging from a loss of 26.2 to a gain of 30.2 mm in soil moisture.

Site 3 had an average loss in 0.8 mm of soil moisture overwinter in the upper soil, and two of the nine monitoring locations gained soil moisture (Table 3.5). There was little variability among tubes ranging from a loss in 2.9 to a gain in 2.4 mm. The subsoil had an average gain of 3.1 mm with all monitoring locations gaining soil moisture (Table

3.5). There was moderate variability among tubes with soil moisture gain ranging from 0.4 to 7.9 mm.

Site 4 had an average loss of 37.9 mm in soil moisture overwinter in the upper soil at all but one monitoring location (Table 3.5). There was high variability among tubes ranging from a loss of 75.8 to a gain of 2.2 mm (Table 3.5). The subsoil had an average site loss of 1.0 mm where half of the monitoring locations lost and half gained soil moisture (Table 3.5). There was high variability among tubes from a loss of 27.4 to a gain of 16.8 mm in soil moisture.

3.5 Soil Moisture Response to Precipitation

The sites gained soil moisture in the upper soil (0 - 50 cm) profile but not all sites gained soil moisture in the subsoil (50 - 100 cm) following a large rain event from July 5 to 11, 2006. Sites 1, 2 and 3 received approximately 75 mm of precipitation and Site 4 approximately 104 mm of precipitation during this time period. At Site 1 soil moisture increased by 42.8 mm in the upper soil profile (Table 3.6). There was high variability among tubes with a gain in soil moisture ranging from 7.4 to 77.2 mm. Overall the subsoil gained 10.1 mm of soil moisture; however, two of the eighteen monitored locations lost soil moisture. There was high variability among tubes from a loss of 2.1 to a gain of 30.3 mm.

Site 2 had an average soil moisture gain of 32.3 mm, in the upper soil, following the precipitation event (Table 3.6). There was high variability among tubes with a gain of soil moisture ranging from 2.1 to 65.2 mm. The subsoil lost 15.3 mm of moisture and soil moisture ranged from 1.3 to 44.3 mm among all tubes.

Site 3 had an average gain in soil moisture of 11.8 mm, in the upper soil with tubes ranging from a gain of 5.7 to 21.1 mm. The subsoil had an average gain of 0.6 mm, and values ranged from a loss of 0.6 to a gain of 3.3 mm of soil moisture.

At Site 4, soil moisture in the upper soil on average increased by 53.8 mm and soil moisture gain ranged from 27.8 to 76.6 mm. The subsoil had an average gain in soil moisture of 44.7 mm with all tubes increasing in soil moisture with a range from 25.3 to 64.0 mm.

4.0 Discussion

Coarse-textured soils typically have higher infiltration rates and saturated hydraulic conductivities and lower AWHCs than fine-textured soils (Hillel 1998). Organic matter content has been shown to increase the volume of water held by soil at FC to a greater extent than the volume of water held at WP, thereby increasing AWHC (Hudson 1994). Bauer and Black (1992) found that increasing organic matter concentration in coarse-textured materials increased the AWHC to a greater extent than when organic matter concentration increased in finer textured materials. There were differences in AWHC among sites, which could be attributable to differences in clay, sand and organic matter content. Sites 1 and 3 with higher organic matter contents had greater AWHC. Thus, the texture of the material and the amount of organic matter material likely influenced the amount of soil moisture that could be retained within a given PMM. During this study's timeframe it appears that Sites 1, 2 and 3 would have held sufficient moisture to sustain plants while Site 4 was subject to low soil moisture that would impair plants.

The FC and WP values for the tailings sand at Sites 3 and 4 appear low relative to moisture contents measured in the laboratory, likely the result of the tailings sand becoming hydrophobic and difficult to saturate once dry. The tailings sand at Sites 3 and 4 and the peat mineral mix at Site 3 were difficult to saturate for the pressure plate analyses, suggesting that these materials are displaying some hydrophobic properties. At Site 3, the hydrophobic property of the PMM is likely inflating the moisture content at FC thereby inflating the AWHC. Other studies on tailings sand storage facilities have also suggested hydrophobic tailings sands (Chaikowsky 2003; Burgers 2005). In addition, Site 3 is unvegetated and hence moisture loss is largely from evaporation. If vegetation were established, the soil moisture regime within the PMM would likely change dramatically.

In general, the PMM had soil moisture regimes that were more dynamic than those deeper within the soil profiles (Figures 2.1 and 2.2). These results concur with previous studies in Alberta's boreal forest region, which have shown temporal soil moisture fluctuations to be greater in the upper soil profile than in the lower subsoil, and that the upper soil profile responds strongly to local precipitation events (Whitson et. al.

2005; Powell and Bork 2007). The variability in the seasonal distribution of precipitation and the resulting soil moisture flux has been shown to have an effect on the growth and development of boreal forest conifer species (Brooks et al. 1998). Annual growth of black spruce was greater in cooler, wetter years and jack pine growth was favoured during seasons with increased temperature and spring precipitation. Overall, Brooks et al. (1998) found that boreal forest tree species responded differently to annual temperature and precipitation distribution.

The soil moisture characteristics at Site 3 did not respond strongly to precipitation events. Rills and channels were observed on this site, which is an indication of surface runoff and has been known to occur at reclaimed areas (Hillel 1998; Guebert and Gardner 2001; Nicolau et al. 2005). The runoff is likely a function of the lack of vegetation and the influence of a hydrophobic soil substrate, which is likely decreasing infiltration. Vegetation protects the soil surface from the erosive potential of rainfall and when not present soil removal by rill and sheet erosion occurs. Also, the peat mineral mix and the tailings sand from this site were difficult to saturate for the pressure plate analyses, suggesting that these materials have some hydrophobic properties. These factors are likely leading to the little loss or gain of moisture that was observed within the soil profile at Site 3.

Sites 1, 2 and 3 held sufficient soil moisture within the PMM during late 2005 and most of the 2006 growing season. Soil moisture content, at Site 4, was within the AWHC during late 2005 but below WP for the majority of the 2006 growing season. This is a south-facing, warm and dry slope with coarse textured soils, which are known to have low soil water contents. Studies in the southern boreal forest of Saskatchewan have found that warm summer seasons coupled with low water holding capacity and high hydraulic conductivity of sandy soils associated with jack pine sites can lead to soil moisture levels at wilting point in the upper soil during dry seasons (Kljun et al. 2006; Grant et al. 2007). In addition, previous studies have found that peat mineral mixes on tailings sands storage facilities are prone to water contents below WP (Burgers 2005). Site 1 is a west-facing slope but did not experience the low moisture contents that occurred at Site 4, likely due to the higher organic matter content in the PMM at Site 1 increasing AWHC and its ability to buffer temporal soil moisture oscillations.

Slope position not affecting soil moisture distribution on the reclaimed hillslopes was an unexpected outcome and could be the result of soil moisture patterns responding to heterogeneity in soil properties and vegetation spatial patterns rather than slope position. The PMM is generally placed on site while still frozen and broken up and evened out to the prescribed application depth by large equipment, once the material has thawed. The handling and placement of the reclamation material by large scale equipment creates large spatial variability in PMM depth and distribution across a site. This spatial variability occurs in variable application depth and distribution of PMM. For the sampled soil profiles, coefficient of variation suggest that there is moderate variability for soil moisture at a given depth/depth interval among soil profiles within a slope position. The coefficient of variation is a measure of the variation within a dataset and the larger the percentage the greater the variability of the parameter (Dollhoph 2000). Janowicz et al. (2003) studied soil moisture of the boreal forest in Wolf Creek watershed in the Yukon. Coefficient of variation values for soil moisture in this boreal forest ecosystem were 46 %, which is less than what was found on the reclaimed sites.

The variation in PMM depths appeared to influence soil moisture variability. Chaikowsky (2003) using regression analysis with topsoil depth found no direct relationship between soil moisture status and topsoil depth; however, she still suggested that the variability of PMM depth had some influence on soil moisture distribution through the profile. In our study, PMM depth was found to be not significant, indicating that PMM was not influencing soil moisture distribution within the soil profile.

Grayson et al. (1997) suggested that there are two states for soil water patterns: a wet state and a dry state. The wet state occurs when precipitation is greater than evapotranspiration and the dominant control on the spatial patterns of soil moisture is topography, which the authors refer to as a non-local control. The dry state occurs when precipitation is less than evapotranspiration and soil moisture spatial patterns are a function of soil and vegetation variability, which they refer to as local control. The authors suggest that soil moisture patterns are less sensitive to topographic spatial patterns during dry conditions than during wet conditions. When soil moisture distribution is dominated by local controls, soil moisture contents within the soil are more random and have greater spatial variability than when soil moisture distribution is dominated by non-local controls. During wet periods soil moisture content variability decreases and the influence of topography on soil moisture distribution increases when compared to drier periods (Western et al. 1999; Gómez-Plaza et al. 2001; Teuling and Troch 2005; Choi et al. 2007).

Annual potential evapotranspiration was calculated using the Penman-Monteith equation for Site 1, and indicated a soil moisture deficit of 284 mm during 2006. The majority of the soil moisture deficit accumulated from May through to October (data not shown). Since this site was experiencing a moisture deficit, it was likely that the other three sites also experienced moisture deficits during the 2006 growing season. The soil moisture patterns are then likely being controlled by local conditions, such as vegetation and soil variability. Slope position effects may not have been observed because the spatial variability of soil moisture across slope positions was similar to or greater than the spatial variability of soil moisture among slope positions. Spatial and temporal variability are inherent characteristics of hillslope-soil-water systems and as a result are scale dependent across space and time (Grayson et al. 1997). Further studies of the topographical effect on soil moisture distribution at reclaimed sites in the AOSR should include increasing the scale of the study and the amount of sample units across a slope position in an attempt to reduce the variability of soil moisture data.

The slope gradients may not have been great enough to have an influence on the topographical distribution of soil moisture. Salazar et al. (2002) found that when the slope gradient was greater than 33% lower slope positions had higher moisture contents than upper slope position on reclaimed coal mines in north-eastern Spain. All the slopes investigated in this study had slope gradients equal to or less than 25%.

Aspect is known to influence the rate of thaw with southern aspects thawing faster than northern aspects (Carey and Woo 1998). The little change in overwinter upper soil moisture at Site 1 and the overwinter loss of soil moisture at Site 4 is likely the result of these sites being west and south facing, respectively. The 2006 spring was warmer than average and had below average overwinter and spring precipitation, which likely lead to high evapotranspiration rates prior to the initial measurement. Sites 2 and 3 are north-facing slopes and both had an increase in overwinter soil moisture. Site 2 had the largest increase in soil moisture likely a combination of the north-facing slope having less incoming solar radiation during the spring, thereby decreasing snow melt and the vegetation lessening the amount of snow melt runoff. Site 3 was unvegetated and likely had high runoff when snowmelt occurred; thus, there was less of an increase in soil moisture in the upper soil. Site 2 had the highest gain in soil moisture in the lower subsoil of all sites, which is due to the combination of factors listed above increasing the amount of soil moisture able to infiltrate.

Conversely, all sites responded with an increase in soil moisture within the upper soil following a large rain event. The two vegetated, coarse-textured sites, Sites 1 and 4 had the highest increase in soil moisture following a rain event. The unvegetated coarse-textured site, Site 3 had the lowest increase in soil moisture. Site 3 likely had high runoff during a precipitation event and little precipitation was able to infiltrate the soil; as a result the soil response at Site 3 was lower. Sites 1, 3 and 4 all had an increase in soil moisture in the lower subsoil following the rain event indicating that these sites are subject to percolation. Conversely, Site 2 lost soil moisture in the lower subsoil. Prior to the large rain event, soil moisture in the PMM was approaching WP at this site. Plants could have been drawing moisture from deeper in the soil profile since the PMM was near WP, thereby reducing soil moisture within the deeper subsoil. In addition, this site had finer textured materials than the other sites, and thus lower hydraulic conductivity (Hillel 1998). The lower hydraulic conductivity, coupled with water stressed plants, could lead to rapid plant uptake of soil moisture as it became available, further reducing the infiltration between the two dates.

5.0 Conclusions

Lower slope positions, on these reclaimed upland slopes, did not have higher moisture contents than the mid and upper slope positions. Available water for plants increased with increasing organic matter and sites that had a greater fraction of coarse textured material within the PMM had higher rates of infiltration during large rain events. The upper soil profiles had highly dynamic moisture regimes which responded more quickly to precipitation events than the lower subsoil. Sites did not respond similarly to overwinter recharge as the sites varied from a loss, or little change in overwinter soil moisture on the coarse-textured south- and west-facing sites to gains at the north-facing sites. Site 3 was an anomaly since there was little response to precipitation events and little temporal change in the soil moisture profiles.

6.0 Literature Cited

Alberta Environmental Protection. 1998. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region. Report # ESD/LM/99-1. 212 pp.

Bauer, A. and Black, A. L. 1992. Organic carbon effects on available water capacity of three soil textural groups. Soil Sci. Soc. Am. J. 56: 248-254.

Brooks, J. R., Flannagan, L. B. and Ehleringer, J. R. 1998. Responses of boreal conifers to climate fluctuations: indications from tree-ring widths and carbon isotope analyses. Can. J. For. Res. 28: 524-533.

Burgers, T. D. 2005. Reclamation of an oil sands tailings storage facility: vegetation and soil interactions. M.Sc. Thesis. Department of Renewable Resources, University of Alberta. Edmonton, AB. 134 Pp.

Burgess, P. J., Reinhard, B. R. and Pasturel, P. 2006. Compatible measurements of volumetric soil water content using a neutron probe and Diviner 2000 after field calibration. Soil Use Manag. 22: 401-404.

Carey, S. K. and Woo, M. K. 1998. Snowmelt hydrology of two subarctic slopes southern Yukon, Canada. Nord. Hydrol. 29: 331-346.

Carroll, C., Merton, L. and Burger, P. 2000. Impact of vegetation cover and slope on runoff, erosion and water quality for field plots on a range of soil and spoil materials on central Queensland coal mines. Aust. J. Soil Res. 38: 313-327.

Chaikowsky, C. L. A. 2003. Soil moisture regime and salinity on a tailings sand storage facility. M.Sc. Thesis. Department of Renewable Resources, University of Alberta. Edmonton, AB. 135 pp.

Choi, M., Jacobs, J. M. and Cosh, M. H. Scaled spatial variability of soil moisture fields. Geophys. Res. Lett. 34: 1-6.

Cumulative Effects Monitoring Association. 2006. Land capability classification for forest ecosystems in the oil sands. Volume 1: Field manual for land capability determination. Third Edition. 65 pp.

Dellhopf, D. J. 2000. Sampling strategies for drastically disturbed land. In: R. I. Barmhisel, R. G. Darmody and W. L. Daniels (eds.). Reclamation of Drastically Disturbed Lands. Agronomy Monograph No. 41. American Society of Agronomy. Madison, WI. Pp. 21-40.

Environment Canada. 2004. Canadian Climate Normals 1971-2000. http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html [Accessed online. September 20, 2006].

Fung, M. Y. P. and Macyk, T. M. 2000. Reclamation of oil sands mining areas. In: R. I. Barmhisel, R. G. Darmody and W. L. Daniels (eds.). Reclamation of Drastically Disturbed Lands. Agronomy Monograph no. 41. American Society of Agronomy. Madison, WI. Pp. 755-774.

Gómez-Plaza, A., Martinez-Mena, M., Albaladejo, J. and Castillo, V. M. 2001. Factors regulating spatial distribution of soil water content in small semiarid catchments. J. Hydrol. 253: 211-226.

Grant, R. F., Barr, A. G., Black, T. A., Gaumont-Guay, D., Iwashita, H. I., Kidson, J., McCaughey, H., Morgenstern, K., Murayama, S., Nesic, Z., Saigusa, N., Shashkov, A. and Zha, T. 2007. Net ecosystem productivity of boreal jack pine stands regenerating from clearcutting under current and future climates. Global Change Biol. 13: 1-18.

Grayson, R. B., Western, A. W. and Chiew, F. H. S. 1997. Preferred states in spatial soil moisture patterns: local and nonlocal controls. Water Resour. Res. 33: 2897-2908.

Groves, S. J. and Rose, S. C. 2004. Calibration equations for Diviner 2000 capacitance measurements of volumetric soil water content of six soils. Soil Use Manag. 20: 96-97.

Guebert, M. D. and Gardner, T. W. 2001. Macropore flow on a reclaimed surface mine: infiltration and hillslope hydrology. Geomorphology 39: 151-169.

Harms, A. 2007. Natural resources analytical laboratory technician. University of Alberta. Personal communication.

Hillel, D. 1998. Environmental Soil Physics. Academic Press. San Diego, CA. 771 pp.

Hudson, B. D. 1994. Soil organic matter and available water capacity. J. Soil Water Cons. 49: 189-194.

Janowicz, J. R., Gray, D. M. and Pomeroy, J. W. 2003. Spatial variability of fall soil moisture and spring snow water equivalent within a mountainous sub-arctic watershed. Proceedings of the 60th Annual Eastern Snow Conference. Pp. 127 - 139.

Kljun, N., Black, T. A, Griffis, T. J., Barr, A. G., Gaumont-Guay, D., Morgenstern, K., McCaughey, J. H. and Nesic, Z. 2006. Response of net ecosystem productivity of three boreal forest stands to drought. Ecosystems 9: 1128-1144.

Li, X. and Fung, M. Y. P. 1998. Creating soil-like materials for plant growth using tailings sand and fine tails. J. Can. Petrol. Tech. 37 (11): 44-47.

Littell, R. C., Milliken, G. A., Stroup, W. W., Wolfinger, R. D. and Schabenberger, O. 2006. SAS System for mixed models. Second edition. SAS Institute Inc. Cary, NC. 814 pp.

Loch, R. J. and Orange, D. N. 1997. Changes in some properties of topsoil at Tarong Coal-Meandu Mine coalmine with time since rehabilitation. Aust. J. Soil Res. 35: 777-784.

Mapfumo, E., Chanasyk, D. S. and Baron, V. S. 2003. Patterns and simulation of soil water under different grazing management systems in central Alberta. Can. J. Soil Sci. 83: 601-614.

Moskal, T. D. 1999. Moisture characteristics of coarse textured soils and peat:mineral mixes. M. Sc. Thesis. Department of Renewable Resources, University of Alberta. Edmonton, AB. 139 pp.

Natural Regions Committee. 2006. Natural regions and subregions of Alberta. Compiled by D. J. Downing and W. W. Pettapiece. Government of Alberta. Pub. No. T/852. 254 pp.

Negley, T. L. and Eshleman, K. N. 2006. Comparison of stormflow responses of surface-mined and forested watersheds in the Appalachian Mountains, USA. Hydrolog. Process. 20: 3467-3483.

Nelson, D.W. and Summers, L.E. 1996. Total carbon, organic carbon, and organic matter. In: D.L. Sparks (ed.). Methods of Soil Analysis, Soil Science Society of America, Madison, WI. pp. 961–1010.

Nicolau, J. M. 2002. Runoff generation and routing on artificial slopes in a Mediterranean-continental environment: the Teruel coalfield, Spain. Hydrolog. Process. 16: 631-647.

Nicolau, J. M., Moreno, M. and Espigares, T. 2005. Ecohydrology of rilled slopes derived from opencast mining reclamation in a semiarid area. Geophys. Res. Abstr. 7: 85-95.

Powell, G. W. and Bork, E. W. 2007. Effects of aspen canopy removal and root trenching on understory microenvironment and soil moisture. Agroforest Syst. 70: 113-124.

Quinn, G. P and Keough, M. J. 2002. Experimental design and data analysis for biologists. Cambridge University Press. Cambridge, UK. 537 pp.

Salazar, M., Poch, R. M. and Bosch, A. D. 2002. Reclamation of steeply sloping coal spoil banks under Mediterranean semi-arid climate. Aust. J. Soil Res. 40: 827-845.

Sentek Pty. Ltd. 1999. Sentek Diviner 2000 user guide version 1.2. Australia Sentek Pty Ltd. Stepney, South Australia. 70 pp.

Sentek Pty. Ltd. 2003. Access tube installation guide version 1.0. Australia Sentek Pty Ltd. Stepney, South Australia. 54 pp.

Sheldrick, B. H. and Wang, C. 1993. Particle size distribution. In: Soil Sampling and Methods of Analysis. Lewis Publishers. Boca Raton, FL. Pp. 499-511.

Steel, R. G. D., Torrie, J. H. and Dickey, D. A. Principles and procedures of statistics: a biometrical approach. Third edition. McGraw-Hill. Madison, WI. 666 pp.

Strong, W. L. and Leggat, K. R. 1981. Ecoregions of Alberta. Alberta Energy and Natural Resources. Edmonton, AB. 64 pp.

Teuling, A. J. and Troch, P. A. 2005. Improved understanding of soil moisture variability dynamics. Geophys. Res. Lett. 32: 1-4.

Topp, G. C., Galganov, Y. T., Ball, B. C. and Carter, M. R. 1983. Soil water desorption curves. In: Soil Sampling and Methods of Analysis. Lewis Publishers. Boca Raton, FL. Pp. 569-579.

Western, A. W., Grayson, R. B., Günter, B., Willgoose, G. R. and McMahon, T. A. 1999. Observed spatial organization of soil moisture and its relation to terrain indices. Water Resour. Res. 35: 797-810.

Whitson, I. R., Chanasyk, D. S. and Prepas, E. E. 2005. Effect of forest harvest on soil temperature and water storage and movement patterns on Boreal Plains hillslopes. J. Environ. Eng. Sci. 4: 429-439.

Yarmuch, M., 2003. Measurement of soil physical parameters to evaluate soil structure quality in reclaimed oil sands, Alberta, Canada. M.Sc. Thesis. University of Alberta. Department of Renewable Resources. Edmonton, AB. 70 pp.

Table 3.1 Site description table.

Site	Site 1	Site 2	Site 3	Site 4
Reclamation Year	2003	1999	2003	1992
Organic capping	20 cm PMM	20 cm PMM	50 cm PMM	20 cm PMM
Peat type	Humic	Mesic	Mesic	Humic
Mineral Substrate	80 cm 2° over LOS+OB	80 cm 2° over Saline/Sodic OB	50 cm 2° over LOS	Tailings sand
Aspect	West	North	North east	South
Slope	25%	20%	24%	25%
Vegetation	*Populus tremuloides, Picea glauca, Betula papyrifera*	*Populus tremuloides, Picea glauca*	None	*Pinus contorta, Populus × jackii*

PMM = peat mineral mix
2° = subsoil material
LOS = lean oil sand
OB = overburden

Table 3.2 Mean monthly air temperatures (°C) in the study region and for all four sites.

	CCN*	Ft. Mc Airport		Site 1		Site 2		Site 3		Site 4	
Month	1971-2000	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
January	-18.8	-19.1	-11.3	-18.3	-10.8	-18.6	-11.3	-18.8	-11.6	-18.0	-10.8
February	-13.7	-11.6	-13.0	-10.4	-10.7	-10.9	-11.0	-11.1	-10.9	-10.1	-10.5
March	-6.5	-4.9	-4.4	-3.6	-3.4	-4.7	-4.3	-4.4	-3.6	-3.5	-3.4
April	3.4	5.3	7.3	6.2	8.6	5.5	8.1	5.8	8.4	6.6	9.3
May	10.4	10.0	10.9	11.1	12.1	10.3	11.5	10.7	12.1	11.1	12.4
June	14.7	13.8	17.1	15.1	18.7	14.3	17.8	14.8	19.2	15.4	19.1
July	16.8	16.2	17.2	17.1	18.2	16.4	17.5	17.0	18.3	17.4	18.6
August	15.3	14.1	15.5	14.7	16.7	14.2	15.9	14.5	16.5	14.9	16.9
September	9.4	8.9	11.2	10.1	12.6	9.5	11.8	9.7	12.4	10.1	12.7
October	2.8	3.9	1.5	4.9	2.4	4.3	na	4.5	2.0	5.1	2.3
November	-8.5	-3.8	-15.1	-2.8	-13.2	-3.3	na	-3.5	-13.6	-3.0	-13.2
December	-16.5	-8.1	-10.0	-7.9	-8.9	-8.1	na	-7.6	-8.8	-7.8	-8.0

*Environment Canada Climate Normals for the Fort McMurray Airport (1971 - 2000)

Table 3.3 Total monthly precipitation (mm) in the study region and including the four study sites.

	CCN*	Ft. Mc Airport		Site 1		Site 2		Site 3		Site 4	
Month	1971-2000	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
January	19.3	14.5	10.0	16.3	2.5	33.6	1.0	1.8	0.2	3.6	0.8
February	15.0	11.0	16.0	8.9	0.3	0.0	3.0	0.8	2.0	4.3	1.3
March	16.1	15.0	24.5	11.7	17.0	0.0	10.4	1.9	0.5	7.4	12.7
April	21.7	16.5	23.5	21.8	14.7	13.7	5.3	19.4	0.0	43.7	8.6
May	36.9	22.5	49.5	24.6	52.1	27.2	41.3	61.4	20.4	31.2	51.3
June	74.8	61.0	50.0	64.3	28.7	56.9	36.0	65.1	24.2	65.5	38.9
July	81.3	136.0	88.5	70.6	106.9	87.3	107.8	120.3	110.2	90.9	138.9
August	72.7	64.5	37.0	59.4	35.8	56.1	35.5	91.1	25.9	86.4	46.5
September	46.8	17.0	23.0	18.8	34.8	9.5	34.4	17.3	15.1	17.5	45.5
October	29.6	3.5	8.5	1.5	9.4	1.1	na	5.9	2.9	1.5	2.8
November	22.2	1.0	21.5	4.8	0.0	1.3	na	0.0	0.0	5.1	0.0
December	19.3	0.0	7.5	7.6	0.0	0.0	na	0.0	0.3	20.6	0.0
October - March#	121.5	94.5	55.0	58.2	33.7	79.4	16.8	84.0	8.6	56.4	42.0
May - September	312.5	301.0	248.0	237.7	258.3	237.0	255.0	355.2	195.8	291.5	321.1

*Environment Canada Climate Normals for the Fort McMurray Airport (1971 - 2000)
#2005 values are the sum of October to December (2004) and January to March (2005) precipitation
na = data unavailable

Table 3.4 Mean soil physical properties of the study sites.

Site	Depth interval (cm)	Clay (%)	Sand (%)	Texture	Field Bulk Density ($Mg\ m^{-3}$)	Laboratory Bulk Density ($Mg\ m^{-3}$)	VMC (%; 0.01 MPa)	VMC (%; 0.03 MPa)	VMC (%; 1.5 MPa)	TOC%
Site 1	0 - 24.9 (2.3)	5.7 (1.1)	56.3 (2.0)	SL	0.62 (0.12)	0.59 (0.06)	33.9 (0.9)	na	12.2 (0.4)	13.8 (4.1)
Site 1	24.9 (2.3) - 82.6 (4.9)	5.3 (1.0)	64.7 (3.5)	SL	1.32 (0.70)	1.00 (0.02)	24.9 (1.1)	na	9.2 (0.3)	na
Site 1	> 82.6 (4.9)	5.5 (1.1)	64.0 (6.1)	SL	1.51 (0.30)	1.07 (0.02)	22.6 (2.3)	na	7.1 (0.4)	na
Site 2	0.0 - 20.0	35.5 (7.8)	37.4 (6.7)	CL	0.84 (0.07)	0.70 (0.03)	na	23.0 (0.5)	12.5 (0.3)	4.9 (0.8)
Site 2	20.0 - 50.0	24.1 (1.5)	34.6 (1.3)	L	na	0.99 (0.01)	na	25.2 (0.4)	14.0 (0.5)	na
Site 2	50.0 - 100	20.1 (1.7)	40.0 (3.6)	L	na	1.04 (0.01)	na	27.4 (0.4)	15.0 (0.9)	na
Site 3	0 - 20.0 (0.0)	14.2 (0.7)	67.8 (0.2)	SL	0.90 (0.02)	0.90 (0.01)	39.6 (0.9)	na	11.0 (0.2)	6.2 (0.2)
Site 3	20.0 (0.0) - 56.9 (5.0)	13.8 (0.9)	65.2 (2.3)	SL	0.86 (0.03)	0.86 (0.01)	32.7 (0.7)	na	11.7 (0.1)	na
Site 3	56.9 (5.0) - 119.9 (5.8)	1.4 (0.8)	92.6 (1.1)	S	1.23 (0.01)	1.34 (0.02)	6.2 (0.3)	na	0.8 (0.1)	na
Site 4	0 - 19.7 (0.3)	14.0 (1.2)	71.1 (0.1)	SL	1.32 (0.05)	1.04 (0.02)	22.8 (0.7)	na	9.7 (0.5)	3.9 (0.5)
Site 4	19.7 (0.3) - 48.4 (4.6)	14.2 (1.3)	73.4 (2.7)	SL	1.21 (0.10)	1.03 (0.02)	26.1 (1.6)	na	8.9 (0.4)	na
Site 4	>48.4 (4.6)	2.4 (0.6)	93.0 (1.2)	S	1.65 (0.06)	1.37 (0.01)	4.8 (0.9)	na	1.8 (0.3)	na

Values reported as mean (standard error)
n = 3 for each clay and sand measurement for each depth interval
n = 9 for depth interval and bulk density at each depth interval for Sites 1 to 3; n = 6 for depth interval and bulk density at each depth interval for Site 1
Note: depth interval samples for Site 2 were taken at exactly 0-20, 20-50 and 50-100; therefore, at this site there is no mean (standard error) for the depth interval values
n = 18 for VMC at a given pressure for each depth interval for Sites 1 to 3; n = 12 for VMC at a given pressure for each depth interval for Site 4
Field and laboratory bulk density are provided for comparison between field conditions and laboratory measurements; laboratory bulk density values were used to calculate VMC at FC and WP
% Organic matter = % TOC * 1.724
na = data unavailable/inapplicable

Table 3.5 Mean overwinter recharge (mm) of the upper soil (0 - 50 cm depth) and lower subsoil (50 - 100 cm) of all the study sites.

	Site 1 recharge (mm)		Site 2 recharge (mm)		Site 3* recharge (mm)		Site 4 recharge (mm)	
Diviner 2000® Tube	0 - 50 cm	50 - 100 cm	0 - 50 cm	50 - 100 cm	0 - 40 cm	60 - 100 cm	0 - 50 cm	50 - 100 cm
1	0.3	-3.4	10.8	0.9	1.8	-0.6	-38.1	-23.5
2	10.7	28.7	-8.0	-26.2	1.3	-2.6	-58.1	-27.4
3	10.5	15.4	13.7	-14.4	1.8	-0.1	-37.9	-13.3
4	4.4	1.2	28.9	7.7	7.9	0.1	-75.8	-7.3
5	0.0	14.9	37.6	4.6	3.7	-2.9	-38.8	6.2
6	7.1	-2.4	42.2	30.2	4.8	-1.6	-30.3	9.4
7	-2.0	-5.7	17.2	15.6	5.4	-0.8	2.2	16.8
8	-1.4	-5.3	36.5	15.2	0.4	-1.2	-34.8	13.6
9	3.9	-13.2	27.4	14.5	1.3	2.4	-29.9	16.8
10	6.1	-3.3	na	na	na	na	na	na
11	-7.3	6.6	na	na	na	na	na	na
12	-11.6	-5.8	na	na	na	na	na	na
13	4.6	-4.5	na	na	na	na	na	na
14	4.0	-2.1	na	na	na	na	na	na
15	6.3	-6.9	na	na	na	na	na	na
16	-26.3	-6.2	na	na	na	na	na	na
17	0.4	1.7	na	na	na	na	na	na
18	-2.6	-3.3	na	na	na	na	na	na
Mean (S.E.)	0.4 (2.1)	0.4 (2.4)	22.9 (5.3)	5.4 (5.7)	3.1 (0.8)	-0.8 (0.5)	-37.9 (7.1)	-1.0 (5.8)

*Site 3 had high erosion and an adjustment in the data was made to compensate for the 5 cm depth values being low because the Diviner 2000® sensor was likely measuring the moisture content of the air; therefore, the upper soil and subsoil depths are 0 - 40 and 60 - 100 cm.

na = data is inapplicable or unavailable; Site 1 had 18 Diviner 2000® tubes and Sites 2, 3 and 4 had 9.

Table 3.6 Mean response of the upper soil (0 - 50 cm) and lower subsoil (50 - 100 cm depth) to a large rain event at all of the study sites.

	Site 1 recharge (mm)		Site 2 recharge (mm)		Site 3* recharge (mm)		Site 4 recharge (mm)	
Diviner 2000® Tube	0 - 50 cm	50 - 100 cm	0 - 50 cm	50 - 100 cm	0 - 40 cm	60 - 100 cm	0 - 50 cm	50 - 100 cm
1	37.4	17.1	35.0	-13.9	10.5	0.9	52.1	29.0
2	62.2	9.9	31.1	-26.6	21.1	1.3	68.7	57.6
3	24.4	12.8	2.1	-44.3	5.7	-0.4	75.0	64.0
4	22.2	30.3	26.6	-1.3	7.9	-0.3	76.6	63.0
5	50.8	10.0	65.2	-2.3	na	na	na	na
6	75.6	10.7	28.8	-17.5	11.1	0.1	27.8	25.5
7	71.0	15.8	27.2	-12.0	10.8	3.3	38.6	25.3
8	27.8	-1.9	33.7	-5.2	16.4	-0.6	43.2	57.8
9	34.2	9.1	41.2	-15.0	10.8	0.4	48.2	35.1
10	33.7	20.7	na	na	na	na	na	na
11	77.2	21.7	na	na	na	na	na	na
12	69.7	16.3	na	na	na	na	na	na
13	25.8	-2.1	na	na	na	na	na	na
14	39.2	7.6	na	na	na	na	na	na
15	31.4	9.4	na	na	na	na	na	na
16	37.2	7.6	na	na	na	na	na	na
17	7.4	0.1	na	na	na	na	na	na
18	42.8	3.7	na	na	na	na	na	na
Mean (S.E.)	42.8 (4.8)	11.1 (2.0)	32.3 (5.5)	-15.3 (4.5)	11.8 (1.7)	0.6 (0.45)	53.8 (6.3)	44.7 (6.2)

*Site 3 had high erosion and an adjustment in the data was made to compensate for the 5 cm depth values being low because the Diviner 2000® sensor was likely measuring the moisture content of the air; therefore, the upper soil and subsoil depths are 0 - 40 and 60 - 100 cm.

na = data is inapplicable or unavailable; Site 1 had 18 Diviner 2000® tubes and Sites 2, 3 and 4 had 9.

Site 1, 2 and 3 had approximately 75 mm of precipitation and Site 4 had approximately 104 mm of precipitation.

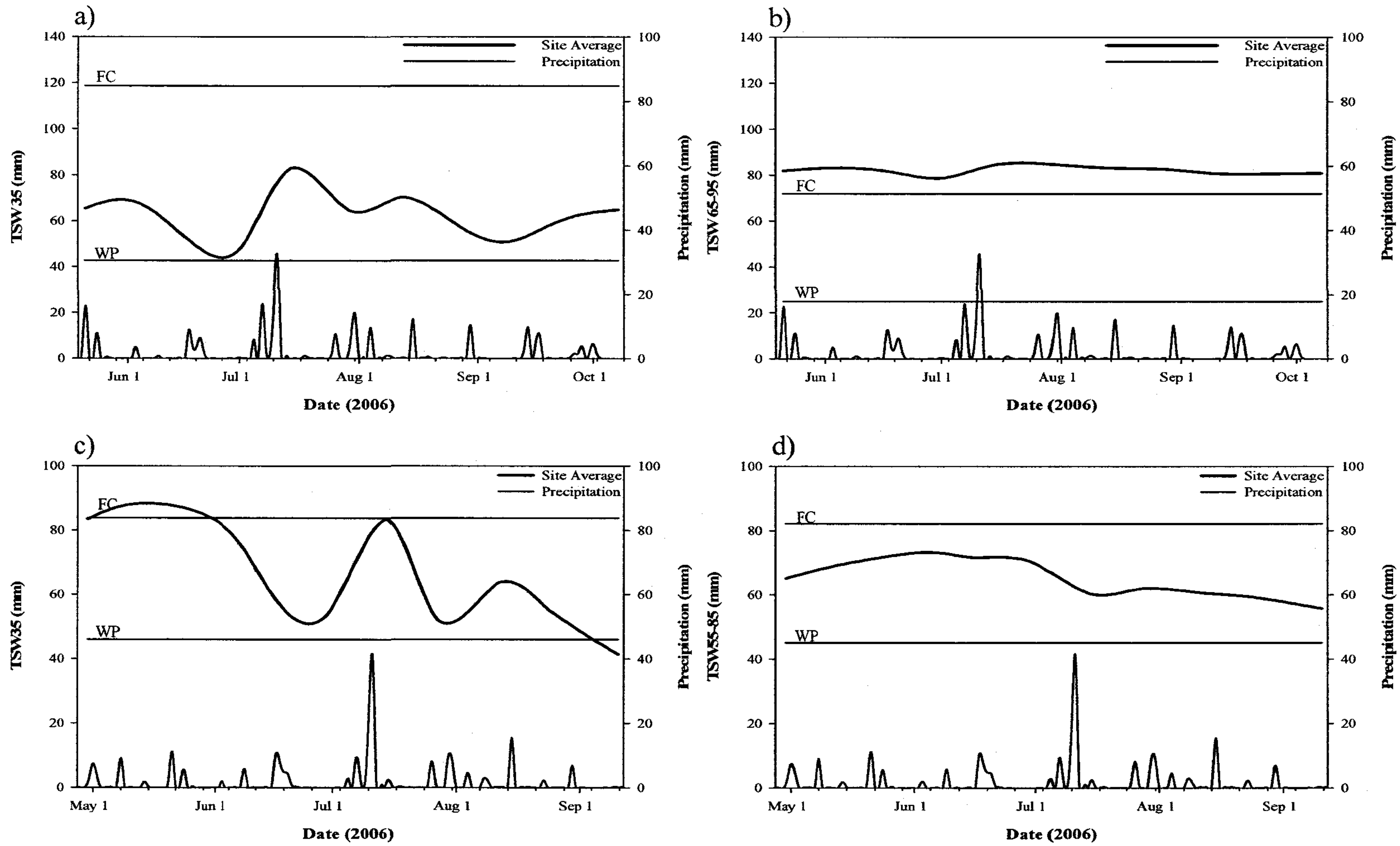


Figure 3.1 Mean TSW (mm) for a) the upper soil profile at Site 1; b) the lower soil profile at Site 1; c) the upper soil profile at Site 2; d) the lower soil profile at Site 2. FC = field capacity 0.01 MPa at Site 1 and 0.03 MPa at Site 2; WP = wilting point 1.5 MPa at both sites.

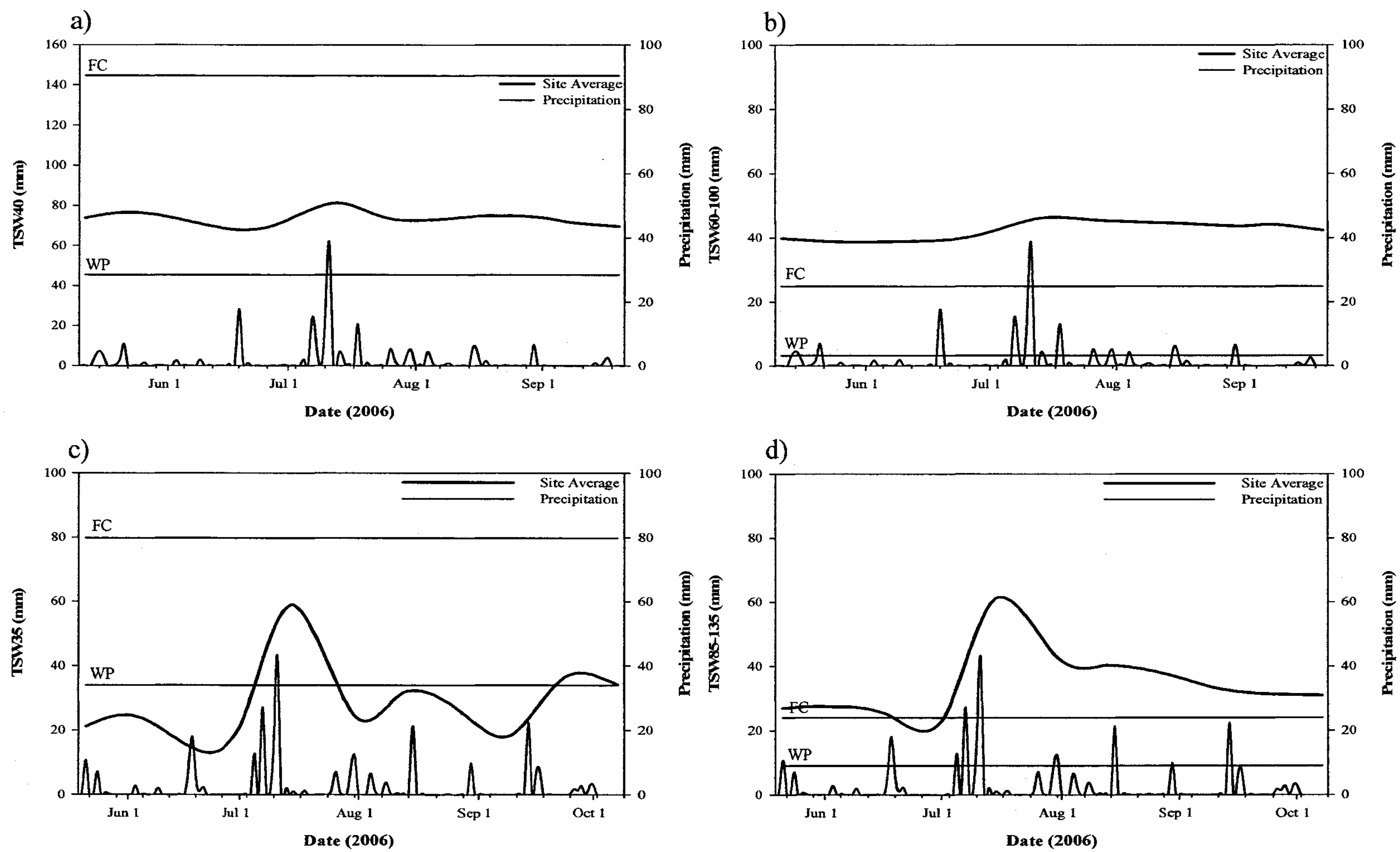


Figure 3.2 Mean TSW (mm) for a) the upper soil profile at Site 3; b) the lower soil profile at Site 3; c) the upper soil profile at Site 4; d) the lower soil profile at Site 4. FC = field capacity 0.01 MPa at both sites; WP = wilting point at both sites.

CHAPTER IV: SOIL NUTRIENT REGIMES OF RECLAIMED UPLAND SLOPES IN THE OIL SANDS REGION OF ALBERTA

1.0 Introduction

Large oil sand deposits are found in the Athabasca Oil Sands Region (AOSR) of Alberta, Canada. These deposits are recovered through surface mining, which creates a significant large scale disturbance. The extent of the current disturbance in the AOSR is 430 km^2 and is projected to increase to 1,767 km^2 (Alberta Environment 2006). These oil sand surface mining operations remove vegetation, soil and subsoil to gain access to the oil-impregnated sands, disrupting the natural hydrologic and nutrient cycles at the landscape scale (Fung and Macyk 2000). Following mining, the fundamental goal of land reclamation is to re-establish maintenance-free, self-sustaining ecosystems, with equivalent land capability to pre-disturbance conditions (Alberta Environmental Protection 1998). In the AOSR the existing landforms, generally flat depression areas, are being replaced with upland landforms as the extraction and processing of oil sands creates overburden piles and tailings sand ponds. Reclaiming these landforms requires obtaining a soil medium by overstripping organic soil to a maximum depth of 3 m to include 25 to 50% of subsoil materials, hence creating a peat-mineral mix (Alberta Environmental Protection 1998; Fung and Macyk 2000). The mineral substrates that are incorporated into the peat mineral mix (PMM) range from fine-textured lacustrine, to coarser-textured fluvial and till material. The PMM is then spread on overburden piles or the slopes of tailings storage facilities as a cover soil.

Reclaimed soils are pedogenically young soils that can have plant-limiting physical and chemical properties such as increased bulk density, poor soil structure, low fertility status and biological activity (Sencindiver and Ammons 2000; Ussiri et al. 2006). A key component of surface mine landscape/ecosystem reclamation is the construction of a favourable soil environment that is capable of supporting a productive ecosystem by retaining and supplying the nutrients required for plant development (Bentham et al. 1992). To ameliorate potentially limiting properties of reclaimed soils, amendments such as biosolids, mulching, liming, compost and fertilizers are often applied (Reid and Naeth 2005; Ussiri and Lai 2005; Stehouwer et al. 2006).

Spatial and seasonal soil nutrient dynamics have been investigated in various natural and disturbed ecosystems. In an Appalachian watershed, 30% vegetation removal by selective cutting and 81% downing of vegetation by a storm event increased soil water NO_3-N and contributed to NO_3-N loading from upper slope positions to lower slope riparian zones (Yeakley et al. 2003). The spatial distribution of soil extractable inorganic nitrogen and phosphorus, within the northern Alberta aspen boreal forest with Gray Luvisols and Eutric Brunisols on the upland slopes, and Gleysols and Organic soils in the low-lying areas, was affected by topographic position with lower slope positions having higher nutrient concentrations (Macrae et al. 2005 and 2006). Ion exchange resin (IER) nitrate and ammonium availability quantified in an Orthic Gray Luvisol of a northern Saskatchewan aspen boreal forest hillslope was higher at lower slope positions than at upper and mid slope positions (Huang and Schoenau 1997). Huang and Schoenau (1997) found a temporal oscillation between NO_3-N and NH_4-N, where NH_4-N was greater in the spring than NO_3-N and decreased throughout the growing season while NO_3-N increased. Finally, soil solution NO_3-N reflected climate variations and NO_3-N concentrations were highest during the winter season and lowest during the growing season in the southern White Mountain region of New Hampshire (Dittman et al. 2007).

Studies on reclaimed soils in the AOSR have investigated salinity (Chaikowsky 2003; Burgers 2005) and compared total carbon, nitrogen and phosphorus concentrations in natural and reclaimed soils (Lanoue 2003). However, to date, there are no studies that have investigated the spatial and temporal variability of soil nutrient availability for various types of reclamation prescriptions. Ion exchange resins (IER) have been used successfully for quantifying nutrient availability under various types of field conditions and are considered to be an appropriate estimate of nutrient availability to plant roots (Qian and Schoenau 1997; Hammermeister et al. 2003; Drohan et al. 2005; Szillery et al. 2006). Ion exchange resins contain either negatively or positively charged surface functional groups and attract ions by electrostatic attraction (Schoenau et al. 1993). PRS probes are IERs that act as an ion sink by adsorbing charged ionic species from the soil solution while buried and have been correlated to plant uptake (Schoenau et al. 1993;

Sulewski et al. 2002). PRS probes have also been shown to be an effective tool to investigate spatial variability of nutrient availability in undulating landscapes (Qian et al. 1994).

The overall objective of this project was to investigate the nutrient availability on reclaimed upland slopes. Specific objectives were: 1) to determine how soil nutrient availability was affected by topographical position and 2) to characterize the seasonal variability of soil nutrient availability at the slope level.

2.0 Materials and Methods

2.1 Experimental Area

The study area is located approximately 50 - 80 km north of Fort McMurray in north-eastern Alberta, within the boreal forest, which is dominated by a continental climate with short summers and long cold winters (Strong and Leggat 1981; Natural Regions Committee 2006). The mean annual temperature is 0.7°C; January is the coldest month with a mean temperature of -18.8°C and July is the warmest with a mean temperature of 16.8°C (Environment Canada 2004). The mean annual precipitation is 455.7 mm; 342.2 mm occurs as rainfall and 155.8 cm occurs as snowfall. The average annual potential evapotranspiration (PET) is 450 to 500 mm (Fung and Macyk 2000). The boreal forest consists of upland mixedwood forests and extensive wetlands in low-lying areas (Natural Regions Committee 2006). The dominant upland mixed forest vegetation is aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) and white spruce (*Picea glauca* (Moench) Voss.). Jack pine (*Pinus banksiana* Lamb.) stands occur on well-drained, sandy soils. Low lying poorly drained areas consist of black spruce (*Picea mariana* Mill.) dominated treed fens, shrubby fens and sedge fens (Fung and Macyk 2000). Luvisolic soils develop on well to imperfectly drained areas under upland mixedwood forest vegetation (Strong and Leggat 1981; Natural Regions Committee 2006). Brunisols develop on well to rapidly drained fluvial and eolian materials. Gleysols and Organic soils develop in the poorly drained wetland areas.

2.2 Experimental Sites

Five reclaimed upland slopes with various reclamation prescriptions were included in this study. Site 1 is a tailings sand storage facility with 20 cm of PMM, over 80 cm of subsoil material. Site 2 is a saline/sodic overburden dump with 20 cm of PMM, over 80 cm of subsoil material, over Cretaceous saline/sodic overburden. Site 3 is a reclamation trial slope for lean oil sands waste material and was created using 50 cm of PMM, over 50 cm of tailings sand, over lean oil sand. Site 4 is a tailings sands storage facility with 20 cm of PMM, over tailings sand. Site 5 is a saline/sodic overburden dump with 20 cm of PMM, over 80 cm of subsoil material, over Cretaceous saline/sodic overburden. Instrumentation on these slopes included PRS probes, weather stations, rain gauges and Diviner 2000® access tubes. Each experimental unit contained a set of PRS probes and a Diviner 2000® access tube. To assess the topographic and seasonal effect of nutrient availability at Sites 1, 2 and 3, there were three experimental units replicated across each slope position (upper, mid and lower). At Site 4, there were three experimental units per treatment, but the sampling was only replicated at two slope positions; on the bench and the toe of the slope. Site 5 had one replicated slope position. As a result Sites 1, 2 and 3 were analyzed for slope position and seasonal effects of nutrient availability and Sites 4 and 5 were included to assess the seasonal effect of nutrient availability of these different reclamation prescriptions.

2.3 Soil Collection

Soil pits were dug on Sites 1, 2 and 3 (9 pits), 4 (6 pits) and 5 (3 pits) 1.5 m down slope and 1.5 m to the right of each experimental unit in August 2005. At Site 2 (9 sample locations) samples were collected in August 2006 using an Eijkelkamp soil auger. Again, samples were collected 1.5 m downslope and 1.5 m to the right of each experimental unit. Three adjacent auger holes were required to obtain adequate amount of composite sample.

Soil samples were separated by depth increments based on the Land Capability Classification for Forest Ecosystems in the Oil Sands (Cumulative Effects Monitoring Association 2006). The depth increments are 0 – 20 cm, 20 – 50 cm and 50 – 100 cm and are classified as topsoil (TS), upper subsoil (US) and lower subsoil (LS), respectively. In some cases, the soil depths for the TS horizon were greater than 20 cm. In these cases a second TS horizon was sampled, or a composite sample for the complete depth was taken, if there were no significant visual differences within the horizon to indicate separating it into two intervals. If the TS horizon was less than 20 cm a composite sample was taken from the horizon and the depth of the horizon was noted as being less than 20 cm. Composite soil samples were taken from each soil horizon, air dried, crushed and sieved to 2 mm then subsampled and these samples were analyzed for chemical and physical properties.

Bulk density samples were collected from the upper part of each horizon in each soil pit. Bulk density samples were collected at Site 4 using an Uhland core with a length of 7.6 cm and a diameter of 7.5 cm (Culley 1993). Coring in sandier substrates proved challenging, as the sand particles would get caught in the inner sleeve and the outer corer casing, causing difficulties removing an intact sample. Thus, at the other sites, bulk density samples were taken with a hammer corer 6.7 cm in length and 7 cm in diameter. The hammer corer allowed for easy removal of an intact soil sample. Soil pits were not dug on Site 2 and as a result bulk density samples were only collected for the TS horizon for this site using the hammer corer described above. All bulk density samples were oven dried at 105 °C for 48 hours and bulk density was calculated by dividing the mass of the oven dried sample by the volume of the core used to obtain the sample. Coarse fragments (> 2 mm), if present, were not removed from the bulk density sample.

2.4 Plant-Root-Simulator Probes (PRS probes)

PRS probes (Western Ag Innovations Inc. Saskatoon, Saskatchewan) are ion membranes embedded in a plastic frame, which can be used to quantify soil nutrient availability under various field conditions (Hammermeister et al. 2003; Drohan et al. 2005; Szillery et al. 2006). Prior to burial in the field cation and anion probes were saturated with Na^+ and HCO_3, respectively by Western Ag Innovations to recharge the probes. Two anion and two cation probes were buried (10.0 cm depth), within each experimental unit, for concurrent four week periods during the 2005 growing season, beginning mid-May though the beginning of September, for a total of four sample periods. During the 2006 growing season, two anion and two cation probes were buried

(10.0 cm depth) within each experimental unit, beginning mid-May though the beginning of September, for concurrent two week periods for a total of eight sampling periods. Following each burial period, the probes were removed from the soil and washed with deionized water to remove soil particles, placed in a Ziploc bag in a cooler and refrigerated at 4°C until they were analyzed. The probes were sent to Western Ag Innovations for elution with 0.5M HCl. Ammonium (NH_4-N), nitrate (NO_3-N) and phosphorus (PO_4) were quantified colourimetrically using an autoanalyzer; potassium (K) and sodium (Na) were quantified using flame emission and inductively-coupled plasma spectroscopy was used to quantify sulphur (SO_4), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn) and boron (B).

2.5 Sentek Diviner 2000® Capacitance Sensor

The Diviner 2000® is a portable soil moisture monitoring system manufactured by Sentek Sensor Technologies, Stepney, AU. The system is a combination of a data logger and a portable probe. The probe is inserted into a PVC access tube (55.5 mm outside diameter) and scaled frequency readings are taken at regular 10 cm intervals though the soil profile (Sentek Pty. Ltd. 1999). O'Kane Consultants Inc. installed Diviner 2000® access tubes on the five sites in August 2005. They also created material specific calibration curves for the reclaimed soils monitored within this study. Soil moisture readings were collected approximately biweekly over the 2006 growing season, beginning in the middle of May and continuing through September, which corresponded to the replacement of the PRS probes.

Soil moisture was expressed as volumetric moisture content (VMC) and total soil water (TSW), for the upper 15 cm of soil. TSW was calculated by multiplying the volumetric moisture content by the thickness of the depth increment (Burk et al. 2000). Total soil water within the upper 15 cm of soil (TSW15) was calculated using the following formula:

$$TSW15 = \left(\frac{VMC10}{100} x150 \right)$$

where:

- VMC10 is the volumetric moisture content (%) at the 10 cm depth and is assumed to represent the top 15 cm of soil.

The depths were chosen to represent the section of the soil profile in which the PRS probes were buried.

2.6 Soil Chemical Analyses

Prior to chemical analysis all soil samples were air-dried and sieved to < 2mm. Soil pH was quantified using 2:1 saturated paste extracts for low organic matter horizons or 4:1 slurries for high organic matter horizons in 0.01 *M* $CaCl_2$ solution following the methods outlined in Kalra and Maynard (1991). Exchangeable cations (Ca, K, Mg and Na) were quantified following the $BaCl_2$ method outlined by Hendershot et al. (1993) using an atomic absorption spectrophotometer (Varian 880, Palo Alto, CA). Effective cation exchange capacity (CECe) was estimated by summation of the exchangeable cations. Total carbon (TC), total organic carbon (TOC) and total nitrogen (TN) were analyzed using dry combustion (Costech Model 4010 Elemental Analyzer Costech Model 4010 Elemental Analyzer, Valencia, CA). Prior to analysis the samples were ground to < 150 µm by ball grinder and TOC was quantified after leaching with 8 *M* HCl to remove the inorganic carbon (Nelson and Summers 1996).

2.7 Statistical Analysis I (Mixed Model - Repeated Measures)

A repeated measures design was used because there were multiple measurements of a response variable on the same experimental unit over time (Littell et al. 2006). The treatment assigned to the experimental unit is slope position and data were collected on the response variables (NH_4-N, NO_3-N, Ca, Mg, K, PO_4 and SO_4) of individual experimental units through time. The design is considered a mixed model because it contains both random and fixed effects; thus, the data were analyzed using the MIXED procedure in SAS 9.1 (Littell et al. 2006). The statistical model for a repeated measures design is:

$$Y_{ijk} = \mu + \alpha_i + \gamma_k + (\alpha\gamma)_{ik} + \beta(x_{ij} - \bar{x}) + \varepsilon_{ijk}$$

where $\mu + \alpha_i + \gamma_k + (\alpha\gamma)_{ik}$ is the mean for slope position i at time k, and accounts for the effect of slope position, time period and slope position*time period interaction.

The $\beta(x_{ij} - \bar{x})$ term represents the combined regression coefficient for the covariate (soil moisture) where x_{ij} is the covariate for the j^{th} replicate observation of the i^{th} treatment and $\bar{x}$ is the mean covariate value. The random error related to the response variable at time k on the j^{th} subject within treatment i is noted by ε_{ijk}.

Soil moisture was included in the model to determine to what degree nutrient availability, quantified by the PRS probes, was influenced by soil water. For Sites 1, 2 and 3 TSW15 was used because it represents the upper 15 cm of soil where the PRS probes were located. When the PRS probes were removed from the soil a soil moisture measurement was taken and this was the measurement that was used to calculate TSW15 and that value was used in the model for the corresponding PRS probe time period.

2.8 Statistical Analysis II (Ordination)

Ordination techniques effectively summarize complex datasets by reducing the dimensionality of the quantified response variables to a low-dimensional model of the underlying multivariate data structure (Kenkel 2006). Non-metric multidimensional scaling (NMS), multiresponse permutation procedure (MRPP) and indicator species analysis were used to examine nutrient availability patterns among slope positions, seasons and sites. The NMS analysis is an unconstrained ordination technique that uses an iterative process to view datasets such that distances in dimensional ordination space reveal similarities or dissimilarities in the original dataset structure (McCune and Mefford 1999; McCune et al. 2002; Hannam et al. 2006). This technique is advantageous for non-normal data or data that are on arbitrary or discontinuous scales (McCune et al. 2002). Thirteen ions (μmol 10^{-2} burial period^{-1}) were modelled after standardization and arcsine square root transformation using NMS ordination in PC-ORD software (version 4.34, MjM Software Design, Gleneden Beach, OR). The ions in the dataset were NH_4-N, NO_3-N, Ca, Mg, K, PO_4, SO_4, Na, Fe, Mn, Cu, Zn, and B.

The multi-response permutation procedure (MRPP) was used to compare differences in nutrient availability among slope positions, seasons and sites (Fisher and Fulé 2004; Hannam et al. 2006). The MRPP compares the within group distances to the between group distances of random permutations to the measured group values. This procedure calculates two statistics, the *A*-statistic, which is an estimate of within-group homogeneity, and the T-statistic, which is an estimate of the separation between groups (McCune et al. 2002). When all data points within a group are identical, $A = 1$, and if heterogeneity within groups equals expectation by chance, then $A = 0$. A more negative T represents a greater separation between groups. The MRPP analyses were completed using the Sørensen distance and Bonferroni corrections were used to control family error rate for among site comparisons. Indicator species analysis was used to identify which ions were especially high and during which time periods (Dufrene and Legendre 1997). Joint plots were used to show the relationship between the PRS probe measured nutrient availability and the sites (McCune et al. 2002). The direction and magnitude of the vectors indicate the direction and strength of the relationship between the ions and the sites.

3.0 Results

3.1 Soil Chemical and Physical Properties

The PMM at Sites 1, 3 and 4 had a sandy loam texture, at Site 2 it was a clay loam and at Site 5 it was a silt loam (Table 4.1). The average bulk density of the PMM at Site 4 was 1.32 Mg m^{-3}, which was nearly five times greater than Site 5 that had an average bulk density of 0.29 Mg m^{-3}. Sites 1 through 3 had average bulk densities ranging from 0.62 to 0.90 Mg m^{-3}.

The highest total carbon (TC) content was 91.8 kg m^{-3} at Site 1 (Table 4.2). Sites 3 and 4 had TC contents of 66.6 and 59.4 kg m^{-3}, respectively and Sites 2 and 5 had TC contents of 42.0 and 42.9 kg m^{-3}, respectively. All the sites had similar carbon/nitrogen (C/N) ratios ranging from 24.9 to 34.9. Sites 3 and 5 had the highest CECe with approximately 32 meq 100 g^{-1} of soil, which was more than twice as much as the CECe at Site 4 (14.0 meq 100 g^{-1} of soil). The PMM at Sites 1, 2, 3 and 4 had pH values ranging from 5.9 to 7.0, while Site 5 had the lowest pH of 4.8.

3.2 Topographical Effect on Nutrient Availability

Slope did not have a consistent effect on nutrient availability at Sites 1, 2 or 3. At Site 1, the results of the mixed model analysis indicated that slope position had a significant effect on PO_4 and SO_4 (Figure 4.1 c and e). The availability of PO_4 was significantly higher at the mid slope position than at the upper and lower slope positions for most of the growing season. The availability of SO_4 was significantly higher at the upper and lower slope positions than the mid slope at all 8 time periods. The NMS results also indicate a slope effect; however, the T-value was low, indicating little separation in nutrient availability among slope positions and the low A-value indicated a large amount of heterogeneity in nutrient availability within a slope position (Figure 4.1 h). The nutrient availability at the slope positions had high coefficients of variation (CVs) that exceeded 150% for NO_3-N, NH_4-N and PO_4 (data not shown).

At Site 2, the results of the mixed model analysis showed that slope position had an effect on PO_4 (Figure 4.2 c). The availability for PO_4 was significantly higher at the mid slope position than at the upper slope position during time periods 1, 5, 6 and 7; the lower slope position had higher PO_4 availability than the upper slope position during time periods 1, 4 and 7. The mid slope position had higher PO_4 availability than the lower slope position during time period 5. The NMS results also indicated a slope effect but, similar to Site 1, both the T-value and A-value were low (Figure 4.2 h). The nutrient availability at the slope positions had high CVs $> 150\%$ for NO_3-N and NH_4-N (data not shown).

At Site 3, slope had a significant effect on NO_3-N, NH_4-N and PO_4 (Figure 4.3 a, b and c). The NO_3-N availability was higher at the upper slope position than at the mid and lower slope positions. There was no pattern for the differences in NH_4-N and P availability among slope positions. The availability of NH_4-N was higher at the upper slope position than the mid slope position during time period 1 and lower slope position during time period 3; higher NH_4-N availability occurred at the upper slope position compared to the lower slope position during time periods 1, 5 and 8. The mid slope position had higher NH_4-N availability than the lower slope position during time period 3. The availability of PO_4 was significantly higher in the upper than the mid and lower slope positions during time period 4. The mid slope position had significantly greater PO_4 availability than the upper or lower slope positions during time period 7. The upper slope had greater PO_4 availability than the lower slope position during time period 6. The NMS results also indicated a slope effect but, similar to Sites 1 and 2, both the T-value and A-value were low (Figure 4.3 h). The CVs were low on this site, indicating that there was less nutrient availability variability within slope positions than on Sites 1 and 2. Only NH_4-N had CVs that exceed 150%; the other nutrients had CVs < 40% (data not shown).

3.3 Seasonal Effect on Nutrient Availability

The mixed model results showed that nutrient availability had a significant season effect at all five sites during the 2006 growing season (Figures 4.1 to 4.5 a to h). There was a seasonal oscillation in nitrogen availability, where NO_3-N and NH_4-N did not follow the same temporal pattern (Figures 4.1 to 4.5 a and b). At Sites 1, 2, 4 and 5, NO_3-N availability decreased to below detectable limits (BDL) in the middle of the growing season and then began to increase in August through September. Site 3 has the highest NO_3-N availability, which was highest during the middle of the growing season and was not BDL. NH_4-N supplies at Sites 1, 2, 4 and 5 were highest during the early growing season, then decreased to BDL later in the growing season. At Site 3, NH_4-N availability was highest during the early growing season then decreased but, unlike the other sites, NH_4-N was above BDL for most of the growing season.

At Site 1, PO_4 availability increased in June, then decreased throughout the growing season, but increased again in September (Figure 4.1 c). At Site 2, PO_4 availability was highest from May to the beginning of July then decreased through July and August and began to increase again in September (Figure 4.2 c). Site 3 PO_4 availability was similar to Site 2 but did not increase at the end of the growing season (Figure 4.3 c). The PO_4 availability at Site 4 was highest in June then decreased throughout the growing season (Figure 4.4 c). The PO_4 availability at Site 5 was highest in the beginning of the growing season and decreased at the end of the growing season (Figure 4.5 c).

The availability of K followed a similar temporal pattern at all sites: low in the beginning and end of the growing season and highest in the middle of the growing season (Figures 4.1 to 4.5 d).

The SO_4 availability for Site 1 was lowest at the beginning and end of the growing season and highest in the middle of the growing season (Figure 4.1 e). The SO_4 availability was similar for Sites 2, 4 and 5 (Figures 4.2, 4.4 and 4.5 e). In general, SO_4 availability was highest during the beginning of the growing season and declined throughout the growing season. Site 3 had the highest SO_4 availability over the growing season; the availability was highest during the middle of the growing season and declined in August and September (Figure 4.3 e).

Ca and Mg had similar temporal availability trends for Sites 1, 2, 4 and 5 (Figures 4.1, 4.2, 4.4 and 4.5 f and g). Ca availability was higher than Mg availability at the four sites. Ca and Mg availability were highest during the first sampling period then declined and availability remained similar at each site throughout the rest of the growing season. At Site 3, there was little change in Ca and Mg supply with the exception of the second and seventh sampling periods, where availability decreased (Figure 4.3 f and g).

The NMS results supported the mixed model results of a seasonal effect on nutrient availability and provided evidence that nutrient availability shifted in the ordination space with changing time periods (4.1 to 4.3 i; 4.4 and 4.5 h). The T-values were negative and the A-values were high indicating lower spatial variability than seasonal variability.

NMS ordination showed distinct nutrient availability patterns for sites with different reclamation prescriptions. There were differences in nutrient availability among sites during the 2005 and 2006 growing seasons (Figure 4.6 a and b). The results of the MRPP analysis suggest that differences among sites were larger in 2005 than in 2006; in particular the *T*-statistic was more negative in 2005 than 2006. Site 3 expressed the smallest within-group heterogeneity with respect to nutrient availability, as it was distinctly separate and has less spread in ordination space than the other sites, during both growing seasons. Removing Site 3 from the MRPP analysis decreased the *T*-statistic and *A*-statistic indicating that this site had distinctly separate nutrient availability, which was also less variable than at the other sites; this effect was more apparent during the 2006 growing season than the 2005 growing season. During the 2005 growing season all sites had statistically significant differences in nutrient availability (data not shown). Conversely, during the 2006 growing season Sites 1 and 4 were not statistically different from each other, indicating that these two sites had similar nutrient availability during this growing season; all other sites had significantly different nutrient availability.

There was less separation in nutrient availability over time than there was among sites during the 2005 growing season. This pattern was similar to the 2006 growing season; however, when Site 3 was removed from the analysis, there was more separation in nutrient availability over time than there was among Sites 1, 2, 4 and 5 (data not shown). This indicates that time had a larger influence on nutrient availability than site did during 2006. The results of the joint plots showed that Site 3 was associated with higher NO_3-N, Ca and SO_4 availability. In addition, the indicator species analysis indicated that NO_3-N, Ca and SO_4 availability were indicators of Site 3, while high PO_4 and K availability were indicators of Site 4 (p-value <0.05, data not shown).

3.4 Soil Moisture Effect on Nutrient Availability

At Site 2, Ca covaried with TSW15 and the results indicated that as soil moisture increased, Ca availability decreased; regression analysis explained 5 % of this correlation ($R^2 = 0.05$ P-value = 0.05). At Site 3, NO_3-N and PO_4 covaried with TSW15 and also decreased as soil moisture increased; regression analysis explained 14 % of the correlation between NO_3-N and TSW15 (R^2=0.14, P=0.0014) and 5 % of the correlation between PO_4 and TSW15 (R^2=0.05, P=0.0713). There were no other significant correlations between nutrient availability and soil moisture.

4.0 Discussion

4.1 Soil Chemical and Physical Properties

Sites 1, 3 and 4 all have the same PMM texture but different bulk densities, which is likely the result of differences in the amount of peat present in the PMM (Table 4.1). Site 4 had the highest bulk density and was the oldest site in this study. Conversely, Site 1, a newly reclaimed site with little organic matter decomposition and large clumps of peat that were not thoroughly mixed with the mineral material, had the second lowest bulk density. It seems that variability in organic matter in the PMM is influencing the bulk density of the PMM on the sites. The operational procedure is to place PMM on site while still frozen, and once thawed, the material is broken up and evened out to the prescribed application depth by large equipment (Fung and Macyk 2000). The handling and placement of reclamation material, on a large scale, creates high spatial variability in the peat/mineral mix depth and distribution across a site. The spatial variability that occurs in peat/mineral mix application depth and microtopography distribution of hummocks was particularly evident on Sites 1 and 2. The organic matter content of PMM is influencing the CECe at the sites; sites with higher organic matter content had higher CECe (Table 4.2).

Organic matter also contributes to pH dependent charges in soils and the BaCl method to quantify CECe was chosen to reduce the effect of pH adjustment (Hendershot et al. 1993). Site 5 had the lowest pH at 4.8, Site 2 had a pH of 5.9 and Sites 1, 3 and 4 had pH ranging from 6.3 to 7.0 (Table 4.2). Sites 1 though 4 have pH values that are considered good for revegetation in the boreal forest region and Site 5 has a fair pH (Alberta Soils Advisory Committee 1987). Revegetation of Site 5 to upland boreal forest species may be challenging because upland species such as white spruce and trembling aspen have optimal growth in soils with pH > 5.0 (Howat 2000). The low pH on this site is likely the influence of the fibric peat material, which has a pH range of 3.6 to 4.2 (Howat 2000).

4.2 Topographical Effect on Nutrient Availability

There were no clear patterns that indicated that topography was influencing nutrient availability. It was expected that there would be a nutrient availability gradient resulting from hydrologic controls on solute transport from upper to lower slope positions, via surface runoff, macropore (lateral) flow or return flow. This mechanism of ion movement on hillslopes is often referred to as the "flushing" hypothesis (Inamadar et al. 2004; Weiler and McDonnell 2006). There was no indication of a consistent nutrient availability gradient at any of the three sites, indicating that availability was likely not affected by hydrologic redistribution to lower slope positions. Other studies have reported nutrient gradients as a result of topography (Qian et al. 1994; Huang and Schoenau 1997; Macrae et al. 2005 and 2006). In particular, Qian et al. (1994) found nutrient availability gradients in agricultural fields with rolling landscapes, and Huang and Schoenau (1997) found nutrient availability gradients in an aspen forest in northern Saskatchewan; both studies used PRS probes to measure nutrient availability. Macrae et al. (2005 and 2006) found gradients to exist in the boreal forest in northern Alberta by quantitatively measuring nutrient concentration from soil cores using laboratory techniques. The reclaimed slopes in this study measured nutrient availability directly on the slopes and not in low lying areas, which may explain why no topographic pattern was observed for the distribution of nutrient availability.

Other factors that should be considered in the interpretation of soil nutrient availability are the age of the reclaimed soils, plant uptake, and heterogeneity of soil chemical and physical characteristics. The reclaimed sites in this study are pedogenetically young and may not have yet developed preferential flow paths for significant ion transport. The topographic effect on NO_3-N distribution has been studied on reclaimed steep coal spoil slopes in the Mediterranean (Salazar et al. 2002) and on steep mine waste slopes in northern Nevada (Leavitt et al. 2000); however, similar to the results of this study, neither study found evidence for nitrate gradients due to topographic effect; both studies quantitatively measured nutrient concentrations from soil cores using laboratory techniques.

Recently established vegetation on these young sites could be utilizing the majority of the available ions thereby reducing the potential for nutrient availability gradients. PRS probes are subject to competition from other nutrient sinks such as microorganisms and vegetation (Qian and Schoenau 2002; Hangs et al. 2004; Johnson et al. 2005). Thus, the observed differences in nutrient availability among slope positions could be the result of the inherent heterogeneity in soil properties and vegetation spatial patterns, rather than to topographic moisture driven gradients.

Coefficient of variation (CV) gives an indication of the variability within a dataset and CV values > 100 % are indicators of high variability (Dellhopf 2000). The CV for nutrient availability had values > 170 %, generally for NO_3-N and NH_4-N, indicating considerable variability among topographic position replicates. The high degree of variability, in the nutrient availability within these reclaimed soils, could be restricting the detection of topographical moisture driven gradients. If the variability among slope position replicates is similar to, or greater than, the soil moisture variability among slope positions, it would be difficult to establish a slope position effect. Where slope position effects occurred, it was likely the manifestation of a combination of abiotic and biotic factors of these heterogeneous soils, which influence PRS probe adsorption of labile ions (Qian and Schoenau 2002).

4.3 Seasonal Effect on Nutrient Availability

Season had a significant effect for all the nutrients analyzed with the mixed models during the 2006 growing season. In addition, when Site 3 was removed from the 2006 MRPP model, there was more separation for nutrient availability among time periods than among sites, indicating a greater variability in nutrient availability through time than among sites. Site 3 was removed because it had distinctly separate and less variable nutrient supply than the other four sites. The results were opposite for nutrient availability during 2005; time showed less separation for nutrient availability than did site. These contradicting results may be due to using two different time scale measurements during the 2005 and the 2006 growing seasons. Probe sampling happened monthly during 2005 and biweekly during 2006. The probe burial period within the soil influences nutrient availability measured, with nutrient availability increasing with increasing burial time (Sulewski et al. 2002). The finer time scale potentially allowed for better characterization of the temporal variability in nutrient availability, thereby being more effective at detecting differences among time periods.

The observed differences between the two growing seasons could be a manifestation of inter-annual climate variability. The 2005 growing season was cooler than the 2006 growing season and, although the amount of precipitation was similar during both growing seasons, the 2006 growing season had fewer rain events, but more intense rain events (data not shown). During the 2006 growing season, long hot and dry periods occurred that did not during the 2005 growing season. Nutrient availability on IER has been shown to be influenced by soil moisture and temperature (Schoenau et al. 1993); thus, it is likely that climatic variability, influencing soil moisture and temperature, would also result in the differences in nutrient availability observed between the two growing seasons. Because of the difference in nutrient availability between the two seasons, 2006 was chosen to analyze the temporal effect of season on nutrient availability. 2006 also had nutrient availability information on a finer time scale, which allowed for a more detailed analysis of the seasonal effect on nutrient availability.

Temporal nitrogen supply dynamics during the 2006 growing season appear to be similar to what has been found in natural soils of a Scots pine forest in Spain (Casals et al. 1995) and an aspen stand in the boreal forest of northern Saskatchewan (Huang and

Schoenau 1997). Both studies, using IER, found seasonal variations in NO_3-N and NH_4-N availability, where NH_4-N was higher in the spring and NO_3-N was higher in the summer. Our study also found seasonal oscillation in nitrogen availability, where NO_3-N and NH_4^+-N did not follow the same temporal pattern. At Sites 1, 2, 4 and 5, NH_4^+-N availability was greater in the early growing season and dramatically reduced later in the season (Figure 4.1, 3.2, 3.4 and 3.5 b). The greater NH_4^+-N supply in the early growing season is likely caused by high ammonification rates and low nitrification rates (Casals et al. 1995, Huang and Schoenau 1997). Ammonium-N then decreased from the middle to the end of the growing season likely as the result of increased nitrification and plant uptake. Nitrate-N decreased throughout the growing season, likely a result of plant uptake and the inhibition of microbial activity in soils of lower moisture contents (Stevenson and Cole 1999). It began to increase again approximately mid August, likely caused by the addition of new litterfall from overstory vegetation, and less competition by plants for NH_4^+-N (Huang 1996; Stevenson and Cole 2000). Site 3 had the highest nitrogen availability, which was likely an effect of this site having no plants to take up inorganic nitrogen. The establishment of vegetation at Site 3 would most likely change nitrogen availability dramatically.

The phosphorus cycle is a dynamic system involving uptake by microorganisms and plants, and recycling through the return of microbial and plant residues to the soil (Stevenson and Cole 1999). Huang (1996), using IER, studied P biogeochemical cycling in boreal forest aspen stands and found that as plant uptake increased, the supply of P in the soil decreased. As vegetation residues were returned through litterfall and root turnover, and decomposed in the soil at the end of the growing season, P concentration increased again (Huang, 1996). A study of P cycling in a hardwood forest in central New Hampshire found the majority of P to be in the mineral soil; however, this P was relatively unavailable to plants, compared to P present in the forest floor (Yanai 1992). Our study found an increase in the P availability at the end of the growing season at Sites 1 and 2, which could be attributed to plant senescence and litter deposition at that time. Site 3 had the lowest phosphorus availability of all the sites. Site 3 may have lower P availability because it lacks vegetation, which appears to be a main recycler of labile P during the growing season. The peat used in the PMM at Site 3 could also be of lower quality and be P deficient. Alternatively, the greater P availability at Site 4 could be an indication that as reclaimed sites become vegetated and an ecosystem develops chemical cycles begin to establish similar to what has been reported in the literature.

The K availability trends were similar for Sites 1, 2, 4 and 5. In general, the K availability increased the middle of growing season, with Site 1 having the highest availability. This increase in K corresponded to a large rain event that occurred where 74 to 104 mm of precipitation fell on the sites. Sardans and Peñuelas (2007) used a conventional laboratory method to quantify K concentration of bulk soil samples collected from an evergreen Mediterranean forest. They found decreased K solubility from primary minerals during periods of low soil moisture content. Likewise, the increase in soil moisture following the rain event may have increased the availability and adsorption of K onto the probes. Site 3 had the lowest availability throughout the growing season and there was little change in availability among time periods, indicating that this site could be K deficient. The low K availability at Site 3 and high K availability at Site 4 was not reflected in the exchangeable K data for these two sites. There are likely other factors, such as atmospheric deposition or leaf litter decomposition, controlling K availability other than peat decomposition.

Sites 1, 2, 4 and 5 had similar SO_4 availability over the 2006 growing season. Huang (1996), using PRS probes, found the S availability in the soil to be highest at the beginning of the growing season and to decrease to near below detectable limits in the summer, in an aspen boreal forest from northern Saskatchewan. The sites had different magnitudes of S supply which may be a result of differences in atmospheric deposition of S. The atmosphere inputs of S can vary greatly in continental areas, specifically near industrial plants where fossil fuels are processed (Stevenson and Cole 1999). Site 3 had the highest magnitude of S availability, perhaps due to the lack of plants on this site to take up S.

The temporal Ca dynamics found on Sites 1, 2, 4 and 5 were similar to those found by Mitchell et al. (1992) in a northern hardwood forest system in New York State. Mitchell et al. (1992), analyzing soil solutions sampled with tension and zero tension lysimeters, found soil Ca concentrations to be highest in the soil during the early growing season after which they decline and remain constant for the remainder of the growing season. They attributed the timing of this decline in Ca to the period of maximum leaf development. Ca is important for the structure and permeability of cell membranes and Mg is the primary constituent of chlorophyll (Havlin et al. 1999). The temporal dynamics of Mg mirrored Ca, perhaps because they have similar biochemical cycles. It is likely that these two nutrients are mostly utilized during the early phonological stages of plants, and that vegetation requirements are lower during the rest of the growing season. Results of our study support this as Ca was reduced in the early growing season. Calcium availability was greater than that of magnesium, which was again consistent with what has been found in various natural forest ecosystems (Fisher and Binkley 2000). Calcium is typically the dominant cation in most forest soils and magnesium concentrations are generally one fifth to one half of calcium concentrations (Fisher and Binkley 2000). Ca and Mg supplies at Site 3 were relatively constant throughout the growing season and generally the highest of all the sites. Again, this site was lacking vegetation so the availability was likely high because there was no plant uptake.

Nutrient availability can change over time with the development of ecosystems over many years, and climate variability from one growing season to another. Dittman et al. (2007) found soil NO_3-N to be highly variable over a 12-year study in which a watershed was heavily logged throughout the 1910 decade, in the southern White Mountain region of New Hampshire. However, during the time period examined in our study, Sites 1, 2, 4 and 5 appear to be exhibiting seasonal nutrient availability dynamics that are, to some degree, similar to those of natural soils. It appears that these reclaimed soils could be re-establishing biogeochemical cycles that can be similar to those of natural soils, but these biogeochemical cycles are likely not analogous to natural soils with respect to the magnitude of biogeochemical cycling. To better understand inter and intra-annual biogeochemical cycling at these reclaimed sites, long-term soil nutrient availability data sets with the same sampling time intervals should be established.

The biochemical cycles behaved differently at Site 3 than at the other four sites by having high NO_3-N, Ca and PO_4 and low K and SO_4 availability for most of the growing season. This site has been unvegetated for four years, and without vegetation influence on biogeochemical cycling, the availability of some ions are higher than would be expected if this site was vegetated. It is not clear why vegetation has not naturally established from the seed bank within the peat mineral mix, which occurs on other reclaimed sites. One possibility is that the site has poor quality peat mineral mix, or has been contaminated during salvage and storage, or a combination of the two. If vegetation were established on this site, soil moisture regime and nutrient availability would likely change dramatically. It is important to note that some of these sites were fertilized which could be influencing the results.

4.4 Soil Moisture Effect on Nutrient Availability

Schoenau et al. (1993), using a laboratory experiment, showed that soil moisture content was related to nutrient availability measured with IER. They showed that as soil moisture decreased from FC to WP, the amount of N, P, K and S absorbed by PRS probes decreased. The moisture content of the soil, during their laboratory experiment, was kept constant during the IER incubation period. In our study, we hypothesized that as soil moisture increased nutrient availability would also increase. We used TSW15 (soil moisture) as a covariate, in the mixed models, to determine the degree of influence it had on nutrient availability. However, nutrient availability rarely correlated with soil moisture status, and in a few cases, a negative relationship was detected, where as the soil moisture increased, nutrient availability decreased. However, K and NO_3-N availabilities appear to be influenced by moisture since the availability of both increased at time period four. During this time period there was a large rain event where more than 75 mm of precipitation fell.

Caution is required in the interpretation of these results because precipitation events that occur during the PRS probe burial period would likely influence nutrient supply, although these events might not have been accounted for with the Diviner 2000® measurements. PRS probes provide an integrated measurement of soil conditions during the burial period while Diviner 2000® data provide a static measurement of the soil moisture at the time the measurement is taken. The unexpected lack of relationships between nutrient availability and soil moisture could be an effect of comparing two different types of soil measurements. PRS probes provide an integrative quantification of nutrient availability by integrating all the factors that affect nutrient availability, including soil moisture, temperature and vegetation (Sulewski et al. 2002). Conversely, the Diviner 2000® measurements provide a "snap-shot" of soil moisture at the time the measurement is taken and do not provide any information on the soil moisture content between two measurements. Thus, there is a two-week time period when the probes were buried in which soil moisture content and its effect on nutrient availability are unknown. Future studies that correlate nutrient availability using PRS probes with soil moisture measurements from the Diviner 2000® system should include multiple soil moisture measurements throughout the PRS probe burial period. To pursue soil moisture and nutrient availability using these techniques, several or continuous soil moisture measurements during the PRS probe burial period would allow for better integration of the PRS probe and Diviner® 2000 data.

5.0 Conclusions

Slope position did not have a consistent effect on nutrient availability at any of the study sites. There was a high degree of variability for nutrient availability within these reclaimed soils Vegetation was not measured in this study but it is likely that spatial distribution of vegetation species and vegetation patch dynamics influenced nutrient measurements of the PRS probes.

Season was found to have more of an influence on nutrient availability than did site as the variability of nutrient availability over time was greater than the variability of nutrient availability among sites. This is an unexpected outcome as each vegetated site had different characteristics related to reclamation prescription, time since reclamation, slope, aspect and vegetation. Finally, some of the reclaimed study sites appear to possess soil characteristics similar to those of natural soils with respect to seasonal nutrient availability.

6.0 Literature Cited

Alberta Environment. 2006. Oil sands. www3.gov.ab.ca/env/land/quality/html/use/oilsands.html. Accessed August 1, 2007.

Alberta Environmental Protection. 1998. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region. Report # ESD/LM/99-1. 212 pp.

Alberta Soils Advisory Committee. 1987. Soil quality criteria relative to disturbance and reclamation. Conservation and Development Branch. Alberta Agriculture, Food and Rural Development. Edmonton, AB. 46 pp.

Bentham, H., Harris, J. A., Birch, P. and Short, K. C. 1992. Habitat classification and soil restoration assessment using analysis of soil microbiological and physico-chemical characteristics. J. Appl. Ecol. 29: 711-718.

Burgers, T. 2005. Reclamation of an oil sands tailings storage facility: vegetation and soil interactions. M. Sc. Thesis. Department of Renewable Resources, University of Alberta. Edmonton, AB. 134 Pp.

Burk, A. R., Chanasyk, D. S. and Mapfumo, E. 2000. Antecedent soil water for managed landscapes in central Alberta. Trans. ASAE. 43: 1467-1475.

Casals, P., Romanyà, J., Cortina, J., Fons, J., Bode, M. and Vallejo, V. R. 1995. Nitrogen supply rate in Scots pine (*Pinus sylvestris* L.) forests of contrasting slope aspect. Plant and Soil 168-169: 67-73.

Chaikowsky, C. L. A. 2003. Soil moisture regime and salinity on a tailings sand storage facility. M. Sc. Thesis. Department of Renewable Resources, University of Alberta. Edmonton, AB. 135 p.

Culley, J. L. B. 1993. Density and compressibility. In: M. R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publishers. Boca Raton, FL. 529-539 Pp.

Cumulative Effects Monitoring Association. 2006. Land capability classification for forest ecosystems in the oil sands. Volume 1: Field manual for land capability determination. Third Edition. 65 pp.

Dellhopf, D. J. 2000. Sampling strategies for drastically disturbed land. In: R. I. Barmhisel, R. G. Darmody and W. L. Daniels (eds.). Reclamation of Drastically Disturbed Lands. Agronomy Monograph no. 41. American Society of Agronomy. Madison, WI. Pp. 21-40.

Dittman, J. A., Driscoll, C. T., Groffman, P. M. and Fahey, T. J. 2007. Dynamics of nitrogen and dissolved organic carbon at the Hubbard Brook experimental forest. Ecology 88: 1153-1166.

Drohan, J. P., Merkler, D. J. and Buck, B. J. 2005. Suitability of the plant root simulator probe for use in the Mojave Desert. Soil Sci. Soc. Am. J. 69: 1482-1491.

Dufrene, M. and Legendre, P. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecol. Monog. 67: 345-365.

Environment Canada. 2004. Canadian Climate Normals 1971-2000. http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html [Accessed online. September 20, 2006].

Fisher, M. A. and Fulé, P. Z. 2004. Changes in forest vegetation and arbuscular mycorrhizae along a steep elevation gradient in Arizona. Forest Ecol. Manag. 200: 293-311.

Fisher, R. F. and Binkley, D. 2000. Ecology and management of forest soils. Third Edition. John Wiley & Sons. Toronto, ON. 489 pp.

Fung, M. Y. P. and Macyk, T. M. 2000. Reclamation of oil sands mining areas. In: R. I. Barmhisel, R. G. Darmody and W. L. Daniels (eds.). Reclamation of Drastically Disturbed Lands. Agronomy Monograph no. 41. American Society of Agronomy. Madison, WI. Pp. 755-774.

Hammermeister, A. M., Naeth, M. A., Schoenau, J. J. and Biederbeck, V. O. 2003. Soil and plant response to wellsite rehabilitation on native prairie in southeastern Alberta, Canada. Can. J. Soil Sci. 83: 507-519.

Hangs, R. D., Greer, K. J. and Sulewski, C. A. 2004. The effect of interspecific competition on conifer seedling growth and nitrogen availability measured using ion-exchange membranes. Can. J. For. Res. 34: 754-761.

Hannam, K. D., Quideau, S. A. and Kishchuk, B. E. 2006. Forest floor microbial communities in relation to stand composition and timber harvesting in northern Alberta. Soil Biol. Biochem. 38: 2565-2575.

Havlin, J. L., Beaton, J. D., Tisdale, S. L. and Nelson, W. L. 1999. Soil fertility and fertilizers: an introduction to nutrient management. Sixth edition. Prentice Hall. Upper Saddle River, NJ. 499 pp.

Hendershot, W. H., Lalande, H. and Duquette, M. 1993. Ion exchange and exchangeable cations. In: M. R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publishers. Boca Raton, FL. 167-176 Pp.

Howat, D. 2000. Acceptable salinity, sodicity and pH values for boreal forest reclamation. Environmental Sciences Division, Alberta Environment. Edmonton, AB. Report # ESD/LM/00-2. 191 pp.

Huang, W. Z. 1996. Dynamics of carbon, nitrogen, phosphorus and sulfur in a boreal aspen forest soil. Ph.D. dissertation. University of Saskatchewan, Department of Soil Science. Saskatoon, SK. 188 pp.

Huang, W. Z. and Schoenau, J. J. 1997. Seasonal and spatial variations in soil nitrogen and phosphorus supply rates in a boreal aspen forest. Can. J. Soil Sci. 77: 597-612.

Inamdar, S. P., Christopher, S. F. and Mitchell, M. J. 2004. Export mechanisms for dissolved organic carbon and nitrate during summer storm events in a glaciated forest catchment in New York, USA. Hydrolog. Process. 18: 2651-2661.

Johnson, D. W., Verburg, P. S. J. and Arnone, J. A. 2005. Soil extraction, ion exchange resin, and ion exchange membrane measures of soil mineral nitrogen during incubation of a tallgrass prairie soil. Soil Sci. Soc. Am. J. 69: 260-265.

Kalra, Y. P. and Maynard, D. G. 1991. Methods manual for forest soil and plant analysis. Forestry Canada. Northwest Region. Northern Forestry Centre. Edmonton, AB. Information Report NOR-X-319. 116 pp.

Kenkel, N. C. 2006. On selecting an appropriate multivariate analysis. Can. J. Plant Sci. 86: 663-676.

Lanoue, A. V. L. 2003. Phosphorus content and accumulation of carbon in boreal forest soils. M. Sc. Thesis. Department of Renewable Resources, University of Alberta. Edmonton, AB. 177 p.

Leavitt, K. J., Fernandez, G. C. J., Nowak, R. S. 2000. Plant establishment on angle of repose mine waste dumps. J. Range Manage. 53: 442-452.

Littell, R. C., Milliken, G. A., Stroup, W. W., Wolfinger, R. D. and Schabenberger, O. 2006. SAS System for mixed models. Second edition. SAS Institute Inc. Cary, NC. 814 pp.

Macrae, M. L., Devito, K. J., Creed, I. F. and Macdonald, S. E. 2006. Relation of soil-, surface-, and ground-water distributions of inorganic nitrogen with topographic position in harvested and unharvested portions of an aspen-dominated catchment in the Boreal Plain. Can. J. Forest Res. 36: 2090-2103.

Macrae, M. L., Redding, T. E., Creed, I. F., Bell, W. R. and Devito, K. J. 2005. Soil, surface water and ground water phosphorus relationships in a partially harvested Boreal Plain aspen catchment. Forest Ecol. Manag. 206: 315-329.

McCune, B. and Mefford, M. J. 1999. PC-Ord. Multivariate analysis of ecological data. Version 4, users guide. MjM Software Design. Gleneden Beach, OR. 237 pp.

McCune, B., Grace, J. B. and Urban, D. L. 2002. Analysis of ecological communities. MjM Software Design. Gleneden Beach, OR. 125-142 Pp.

Mitchell, M. J., Burke, M. K. and Shepard, J. P. 1992. Seasonal and spatial patterns of S, Ca and N dynamics of a Northern Hardwood forest ecosystem. Biogeochemistry 17: 165-189.

Natural Regions Committee. 2006. Natural regions and subregions of Alberta. Compiled by D. J. Downing and W. W. Pettapiece. Government of Alberta. Pub. No. T/852. 254 pp.

Nelson, D.W. and Summers, L.E. 1996. Total carbon, organic carbon, and organic matter. In: D.L. Sparks (ed.). Methods of Soil Analysis, Soil Science Society of America, Madison, WI. pp. 961–1010.

Qian, P. and Schoenau, J. J., Cowell, L. E. and Dennis, L. 1994. Assessing nutrient availability variations in landscapes. In: Soils and Crops Workshop Proc. Pp. 274-279. University of Saskatchewan. Saskatoon, SK.

Qian, P. and Schoenau, J. J. 1997. Recent developments in use of ion exchange membranes in agricultural and environmental research. Recent Res. Devel. Soil Sci. 1: 43-54.

Qian P. and Schoenau. J. J. 2002. Practical applications of ion exchange resins in agricultural and environmental soil research. Can. J. Soil Sci. 82: 9-21.

Reid, N. B. and Naeth, M. A. 2005. Establishment of a vegetation cover on tundra kimberlite mine tailings: 2. A field study. Restor. Ecol. 13: 602-608.

Salazar, M., Poch, R. M. and Bosch, A. D. 2002. Reclamation of steeply sloping coal spoil banks under Mediterranean semi-arid climate. Aust. J. Soil. Res. 40: 827-845.

Sardans, J. and Peñuelas, J. 2007. Drought changes phosphorus and potassium accumulation patterns in an evergreen Mediterranean forest. Funct. Ecol. 21: 191-201.

Schoenau, J. J., Qian, P. and Huang, W. Z. 1993. Ion exchange resin membranes as plant root simulators. Proc. Soil and Crops Workshop. University of Saskatchewan. Saskatoon, SK. Pp. 392-400.

Sencindiver, J. C. and Ammons, J. T. 2000. Minesoil genesis and classification. In: R. I. Barmhisel, R. G. Darmody and W. L. Daniels (eds.). Reclamation of Drastically Disturbed Lands. Agronomy Monograph no. 41. American Society of Agronomy. Madison, WI. Pp. 595-613.

Sentek Pty. Ltd. 1999. Sentek Diviner 2000 User Guide Version 1.2. Australia Sentek Pty Ltd. Stepney, South Australia. 70 pp.

Stehouwer, R., Day, R. L. and Macneal, K. E. 2006. Nutrient and trace element leaching following mine reclamation with biosolids. J. Environ. Qual. 35: 1118-1126.

Stevenson, F. J. and Cole, M. A. 1999. Cycles of soil: carbon, nitrogen, phosphorus, sulphur, macronutrients. Second edition. John Wiley & Sons, Inc. New York, NY. 427 pp.

Strong, W. L. and Leggat, K. R. 1981. Ecoregions of Alberta. Alberta Energy and Natural Resources. Edmonton, AB. 64 pp.

Sulewski, C. A., Greer, K. J., Schoenau, J. J. and Baron, V. S. 2002. Factors affecting nutrient supply rate measurements with PRS™-probes. In: Soils and Crops Workshop Proc. Pp (in print). University of Saskatchewan. Saskatoon, SK.

Szillery, J. E., Fernandez, I. J., Norton, S. A., Rustad, L. E. and White, A. S. 2006. Using ion-exchange resins to study soil response to experimental watershed acidification. Environ. Monit. Assess. 116: 383-398.

Ussiri, D. A. N. and Lal, R. 2005. Carbon sequestration in reclaimed minesoils. Crit. Rev. Plant Sci. 24: 151-165.

Ussiri, D. A. N., Lal, R. and Jacinthe, P. A. 2006. Soil properties and carbon sequestration of afforested pastures in reclaimed minesoils of Ohio. Soil Sci. Soc. Am. J. 70: 1797-1806.

Weiler, M. and McDonnell, J. J. 2006. Testing nutrient flushing hypotheses at the hillslope scale: A virtual experiment approach. J. Hydrol. 319: 339-356.

Yanai, R. D. 1992. Phosphorus budget of a 70-year-old northern hardwood forest. Biogeochemistry 17: 1-22.

Yeakley, J. A., Coleman, D. C., Haines, B. L., Kloeppel, B. D., Meyer, J. L., Swank, W. T., Argo, B. W., Deal, J. M. and Taylor, S. F. 2003. Hillslope nutrient dynamics following upland riparian vegetation disturbance. Ecosystems 6: 154-167.

Table 4.1 Physical properties of peat mineral mix (PMM) at all five study sites

Site	Thickness (cm)	Bulk Density ($Mg\ m^{-3}$)	Clay (%)	Silt (%)	Sand (%)
Site 1	24.9 (2.3)	0.62 (0.12)	5.7 (1.1)	37.9 (1.7)	56.3 (2.0)
Site 2	20.0 (0.0)	0.84 (0.07)	35.5 (7.8)	27.2 (1.3)	37.4 (6.7)
Site 3	20.0 (0.0)	0.90 (0.02)	14.2 (0.7)	18.0 (0.5)	67.8 (0.2)
Site 4	19.7 (0.3)	1.32 (0.05)	14.0 (1.2)	14.9 (1.8)	71.1 (0.1)
Site 5	33.7 (3.5)	0.29 (0.01)	3.39 (na)	59.96 (na)	36.65 (na)

Values reported as mean (standard error)
na = not applicable because n = 1
n = 9 for thickness and bulk density at Sites 1, 2 and 3; n = 6 for thickness and bulk density at Site 4; n = 3 for thickness and bulk density at Site 5
n = 3 for particle size analysis for Sites 1 through 4; n = 1 for Site 5 particle size analysis

Table 4.2 Chemical properties of peat mineral mix (PMM) at all five study sites

Site	Thickness (cm)	pH	CECe $cmol_c\ kg^{-1}$ soil	Na $cmol_c\ kg^{-1}$ soil	K $cmol_c\ kg^{-1}$ soil	Mg $cmol_c\ kg^{-1}$ soil	Ca $cmol_c\ kg^{-1}$ soil	TC ($kg\ m^{-3}$)	TOC ($kg\ m^{-3}$)	C/N ratio
Site 1	24.9 (2.3)	6.3 (0.1)	21.8 (5.7)	1.00 (0.5)	0.08 (0.02)	4.0 (1.4)	29.5 (8.8)	91.8 (26.0)	85.6 (25.4)	24.9 (1.0)
Site 2	20.0 (0.0)	5.9 (0.3)	19.3 (6.7)	0.13 (0.02)	0.12 (0.06)	3.4 (0.5)	16.9 (4.5)	42.0 (6.7)	41.2 (6.7)	29.3 (0.7)
Site 3	20.0 (0.0)	7.0 (0.0)	31.4 (0.6)	0.16 (0.00)	0.06 (0.00)	2.9 (0.05)	34.67 (0.66)	66.6 (1.8)	55.8 (1.8)	25.0 (0.3)
Site 4	19.7 (0.3)	6.8 (0.1)	14.0 (2.6)	0.07 (0.00)	0.05 (0.01)	2.5 (0.2)	16.1 (4.1)	59.4 (7.9)	51.5 (6.6)	27.9 (1.5)
Site 5	33.7 (3.5)	4.8 (0.7)	31.5 (0.3)	0.18 (0.02)	0.10 (0.01)	3.6 (0.6)	16.1 (1.5)	42.9 (10.7)	40.6 (10.1)	34.9 (1.9)

Values reported as mean (standard error)
n = 9 for thickness and pH at Sites 1, 2 and 3; n = 6 for thickness and pH at Site 4; n = 3 for thickness and pH at Site 5
n = 3 for all sites for CECe, Na, K, Mg, Ca, total carbon (TC) and total organic carbon (TOC)

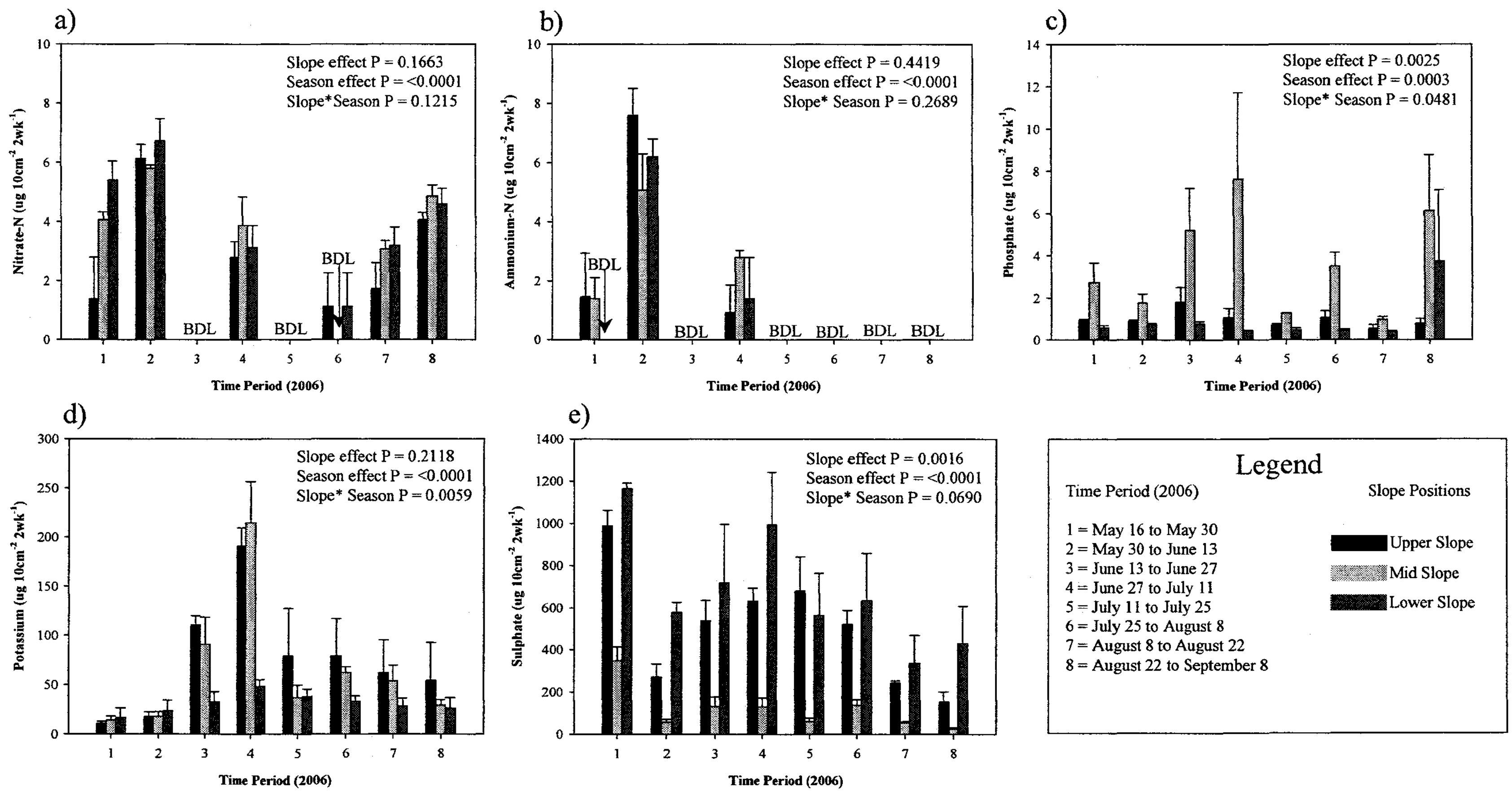


Figure 4.1 Mean nutrient availability (columns) and standard errors (verticals) for Site 1 during the 2006 growing season; a) NO_3-N availability; b) NH_4-N availability; c) PO_4 availability; d) K availability; e) SO_4 availability. For each slope position n = 3. Slope position and time periods that do not have a bar the nutrient was below the detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

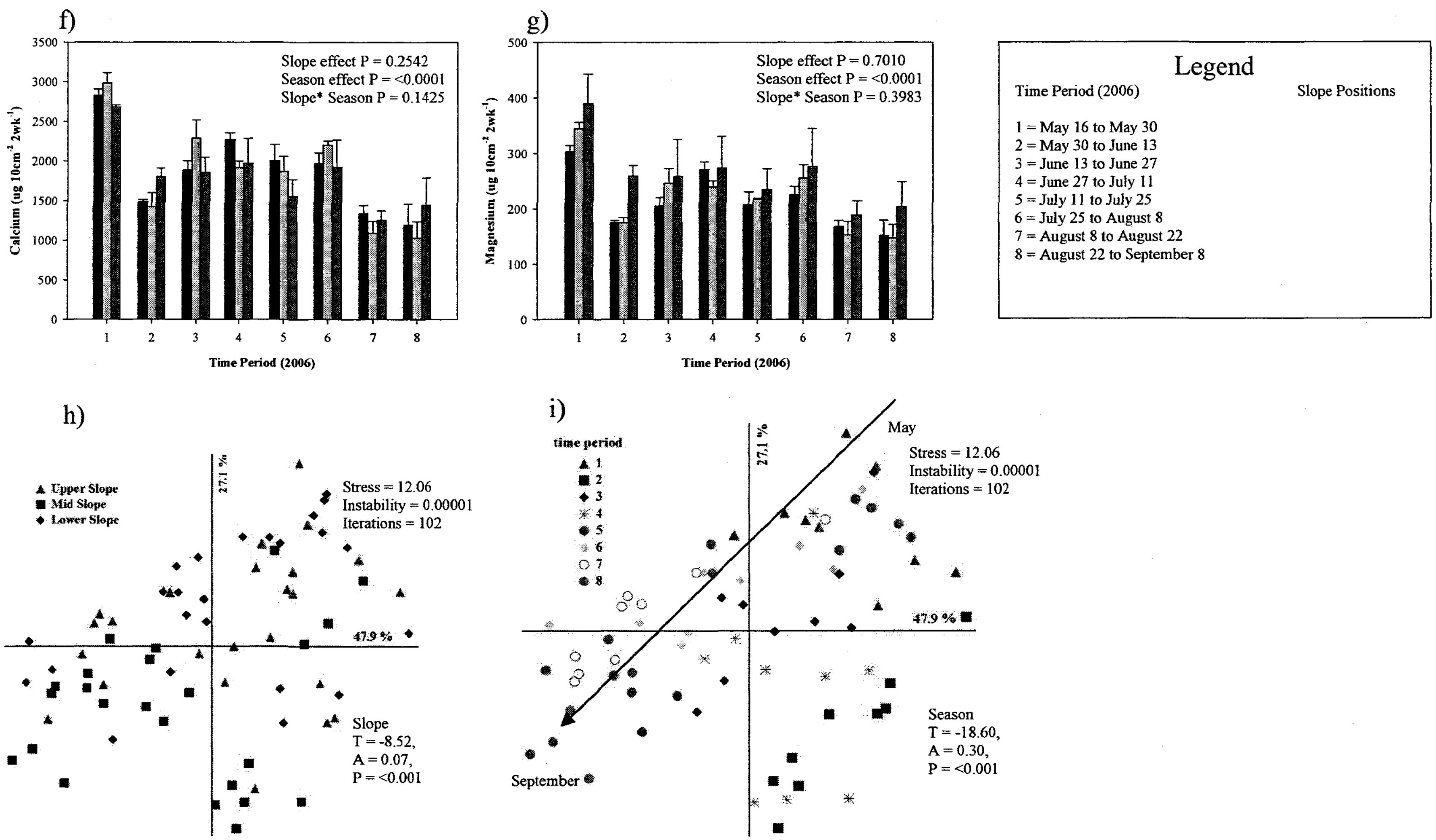


Figure 4.1 (cont'd) Mean nutrient availability (columns) and standard errors (verticals) for Site 1 during the 2006 growing season; f) Ca availability; g) Mg availability; h) NMS results for slope position; i) NMS results for season. For each slope position n = 3. Slope positions that do not have a bar the nutrient was below detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

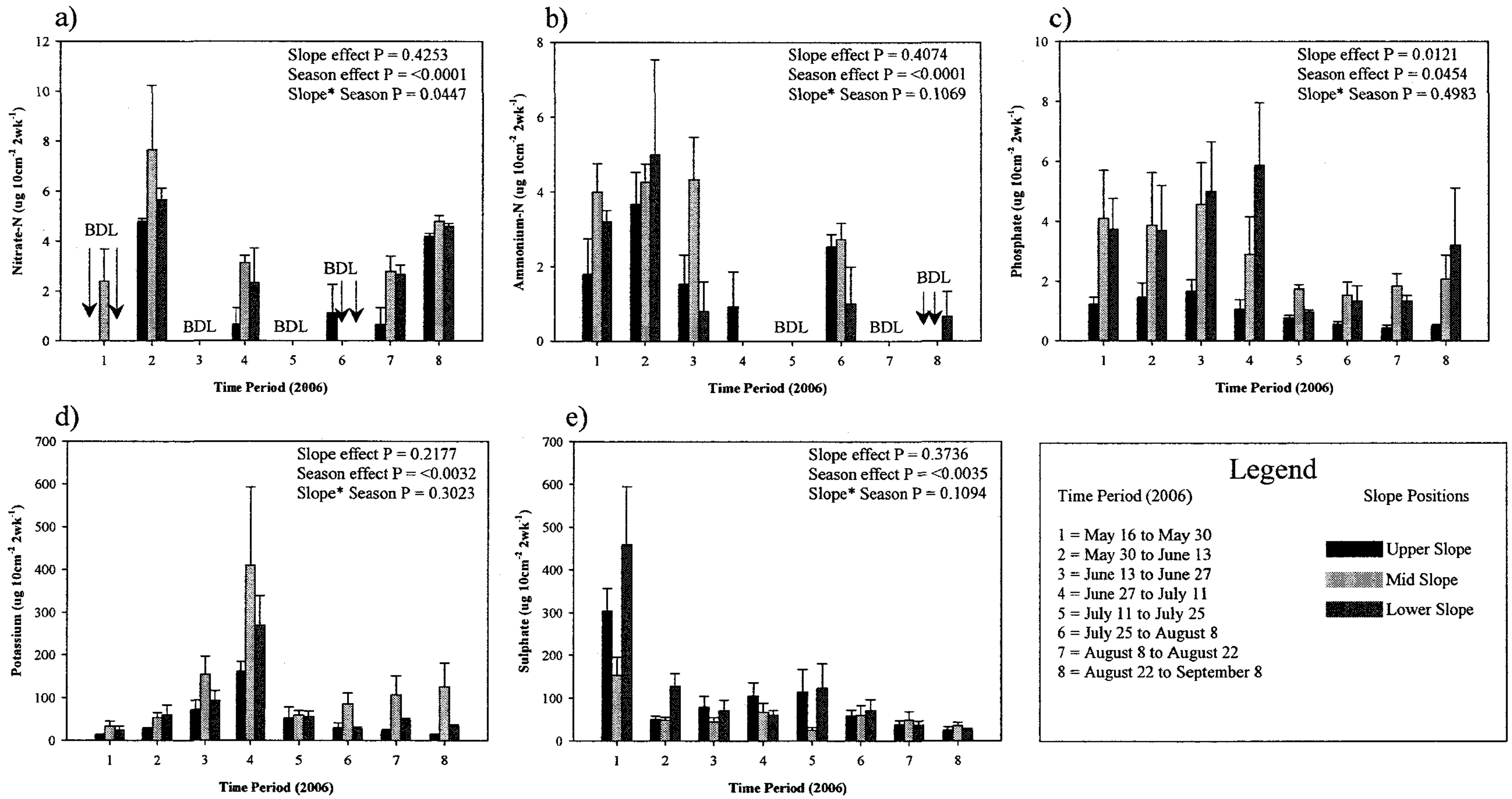


Figure 4.2 Mean nutrient availability (columns) and standard errors (verticals) for Site 2 during the 2006 growing season; a) NO_3-N availability; b) NH_4-N availability; c) PO_4 availability; d) K availability; e) SO_4 availability. For each slope position n = 3. Slope position and time periods that do not have a bar the nutrient was below the detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

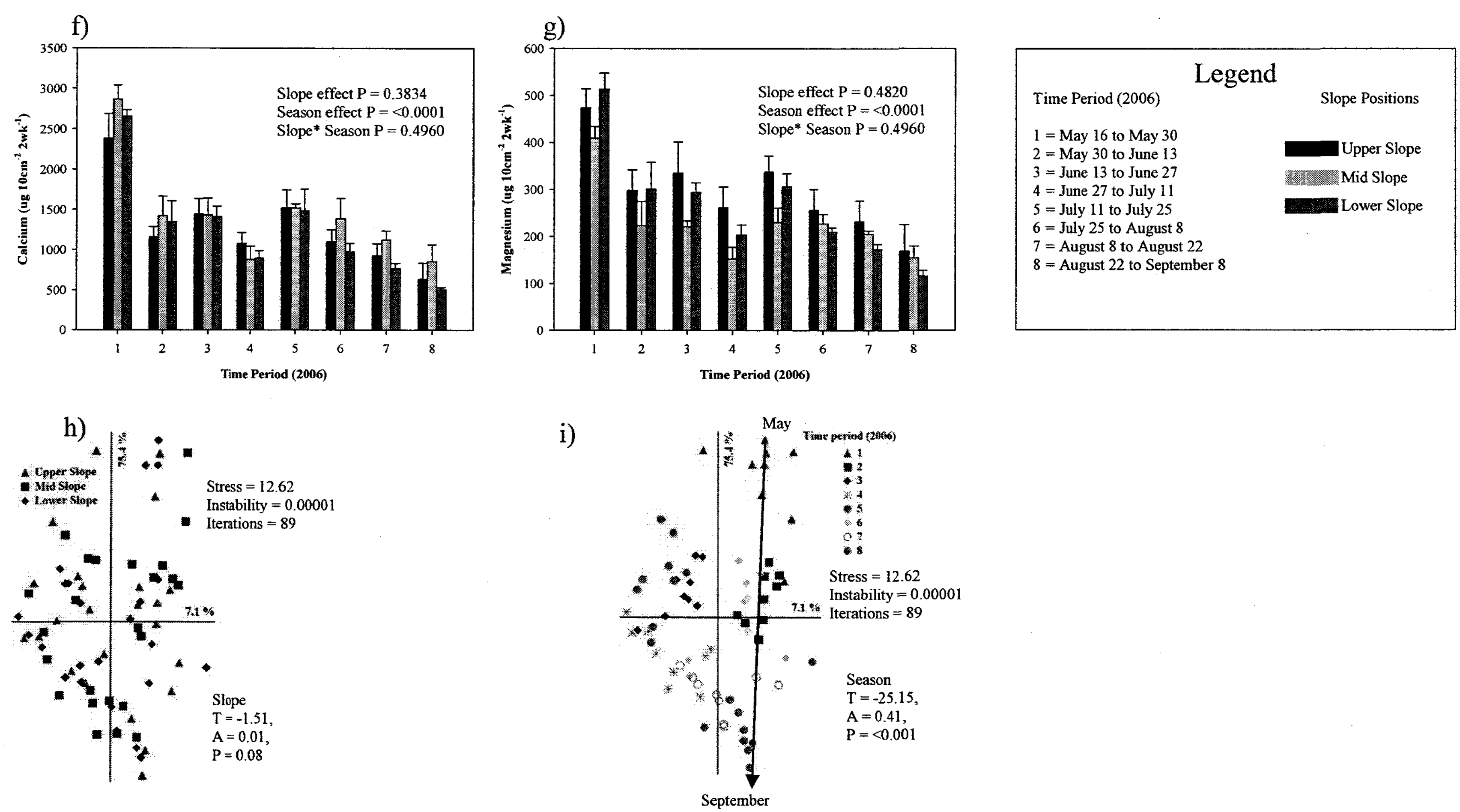


Figure 4.2 (cont'd) Mean nutrient availability (columns) and standard errors (verticals) for Site 2 during the 2006 growing season; f) Ca availability; g) Mg availability; h) NMS results for slope position; i) NMS results for season. For each slope position n = 3. Slope positions that do not have a bar the nutrient was below detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

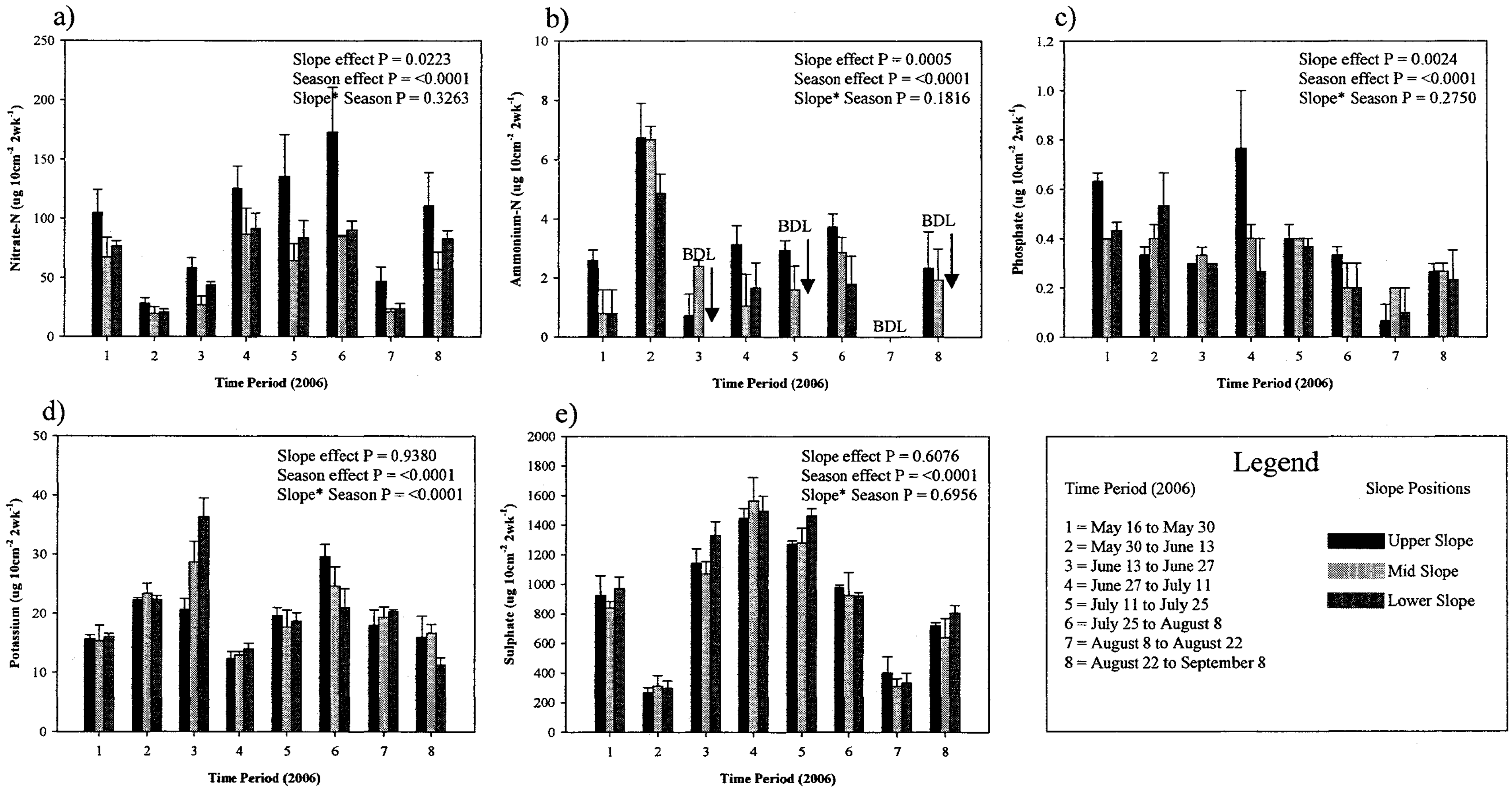


Figure 4.3 Mean nutrient availability (columns) and standard errors (verticals) for Site 3 during the 2006 growing season; a) NO_3-N availability; b) NH_4-N availability; c) PO_4 availability; d) K availability; e) SO_4 availability. For each slope position n = 3. Slope position and time periods that do not have a bar the nutrient was below the detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

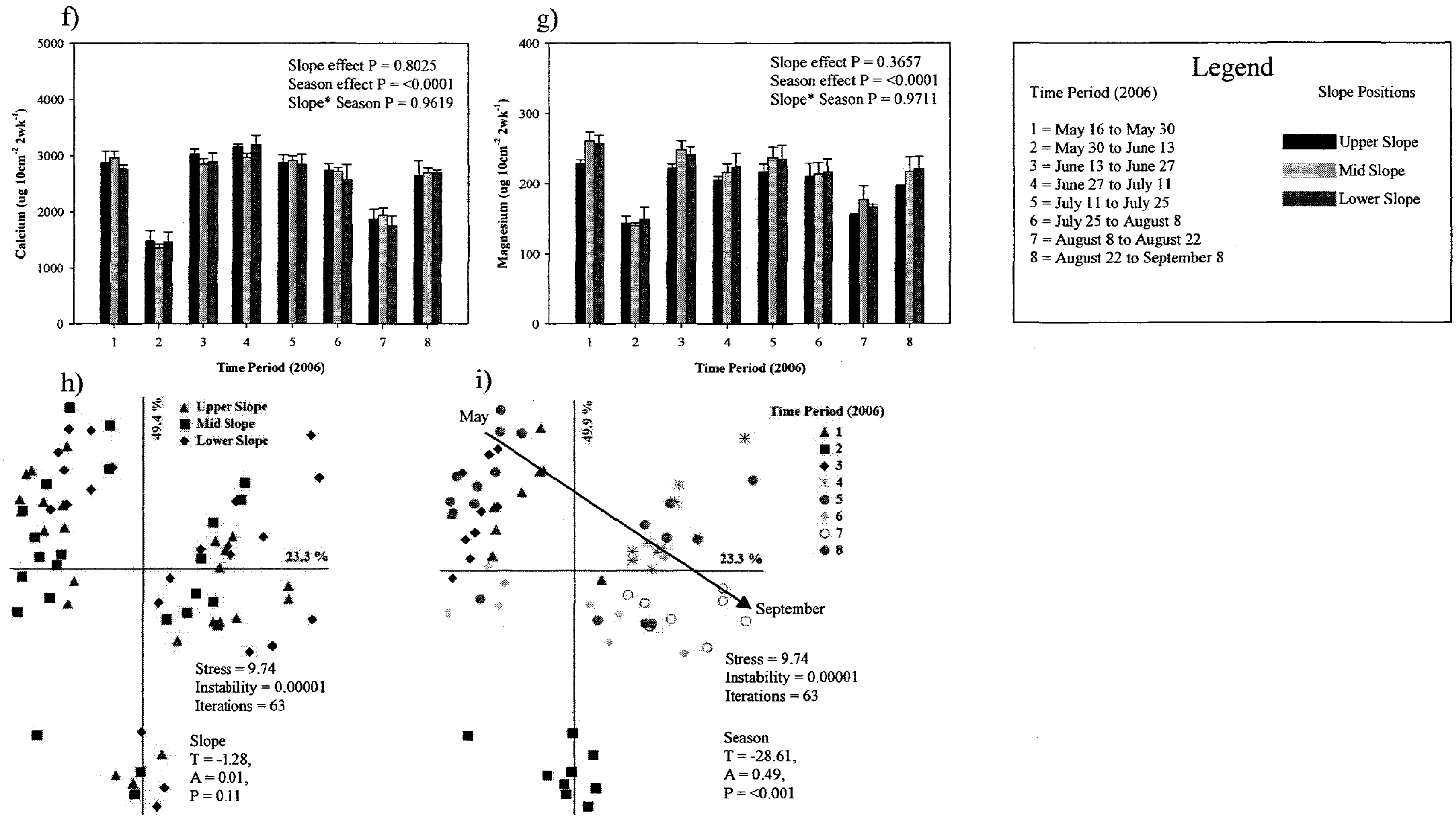


Figure 4.3 (cont'd) Mean nutrient availability (columns) and standard errors (verticals) for Site 3 during the 2006 growing season; f) Ca availability; g) Mg availability; h) NMS results for slope position; i) NMS results for season. For each slope position n = 3. Slope positions that do not have a bar the nutrient was below detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

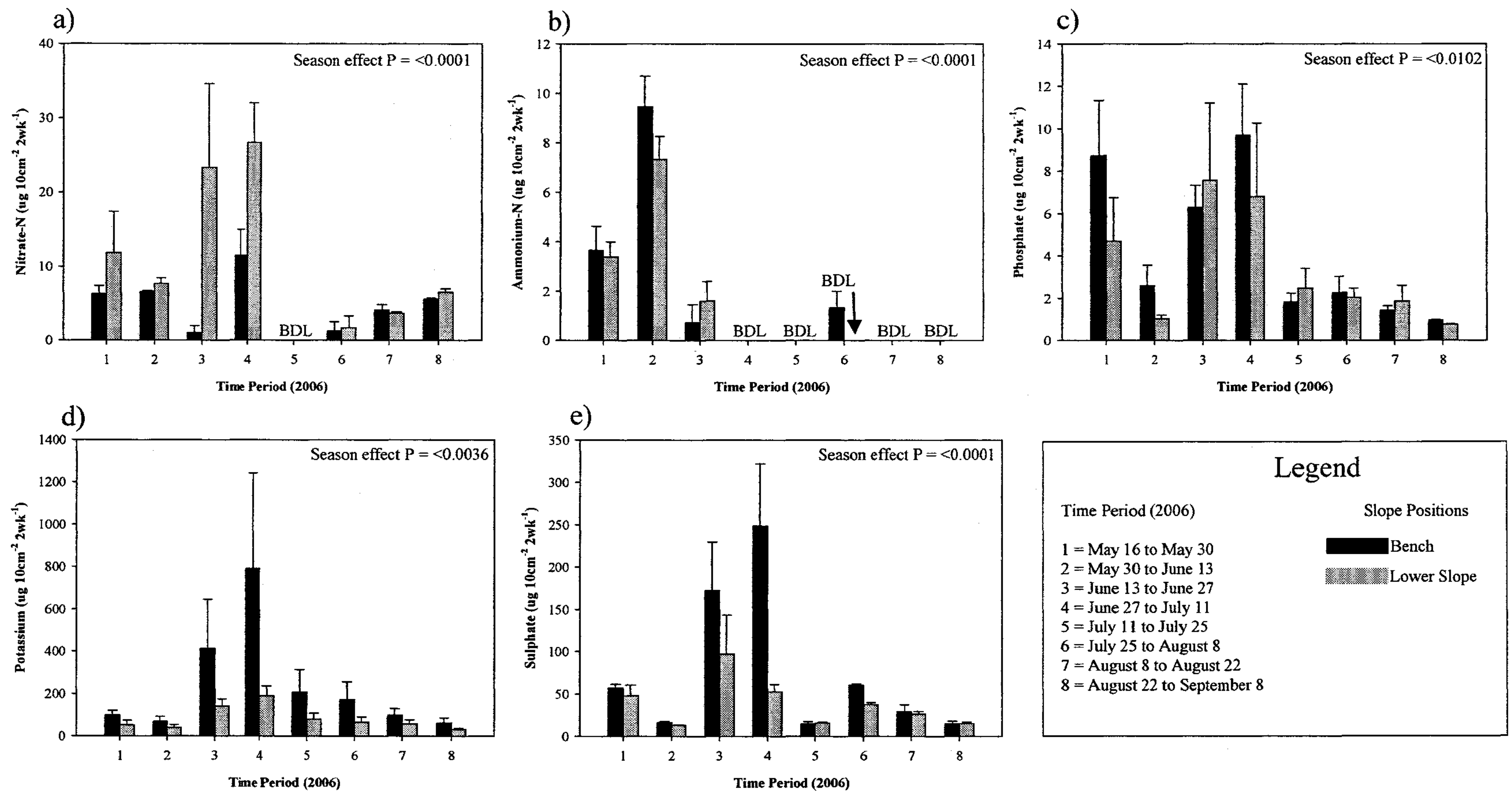


Figure 4.4 Mean nutrient availability (columns) and standard errors (verticals) for Site 4 during the 2006 growing season; a) NO_3-N availability; b) NH_4-N availability; c) PO_4 availability; d) K availability; e) SO_4 availability. For each slope position n = 3. Slope position and time periods that do not have a bar the nutrient was below the detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

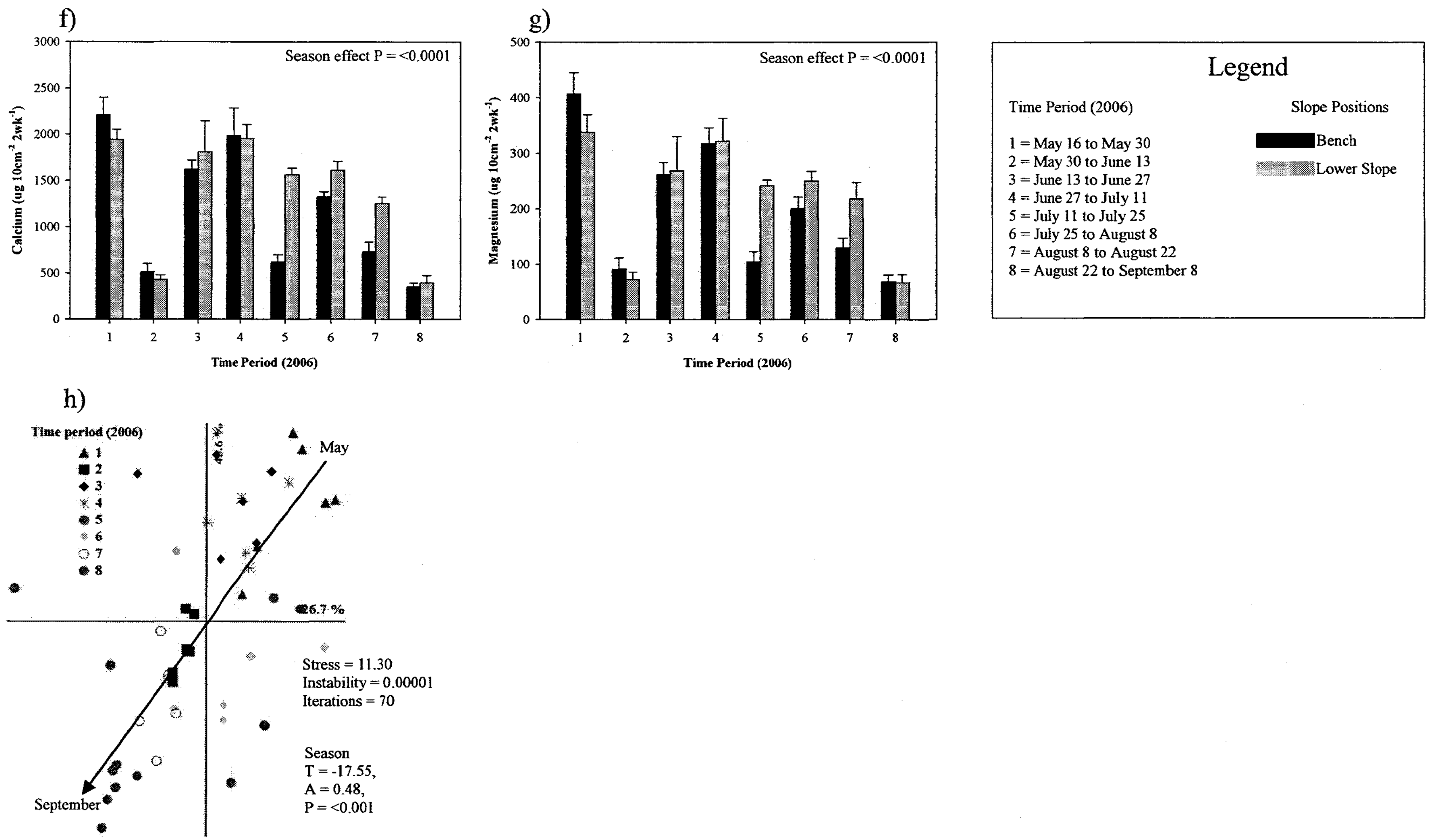


Figure 4.4 (cont'd) Mean nutrient availability (columns) and standard errors (verticals) for Site 4 during the 2006 growing season; f) Ca availability; g) Mg availability; h) NMS results for slope position; i) NMS results for season. For each slope position n = 3. Slope positions that do not have a bar the nutrient was below detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

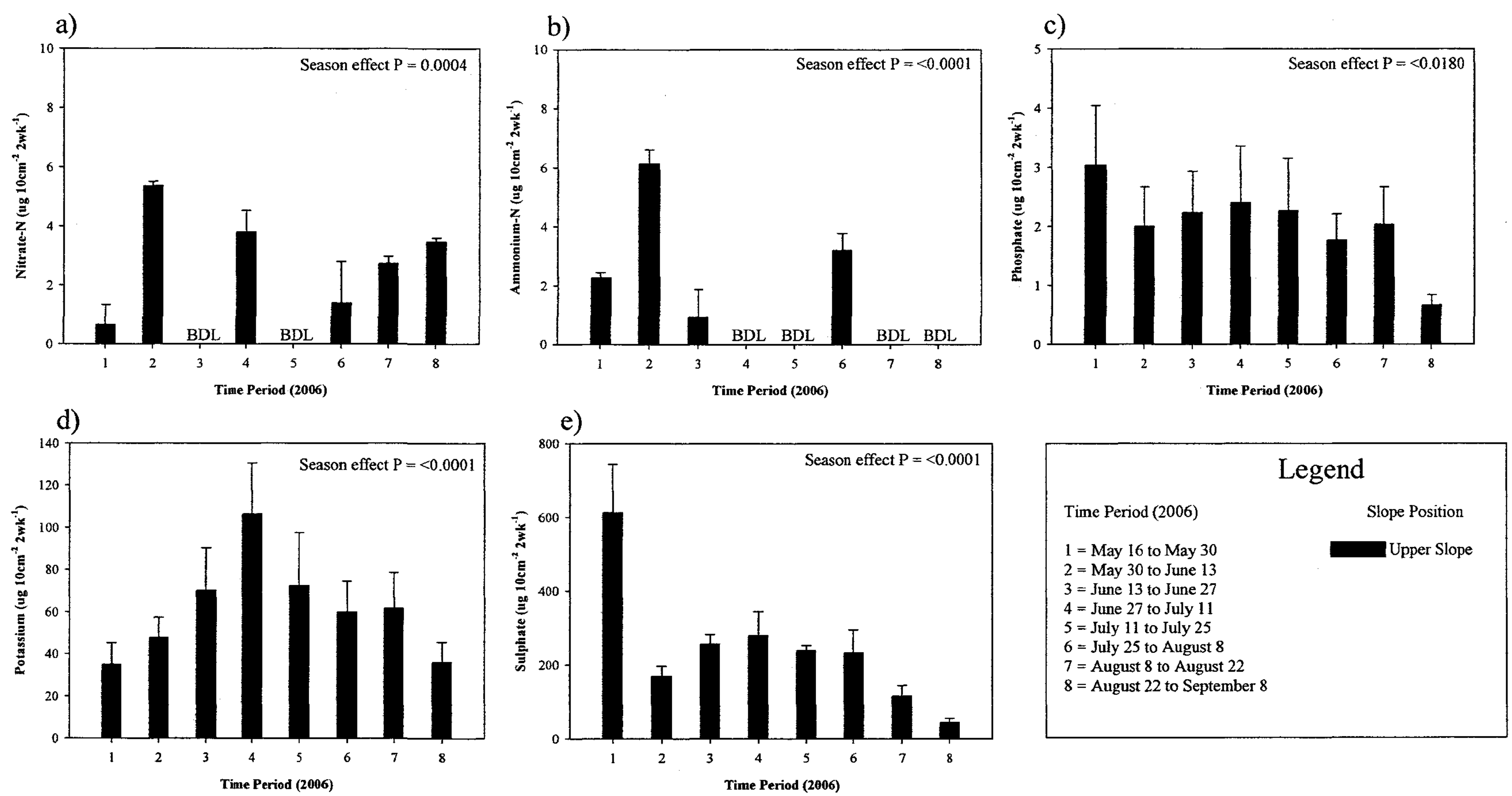


Figure 4.5 Mean nutrient availability (columns) and standard errors (verticals) for Site 5 during the 2006 growing season; a) NO_3-N availability; b) NH_4-N availability; c) PO_4 availability; d) K availability; e) SO_4 availability. For each slope position n = 3. Slope position and time periods that do not have a bar the nutrient was below the detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

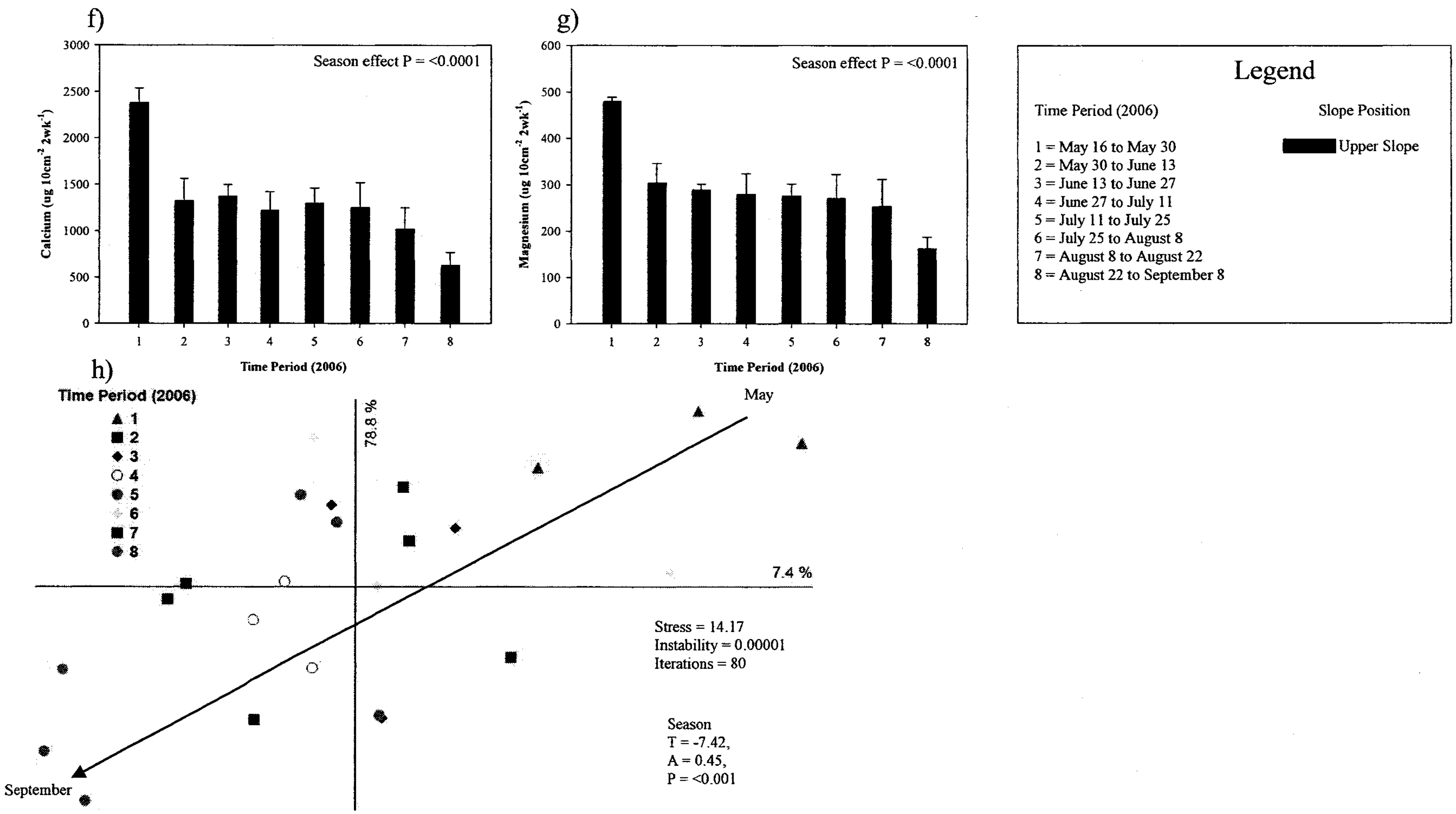


Figure 4.5 (cont'd) Mean nutrient availability (columns) and standard errors (verticals) for Site 5 during the 2006 growing season; f) Ca availability; g) Mg availability; h) NMS results for slope position; i) NMS results for season. For each slope position n = 3. Slope positions that do not have a bar the nutrient was below detectable limit (BDL). Level of significance determined at $P \leq 0.10$.

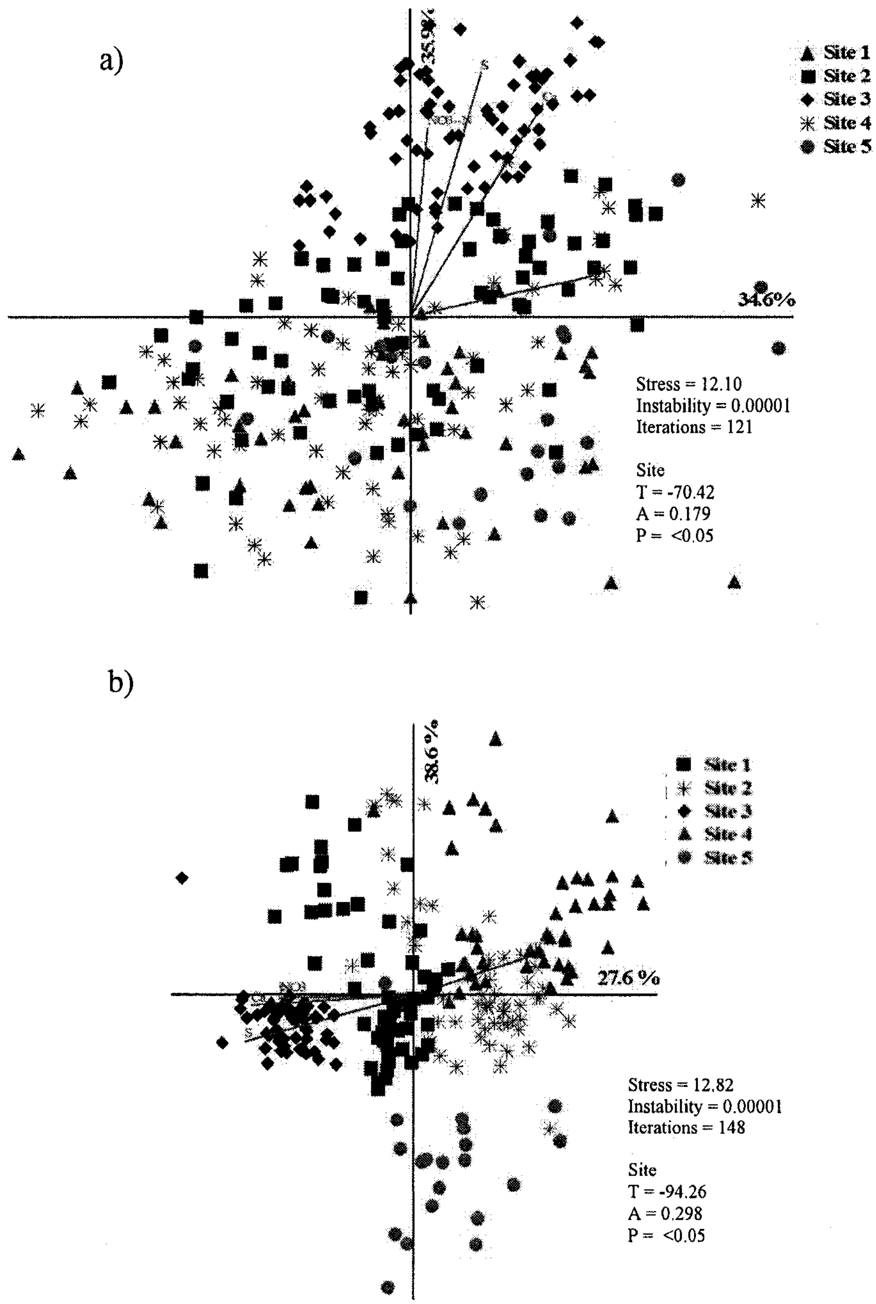


Figure 4.6 NMS results for a) 2006 PRS probe data and b) 2005 PRS probe data. Level of significance determined at $P \leq 0.10$.

CHAPTER V: SYNTHESIS

1.0 Research Summary

1.1 Overview

An operational scale field experiment investigated the spatial and temporal dynamics of soil moisture and nutrient regimes of small reclaimed watersheds with a range of reclamation prescriptions and ages. Soil moisture regimes were quantified at four reclamation sites and soil nutrient regimes were quantified at five sites. Slope position effects for soil moisture and nutrients were determined using a repeated measures model for each site individually. Non-metric multidimensional scaling was used to investigate spatial and seasonal variability in nutrient availability at the reclaimed sites.

1.2 Soil Moisture Regimes of Reclaimed Upland Slopes

There was little slope effect on soil moisture distribution at the sites. The 2006 growing season was warmer than average for the region and the precipitation was similar to long-term averages because of large, intermittent rain events. A large rain event that lasted from July 5^{th} to the 11^{th} accounted for the majority of the precipitation accumulated over the growing season. This was reflected by an increase in soil moisture but soil moisture at none of the sites exceeded field capacity during the growing season. However, the sites, with the exception of Site 4, held soil moisture within the plant available range for the majority of the growing season.

Overall, the upper portions of the soil profiles were more dynamic in response to precipitation than the deeper soil profiles, suggesting that there was little percolation to the underlying material. Site 4 was an exception since it had high rates of infiltration during the high rainfall event, which can be attributed to the coarse texture of the peat-mineral mix (PMM) material and the underlying tailings sand, with high hydraulic conductivity and percolation. Site 3 soil cover was designed to minimize through-flow to the underlying saline/sodic shale (Elshorbagy et al. 2005). During the time period this site was monitored, there was little percolation from the upper soil profile to depth. This study included soil moisture data from the end of the 2005 growing season and the complete 2006 growing season. To completely evaluate the soil cover's performance and soil moisture dynamics at these sites will require continuous monitoring over several growing seasons.

1.3 Soil Nutrient Regimes of Reclaimed Upland Slopes

The expected outcome of a nutrient availability gradient from upper slope to lower slope positions resulting from hydrologic control did not occur. It is possible that the pedogenetically young soils have yet to develop preferential flow paths that would significantly affect nutrient transport. The observed differences in nutrient availability among slope positions could be the result of the inherent heterogeneity in soil properties and vegetation spatial patterns, rather than topographic-moisture-driven gradients.

There was little effect of slope position on nutrient availability due to hydrologic control at the reclaimed upland slopes. There was a significant inter- and intra-annual variability in nutrient availability between the 2005 and 2006 growing seasons. The effect of inter-annual climatic variability was likely the result of the 2006 growing season being warmer and having more intense but less frequent rain events than the 2005 growing season. This climatic variability likely influenced soil moisture and temperature, which in turn influenced the nutrient availability quantified by the PRS probes.

2.0 Implications for Reclamation

Field reclamation experiments are challenging because they are often pseudoreplicated and reflect operational scale reclamation; however, they are necessary to evaluate the performance of reclaimed landscapes and to improve reclamation strategies. They are essential in the Athabasca Oil Sands region (AOSR) because of the large area of land that has been, or will be, disturbed and altered during oil sand mining. Results from the sites investigated in this study suggest that the soil moisture and nutrient regimes are exhibiting characteristics that are similar, to some degree, with what has been reported in natural ecosystems. However, these results should not be interpreted to suggest that reclaimed areas are, in fact, analogous to natural areas. These results do, however, provide insight into the moisture and nutrient dynamics of reclaimed soils and on how they may be similar, or different, to other reclaimed soils and early successional natural areas.

The reclaimed slopes had temporally and spatially complex soil moisture and nutrient regimes. Because reclaimed systems are pedogenically young compared to boreal forest systems, it may be more appropriate to compare the temporal and spatial dynamics of soil moisture and nutrient status of reclaimed systems to immature boreal systems and other reclaimed systems than to compare the magnitude, or difference in, soil moisture or nutrient status between reclaimed and mature boreal forest ecosystems.

The vegetation component of the reclaimed ecosystems was not accounted for in this study. Vegetation is likely influencing the temporal and spatial variability of soil moisture and nutrients found in this study. Future research should couple soil moisture and nutrient dynamics with vegetation studies at these reclaimed sites. The ultimate goal is to predict the future productivity of these ecosystems and linking vegetation with soil moisture and nutrient regimes is the next logical step.

3.0 Literature Cited

Elshorbagy, A., Jutla, A., Barbour, L. and Kells, J. 2005. System dynamics approach to assess the sustainability of reclamation of disturbed watersheds. Can. J. Civ. Eng. 32: 144-158.

APPENDIX A - SOIL MOISTURE DATA

Table A.1 Soil water average values for TSW35 at Site 1 for the 2005 and 2006 growing seasons

Date	Precipitation (mm)	Slope1	Slope2	Slope3	Slope4	Slope5	Slope6	Site Average
14-May-05	-	-	-	-	108.7 (19.5)	-	-	108.7 (19.5)
13-Jun-05	30.2	-	-	-	77.6 (19.3)	-	-	77.6 (19.3)
24-Jun-05	50.5	-	-	-	130.0 (25.7)	-	-	130.0 (25.7)
30-Jun-05	3.6	-	-	-	111.9 (24.1)	-	-	111.9 (24.1)
07-Jul-05	10.4	-	-	-	106.8 (24.9)	-	-	106.8 (24.9)
15-Jul-05	2.8	-	-	-	81.6 (17.8)	-	-	81.6 (17.8)
27-Jul-05	50.5	-	-	-	129.8 (24.7)	-	-	129.8 (24.7)
02-Aug-05	6.9	53.4 (8.7)	67.8 (20.9)	55.0 (23.8)	94.2 (24.8)	74.9 (21.8)	75.3 (23.9)	70.1 (8.1)
15-Aug-05	26.9	52.6 (8.2)	73.1 (22.4)	62.7 (26.0)	103.1 (23.2)	81.6 (19.5)	77.7 (24.2)	75.1 (8.3)
22-Aug-05	19.8	65.9 (9.0)	86.7 (24.3)	68.4 (29.5)	119.8 (23.6)	93.4 (21.1)	85.1 (27.2)	86.5 (9.1)
29-Aug-05	6.6	50.7 (6.6)	66.2 (20.1)	52.7 (20.2)	96.3 (19.8)	76.2 (19.4)	75.8 (23.1)	69.6 (7.5)
04-Sep-05	14.7	53.7 (7.7)	73.2 (20.7)	59.7 (24.1)	104.0 (19.2)	82.0 (19.5)	81.3 (24.5)	75.6 (8.0)
12-Sep-05	1.0	46.9 (6.2)	65.1 (19.9)	49.7 (17.6)	91.1 (17.7)	73.2 (19.7)	77.7 (23.3)	67.3 (7.3)
19-Sep-05	5.1	46.5 (5.6)	64.1 (19.0)	48.7 (17.3)	89.7 (17.4)	73.8 (18.9)	77.3 (22.7)	66.7 (7.1)
26-Sep-05	3.6	42.2 (5.5)	61.9 (20.1)	47.2 (16.8)	70.3 (10.7)	70.9 (18.8)	75.5 (23.5)	60.8 (6.8)
19-May-06	-	49.9 (7.6)	65.9 (17.8)	49.3 (16.6)	85.9 (13.8)	75.4 (18.7)	65.8 (20.7)	65.4 (6.5)
1-Jun-06	26.9	50.0 (8.1)	70.2 (18.0)	53.0 (17.9)	87.2 (16.2)	78.5 (17.6)	68.6 (19.7)	67.9 (6.6)
15-Jun-06	4.3	36.0 (5.3)	48.0 (16.0)	39.5 (14.3)	61.6 (6.9)	62.2 (17.5)	59.9 (18.4)	51.2 (5.5)
29-Jun-06	24.4	34.0 (4.6)	44.0 (15.4)	37.1 (14.3)	57.4 (6.1)	58.8 (15.2)	56.3 (14.9)	47.9 (5.0)
12-Jul-06	73.9	69.0 (12.3)	84.3 (21.8)	68.2 (23.5)	104.3 (16.6)	88.9 (13.0)	83.4 (24.6)	83.0 (7.2)
27-Jul-06	2.8	51.4 (7.2)	67.2 (18.4)	50.5 (16.9)	76.0 (8.9)	71.0 (9.9)	70.9 (20.0)	64.5 (5.5)
10-Aug-06	42.4	56.0 (6.4)	69.4 (18.2)	59.9 (21.0)	89.0 (15.7)	76.8 (10.0)	70.7 (21.1)	70.3 (6.2)
25-Aug-06	13.0	43.2 (3.2)	55.6 (17.4)	48.0 (16.6)	72.5 (13.1)	63.6 (8.3)	61.0 (17.3)	57.3 (5.3)
7-Sep-06	10.7	37.9 (4.0)	50.7 (17.8)	40.2 (14.2)	65.1 (10.4)	54.5 (8.9)	57.4 (16.5)	51.0 (5.0)
21-Sep-06	25.4	51.3 (11.5)	62.8 (17.1)	45.5 (16.4)	76.6 (13.5)	61.2 (7.9)	66.4 (20.0)	60.6 (5.7)
5-Oct-06	15.2	55.6 (11.9)	69.3 (17.8)	47.4 (13.9)	83.4 (16.5)	67.2 (6.8)	66.2 (19.5)	64.9 (5.8)
FC35	-	109.6	109.6	109.6	109.6	109.6	109.6	109.6
WP35	-	39.7	39.7	39.7	39.7	39.7	39.7	39.7

Precipitation is cumulative from previous measuring date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
There were no significant differences in slope position for 2005 or 2006 growing season ($p \leq 0.1$)

Table A.2 Soil water numerical average for TSW65-95 at Site 1 for the 2005 and 2006 growing seasons

Date	Precipitation (mm)	Slope1	Slope2	Slope3	Slope4	Slope5	Slope6	Site Average
14-May-05	-	-	-	-	85.6 (6.7)	-	-	85.6 (6.7)
13-Jun-05	30.2	-	-	-	84.6 (5.6)	-	-	84.6 (5.6)
24-Jun-05	50.5	-	-	-	81.2 (4.5)	-	-	81.2 (4.5)
30-Jun-05	3.6	-	-	-	84.6 (4.9)	-	-	84.6 (4.9)
07-Jul-05	10.4	-	-	-	83.1 (5.9)	-	-	83.1 (5.9)
15-Jul-05	2.8	-	-	-	82.2 (4.6)	-	-	82.2 (4.6)
27-Jul-05	50.5	-	-	-	84.8 (0.0)	-	-	84.8 (0.0)
02-Aug-05	6.9	94.6 (16.4)	113.7 (6.4)	84.4 (21.7)	71.1 (11.0)	77.7 (17.1)	59.4 (25.4)	83.5 (7.3)
15-Aug-05	26.9	94.7 (15.5)	108.1 (5.9)	83.4 (20.8)	69.9 (10.9)	75.6 (17.2)	59.8 (24.0)	81.9 (6.9)
22-Aug-05	19.8	95.8 (14.2)	110.6 (7.6)	83.3 (21.2)	68.7 (10.4)	76.3 (16.3)	66.0 (25.2)	83.4 (6.9)
29-Aug-05	6.6	96.8 (15.8)	112.9 (7.6)	83.3 (21.2)	70.0 (10.8)	77.3 (16.1)	61.5 (25.6)	83.6 (7.2)
04-Sep-05	14.7	93.9 (16.5)	111.7 (6.7)	82.9 (21.2)	70.7 (9.4)	77.4 (16.4)	61.1 (24.9)	83.0 (7.1)
12-Sep-05	1.0	94.3 (15.9)	108.4 (6.1)	82.0 (21.1)	69.7 (9.8)	76.2 (16.1)	60.9 (24.0)	81.9 (6.9)
19-Sep-05	5.1	95.4 (15.1)	108.4 (6.2)	82.4 (20.7)	70.5 (9.9)	75.8 (16.3)	60.1 (24.2)	82.1 (6.9)
26-Sep-05	3.6	91.3 (14.2)	106.3 (6.7)	80.5 (19.8)	68.6 (16.7)	75.1 (16.1)	60.3 (24.0)	81.1 (7.0)
19-May-06	-	105.1 (9.7) [ab]	113.4 (8.6) [ab]	78.1 (19.8) [abc]	70.3 (10.5) [ac]	69.4 (16.3) [ac]	54.8 (23.6) [c]	105.1 (9.7) [ab]
1-Jun-06	26.9	107.1 (10.6) [ab]	115.0 (9.0) [ab]	80.0 (20.6) [abc]	71.2 (10.4) [ac]	70.8 (16.5) [ac]	54.7 (22.2) [c]	107.1 (10.6) [ab]
15-Jun-06	4.3	100.1 (6.5) [ab]	115.6 (7.8) [ab]	79.2 (20.5) [abc]	69.0 (10.8) [ac]	71.8 (16.7) [ac]	54.4 (22.9) [c]	100.1 (6.5) [ab]
29-Jun-06	24.4	92.4 (10.0) [ab]	112.9 (7.4) [ab]	78.0 (20.7) [abc]	68.3 (9.6) [ac]	67.9 (18.1) [ac]	53.3 (21.5) [c]	92.4 (10.0) [ab]
12-Jul-06	73.9	101.6 (10.1) [ab]	121.2 (8.6) [ab]	80.2 (22.5) [ac]	77.9 (8.0) [ac]	71.4 (16.6) [ac]	54.7 (21.8) [c]	101.6 (10.1) [ab]
27-Jul-06	2.8	102.9 (11.0) [ab]	122.0 (8.9) [ab]	82.3 (23.0) [ac]	73.5 (9.6) [ac]	71.8 (16.9) [ac]	56.2 (22.5) [c]	102.9 (11.0) [ab]
10-Aug-06	42.4	103.5 (10.4) [ab]	120.0 (9.0) [ab]	80.7 (22.5) [a]	69.7 (8.6) [a]	70.3 (16.7) [a]	55.2 (21.8) [b]	103.5 (10.4) [ab]
25-Aug-06	13.0	103.2 (10.1) [a]	119.6 (9.6) [a]	80.8 (21.2) [ab]	69.1 (7.2) [ab]	68.6 (17.5) [ab]	54.9 (22.0) [b]	103.2 (10.1) [a]
7-Sep-06	10.7	97.5 (8.8) [ab]	118.9 (10.1) [ab]	79.3 (20.7) [a]	66.9 (7.9) [a]	66.8 (17.3) [a]	55.6 (21.1) [b]	97.5 (8.8) [ab]
21-Sep-06	25.4	101.7 (10.3) [ab]	115.0 (9.0) [ab]	78.1 (21.3) [abc]	70.9 (7.7) [ac]	64.2 (17.5) [c]	54.0 (21.2) [c]	101.7 (10.3) [ab]
5-Oct-06	15.2	101.4 (9.6) [ab]	116.3 (8.6) [ab]	78.1 (21.1) [ac]	67.5 (7.3) [ac]	64.3 (17.3) [ac]	58.0 (21.8) [c]	101.4 (9.6) [ab]
FC65-95	-	71.9	71.9	71.9	71.9	71.9	71.9	71.9
WP65-95	-	25	25	25	25	25	25	25

Precipitation is cumulative from previous measuring date; Slope position values reported as Mean (S.E.)
There were no significant differences in slope position for 2005 ($p \leq 0.1$); n = 3 for each slope position
2006 Slope positions with the same letters in a row are not significantly different ($p \leq 0.1$)

Table A.3 Soil water average values for TSW35 at Site 2 for the 2005 and 2006 growing seasons

Date	Precipitation (mm)	Upper	Mid	Lower	Site Average
27-Aug-05	-	81.7 (14.4)	85.0 (12.9)	74.1 (2.9)	80.3 (5.9)
7-Sep-05	18.0	86.6 (10.5)	88.1 (12.5)	76.7 (2.5)	83.8 (5.1)
27-Sep-05	7.2	77.3 (10.3)	72.3 (7.8)	71.5 (4.8)	73.7 (4.1)
12-Oct-05	1.1	71.4 (9.4)	71.6 (8.3)	68.8 (6.1)	70.6 (4.1)
25-Oct-05	0.0	66.8 (10.8)	66.2 (8.6)	62.8 (4.3)	65.3 (4.2)
27-Apr-06	-	73.6 (8.5) [a]	88.4 (18.3) [b]	83.0 (5.8) [ab]	83.4 (5.3)
11-May-06	23.1	78.6 (6.0) [a]	89.2 (21.4) [a]	86.3 (2.9) [a]	88.4 (5.7)
1-Jun-06	20.7	74.0 (7.5) [a]	78.2 (11.9) [a]	79.6 (3.3) [a]	81.2 (5.2)
13-Jun-06	7.8	57.0 (8.1) [a]	56.2 (5.1) [a]	60.1 (3.5) [a]	61.0 (4.1)
27-Jun-06	28.2	48.3 (4.2) [a]	50.0 (5.5) [a]	55.6 (2.5) [a]	53.5 (2.8)
12-Jul-06	76.2	69.7 (8.4) [a]	90.5 (21.9) [b]	86.1 (4.6) [bc]	83.3 (5.9)
25-Jul-06	3.4	40.1 (6.2) [a]	53.5 (7.0) [b]	56.0 (4.9) [bc]	51.8 (4.3)
9-Aug-06	36.1	53.6 (6.3) [a]	67.5 (11.7) [b]	66.5 (6.1) [bc]	63.6 (4.2)
22-Aug-06	18.1	44.1 (4.8) [a]	63.4 (13.1) [b]	55.1 (7.7) [bc]	54.6 (4.6)
8-Sep-06	9.5	29.6 (3.7) [a]	48.1 (7.1) [b]	43.0 (7.7) [bc]	41.3 (4.3)
FC35 (mm)	-	83.8	83.8	83.8	83.8
WP35 (mm)	-	46	46	46	46

Precipitation is cumulative from previous measuring date; Slope position values reported as Mean (S.E.)
There were no significant differences in slope position for 2005 ($p \leq 0.1$); n = 3 for each slope position
2006 Slope positions with the same letters in a row are not significantly different ($p \leq 0.1$)

Table A.4 Soil water average values for TSW55-85 at Site 2 for the 2005 and 2006 growing seasons

Date	Precipitation (mm)	Upper	Mid	Lower	Site Average
27-Aug-05	-	88.3 (12.0)	45.7 (29.6)	64.6 (24.8)	66.2 (13.2)
7-Sep-05	18.0	85.6 (12.9)	46.2 (30.2)	64.1 (24.4)	65.3 (13.1)
27-Sep-05	7.2	84.8 (12.2)	44.9 (29.7)	62.0 (24.3)	63.9 (13.0)
12-Oct-05	1.1	83.1 (12.3)	42.8 (28.5)	60.0 (22.8)	61.9 (12.5)
25-Oct-05	0.0	84.1 (10.5)	41.8 (27.5)	58.8 (22.5)	61.6 (12.3)
27-Apr-06	-	74.8 (5.0)	93.5 (11.7)	67.5 (24.2)	65.1 (12.5)
11-May-06	23.1	80.4 (19.5)	96.9 (14.6)	75.5 (23.4)	69.5 (15.1)
1-Jun-06	20.7	86.8 (11.8)	90.0 (13.7)	75.1 (24.1)	73.3 (14.1)
13-Jun-06	7.8	85.0 (11.6)	65.9 (10.2)	73.6 (23.9)	71.6 (13.5)
27-Jun-06	28.2	82.8 (9.6)	56.5 (7.3)	73.5 (24.9)	70.5 (14.0)
12-Jul-06	76.2	65.9 (6.6)	94.2 (13.2)	65.4 (22.8)	60.4 (12.3)
25-Jul-06	3.4	67.3 (6.4)	59.3 (7.1)	67.9 (23.2)	61.9 (12.8)
9-Aug-06	36.1	64.5 (5.5)	70.8 (7.5)	66.8 (23.5)	60.6 (12.6)
22-Aug-06	18.1	63.8 (6.2)	65.4 (7.8)	64.1 (22.3)	59.2 (12.1)
8-Sep-06	9.5	60.6 (4.7)	51.3 (5.2)	58.2 (20.4)	55.7 (11.6)
FC5585 (mm)	-	82.2	82.2	82.2	82.2
WP55-85 (mm)	-	45	45	45	45

Precipitation is cumulative from previous measuring date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
There were no significant differences in slope position for 2005 ($p \leq 0.1$)

Table A.5 Soil water average values for TSW40 at Site 3 for the 2005 and 2006 growing seasons

Date	Precipitation (mm)	Upper	Mid	Lower	Site Average
26-May-05	-	-	73.1 (12.1)	-	73.1 (12.1)
02-Jun-05	9.0	-	69.4 (12.8)	-	69.4 (12.8)
09-Jun-05	0.0	-	67.1 (13.1)	-	67.1 (13.1)
16-Jun-05	17.1	-	69.3 (12.3)	-	69.3 (12.3)
27-Jun-05	37.6	-	74.4 (12.0)	-	74.4 (12.0)
30-Jun-05	10.4	-	76.5 (12.2)	-	76.5 (12.2)
07-Jul-05	35.6	-	74.5 (12.3)	-	74.5 (12.3)
14-Jul-05	11.8	-	69.9 (12.3)	-	69.9 (12.3)
21-Jul-05	34.7	-	70.4 (12.5)	-	70.4 (12.5)
02-Aug-05	43.8	-	75.1 (12.1)	-	75.1 (12.1)
8-Aug-05	11.1	75.9 (1.8)	73.2 (12.6)	89.9 (6.2)	79.6 (4.8)
16-Aug-05	20.1	80.2 (1.8)	75.4 (12.7)	95.0 (6.5)	83.5 (5.1)
24-Aug-05	31.1	81.7 (1.8)	77.9 (12.7)	96.6 (6.5)	85.4 (5.0)
6-Sep-05	25.7	74.9 (0.9)	71.5 (12.3)	88.7 (7.4)	78.4 (4.9)
15-Sep-05	2.8	72.0 (0.4)	68.7 (12.5)	86.4 (6.7)	75.7 (4.9)
3-Oct-05	12.0	68.8 (1.6)	65.0 (12.6)	82.7 (7.5)	72.2 (5.0)
11-Oct-05	0.4	68.5 (1.6)	64.9 (13.0)	82.7 (7.6)	72.0 (5.1)
18-Oct-05	5.5	65.9 (2.3)	62.8 (12.6)	79.1 (8.1)	69.3 (5.0)
24-Oct-05	0.0	67.7 (1.9)	63.8 (12.9)	80.8 (7.9)	70.6 (5.1)
11-May-06	-	68.9 (2.1)	69.2 (14.0)	83.2 (9.0)	73.8 (5.4)
25-May-06	19	71.9 (1.5)	70.4 (14.3)	86.8 (7.5)	76.4 (5.4)
12-Jun-06	5.4	65.5 (3.3)	65.8 (13.4)	77.5 (8.6)	69.6 (5.1)
27-Jun-06	20	66.3 (2.7)	67.0 (13.9)	76.9 (9.5)	70.1 (5.2)
12-Jul-06	74.6	78.7 (2.5)	75.8 (13.4)	89.6 (7.7)	81.4 (5.0)
26-Jul-06	20.3	69.4 (1.0)	70.7 (12.7)	79.5 (8.5)	73.2 (4.7)
16-Aug-06	28.7	71.0 (0.4)	70.7 (13.2)	82.6 (7.9)	74.8 (4.9)
31-Aug-06	12.7	69.7 (1.1)	69.5 (13.3)	82.9 (8.0)	74.0 (5.0)
7-Sep-06	0	67.4 (2.7)	69.0 (13.4)	78.7 (7.8)	71.7 (4.9)
19-Sep-06	4.4	65.5 (2.6)	66.0 (13.2)	77.4 (8.3)	69.7 (4.9)
FC40 (mm)	-	144.6	144.6	144.6	144.6
WP40 (mm)	-	45.4	45.4	45.4	45.4

Precipitation is cumulative from previous measuring date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
There were no significant differences in slope position for 2005 or 2006 growing season ($p \leq 0.1$)

Table A.6 Soil water average values for TSW60-100 at Site 3 for the 2005 and 2006 growing seasons

Date	Precipitation (mm)	Upper	Mid	Lower	Site Average
26-May-05	-	-	57.8 (5.1)	-	57.8 (5.1)
02-Jun-05	9.0	-	56.8 (5.3)	-	56.8 (5.3)
09-Jun-05	0.0	-	55.8 (5.3)	-	55.8 (5.3)
16-Jun-05	17.1	-	54.1 (5.8)	-	54.1 (5.8)
27-Jun-05	37.6	-	56.7 (6.7)	-	56.7 (6.7)
30-Jun-05	10.4	-	56.4 (6.6)	-	56.4 (6.6)
07-Jul-05	35.6	-	56.8 (6.6)	-	56.8 (6.6)
14-Jul-05	11.8	-	56.1 (6.4)	-	56.1 (6.4)
21-Jul-05	34.7	-	56.8 (5.7)	-	56.8 (5.7)
02-Aug-05	43.8	-	59.5 (6.0)	-	59.5 (6.0)
8-Aug-05	11.1	31.6 (12.1)	58.8 (6.0)	43.6 (8.2)	44.7 (6.0)
16-Aug-05	20.1	31.5 (11.9)	57.9 (5.9)	42.9 (8.0)	44.1 (5.9)
24-Aug-05	31.1	33.9 (11.6)	59.9 (6.3)	45.5 (8.2)	46.4 (5.8)
6-Sep-05	25.7	33.1 (11.8)	58.1 (6.0)	44.0 (7.7)	45.0 (5.7)
15-Sep-05	2.8	32.4 (12.0)	56.5 (6.0)	42.9 (7.4)	44.0 (5.6)
3-Oct-05	12.0	31.5 (12.1)	54.0 (6.0)	40.9 (7.0)	42.1 (5.5)
11-Oct-05	0.4	31.0 (12.1)	52.8 (5.9)	40.2 (6.8)	41.3 (5.4)
18-Oct-05	5.5	30.3 (11.9)	51.6 (6.0)	39.0 (6.9)	40.3 (5.3)
24-Oct-05	0.0	30.3 (12.0)	52.0 (6.1)	39.5 (6.8)	40.6 (5.4)
11-May-06	-	29.2 (11.2)	50.6 (6.9)	39.6 (7.9)	39.8 (5.4)
25-May-06	19.0	28.3 (11.0)	50.2 (6.8)	37.7 (6.8)	38.7 (5.3)
12-Jun-06	5.4	28.5 (11.0)	50.7 (6.8)	37.6 (6.5)	38.9 (5.3)
27-Jun-06	20.0	30.1 (11.5)	53.0 (7.0)	38.8 (6.6)	40.6 (5.5)
12-Jul-06	74.6	30.7 (11.8)	67.3 (9.4)	39.9 (6.3)	46.0 (7.2)
26-Jul-06	20.3	31.7 (12.3)	64.0 (5.0)	41.0 (6.6)	45.6 (6.4)
16-Aug-06	28.7	32.0 (12.4)	60.5 (4.1)	40.9 (6.3)	44.5 (5.9)
31-Aug-06	12.7	31.9 (12.1)	58.3 (4.5)	40.7 (6.4)	43.6 (5.7)
7-Sep-06	0.0	32.2 (12.4)	59.0 (5.0)	41.1 (6.7)	44.1 (5.8)
19-Sep-06	4.4	31.1 (11.8)	56.4 (5.3)	39.3 (6.3)	42.3 (5.6)
FC60-100 (mm)	-	24.8	24.8	24.8	24.8
WP60-100 (mm)	-	3.2	3.2	3.2	3.2

Precipitation is cumulative from previous measuring date

Slope position values reported as Mean (S.E.); n = 3 for each slope position

There were no significant differences in slope position for 2005 or 2006 ($p \leq 0.1$)

Table A.7 Soil water average values for TSW35 at Site 4 for the 2005 and 2006 growing seasons

Date	Precipitation (mm)	Upper	Mid	Lower	Site Average
15-May-05	-	-	46.4 (7.8)	-	46.4 (7.8)
10-Jun-05	20.1	-	31.2 (9.2)	-	31.2 (9.2)
24-Jun-05	60.7	-	84.5 (9.0)	-	84.5 (9.0)
30-Jun-05	3.6	-	64.3 (12.2)	-	64.3 (12.2)
7-Jul-05	10.4	-	56.7 (7.8)	-	56.7 (7.8)
15-Jul-05	2.8	-	36.6 (8.6)	-	36.6 (8.6)
26-Jul-05	53.8	89.2 (19.1)	70.2 (10.8)	59.2 (18.5)	72.9 (28.1)
2-Aug-05	15.5	84.3 (11.5)	67.8 (12.1)	55.4 (14.8)	69.2 (23.1)
15-Aug-05	22.4	72.8 (7.5)	54.0 (10.3)	49.6 (12.5)	58.8 (18.8)
22-Aug-05	23.1	101.8 (8.9)	90.5 (10.4)	66.3 (23.7)	88.7 (23.2)
29-Aug-05	6.4	63.7 (2.9)	59.3 (11.9)	46.2 (13.0)	56.4 (17.4)
6-Sep-05	38.9	78.9 (11.1)	75.8 (14.0)	56.8 (13.0)	70.5 (21.7)
12-Sep-05	1.0	67.1 (12.7)	60.2 (12.6)	46.6 (13.1)	56.8 (20.2)
19-Sep-05	4.1	53.6 (7.7)	54.6 (11.4)	43.6 (13.0)	50.6 (17.2)
19-May-06	-	21.8 (3.1)	18.2 (3.9)	23.3 (4.2)	21.1 (6.0)
1-Jun-06	19.55	26.0 (3.8)	21.9 (3.8)	24.3 (3.2)	24.1 (5.7)
15-Jun-06	5.08	17.9 (2.7)	14.0 (3.1)	12.6 (2.7)	14.8 (4.9)
29-Jun-06	33.78	28.8 (5.6)	24.0 (3.2)	14.5 (3.3)	22.3 (9.2)
12-Jul-06	104.14	76.3 (10.4)	55.0 (11.8)	45.9 (4.6)	59.1 (19.6)
28-Jul-06	14.22	27.6 (4.0)	24.3 (5.1)	22.7 (3.4)	24.9 (6.7)
10-Aug-06	34.79	37.2 (6.5)	31.4 (8.6)	26.6 (5.2)	31.7 (11.4)
25-Aug-06	22.36	27.5 (4.6)	26.9 (10.1)	22.0 (5.0)	25.5 (10.9)
7-Sep-06	9.91	20.1(3.1)	18.7 (6.2)	16.6 (4.1)	18.4 (7.1)
21-Sep-06	36.82	42.9 (9.5)	32.2 (9.1)	34.2 (6.7)	36.4 (13.8)
5-Oct-06	11.68	38.2 (8.2)	30.9 (9.3)	33.3 (5.9)	34.2 (12.3)
FC35 (mm)	-	84.9	84.9	84.9	84.9
WP35 (mm)	-	32.7	32.7	32.7	32.7

Precipitation is cumulative from previous measuring date
Slope position values reported as Mean (S.E.); $n = 3$ for each slope position
There were no significant differences in slope position for 2005 or 2006 growing season ($p \leq 0.1$)

Table A.8 Soil water average values for TSW85-135 at Site 4 for the 2005 and 2006 growing seasons

Date	Precipitation (mm)	Upper	Mid	Lower	Site Average
15-May-05	-	-	22.2 (5.9)	-	22.2 (5.9)
10-Jun-05	20.1	-	18.1 (4.1)	-	18.1 (4.1)
24-Jun-05	60.7	-	16.7 (3.3)	-	16.7 (3.3)
30-Jun-05	3.6	-	16.7 (3.2)	-	16.7 (3.2)
7-Jul-05	10.4	-	15.9 (2.9)	-	15.9 (2.9)
15-Jul-05	2.8	-	15.3 (2.5)	-	15.3 (2.5)
26-Jul-05	53.8	18.8 (6.8)	10.8 (3.5)	10.4 (4.2)	13.3 (2.9)
2-Aug-05	15.5	18.4 (6.7)	10.5 (3.5)	10.5 (4.3)	13.1 (2.8)
15-Aug-05	22.4	17.9 (6.5)	9.9 (3.2)	9.9 (4.1)	12.5 (2.8)
22-Aug-05	23.1	17.6 (6.5)	9.7 (3.1)	5.1 (4.2)	10.8 (3.0)
29-Aug-05	6.4	17.8 (6.5)	9.5 (3.0)	9.4 (3.8)	12.2 (8.2)
6-Sep-05	38.9	19.5 (6.3)	10.4 (2.9)	15.8 (5.5)	15.2 (2.9)
12-Sep-05	1.0	10.0 (7.1)	9.4 (2.8)	13.3 (5.1)	10.9 (2.7)
19-Sep-05	4.1	18.6 (6.0)	10.0 (2.7)	13.1 (4.9)	13.9 (2.9)
19-May-06	-	21.9 (7.2)	22.7 (3.5)	36.2 (5.2)	26.9 (3.6)
1-Jun-06	19.55	22.6 (7.2)	23.6 (3.7)	35.7 (5.1)	27.3 (3.5)
15-Jun-06	5.08	20.0 (5.5)	23.3 (3.5)	30.6 (4.4)	24.6 (2.8)
29-Jun-06	33.78	21.2 (6.0)	21.7 (5.2)	27.7 (4.3)	23.6 (2.9)
12-Jul-06	104.14	56.1 (22.9)	61.1 (9.6)	66.0 (20.5)	61.1 (9.4)
28-Jul-06	14.22	35.7 (12.8)	45.3 (3.0)	48.6 (7.6)	43.2 (4.8)
10-Aug-06	34.79	33.2 (11.7)	43.2 (1.4)	44.5 (7.3)	40.3 (4.4)
25-Aug-06	22.36	31.0 (11.0)	41.6 (0.5)	40.6 (8.2)	37.7 (4.3)
7-Sep-06	9.91	28.7 (10.3)	37.5 (0.6)	33.9 (6.0)	33.4 (3.7)
21-Sep-06	36.82	27.2 (9.4)	35.6 (0.5)	31.3 (5.9)	31.4 (3.4)
5-Oct-06	11.68	26.7 (8.9)	35.1 (0.8)	31.0 (5.8)	31.0 (3.3)
FC85-135 (mm)	-	24.0	24.0	24.0	24.0
WP85-135 (mm)	-	9.0	9.0	9.0	9.0

Precipitation is cumulative from previous measuring date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
There were no significant differences in slope position for 2005 or 2006 growing season ($p \leq 0.1$)

APPENDIX B - SOIL NUTRIENT DATA

Table B.1 Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 1 for the 2005 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Mid	Lower
NO_3	May 20 - June 20	35.1	0.2 (0.1)	0.1 (0.0)	3.8 (1.4)
	June 20 - July20	61.0	0.1 (0.0)	0.2 (0.0)	0.1 (0.0)
	July 20 - Aug 20	85.3	0.4 (0.0)	3.0 (1.0)	0.1 (0.0)
	Aug 20 - Sept 20	31.7	0.3 (0.1)	0.4 (0.1)	0.3 (0.0)
NH_4	May 20 - June 20	35.1	0.2 (0.0)	0.4 (0.0)	0.5 (0.0)
	June 20 - July20	61.0	BDL	BDL	BDL
	July 20 - Aug 20	85.3	BDL	BDL	BDL
	Aug 20 - Sept 20	31.7	0.1 (0.1)	BDL	BDL
Ca	May 20 - June 20	35.1	121.4 (1.9)	112.7 (2.5)	114.6 (6.1)
	June 20 - July20	61.0	126.4 (3.8)	117.4 (4.1)	121.9 (1.9)
	July 20 - Aug 20	85.3	126.9 (2.6)	127.9 (3.6)	127.8 (1.7)
	Aug 20 - Sept 20	31.7	133.8 (3.9)	123.6 (5.8)	126.3 (7.2)
Mg	May 20 - June 20	35.1	19.9 (0.6)	19.8 (0.8)	24.0 (1.3)
	June 20 - July20	61.0	26.3 (1.4)	21.3 (1.0)	20.9 (0.7)
	July 20 - Aug 20	85.3	27.1 (2.1)	22.7 (0.6)	20.9 (0.7)
	Aug 20 - Sept 20	31.7	22.0 (0.6)	22.3 (0.9)	26.9 (2.4)
K	May 20 - June 20	35.1	0.3 (0.0)	0.6 (0.1)	0.8 (0.2)
	June 20 - July20	61.0	0.6 (0.1)	0.6 (0.1)	0.3 (0.0)
	July 20 - Aug 20	85.3	0.6 (0.2)	0.5 (0.1)	0.2 (0.0)
	Aug 20 - Sept 20	31.7	0.3 (0.1)	0.4 (0.1)	0.5 (0.1)
P	May 20 - June 20	35.1	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)
	June 20 - July20	61.0	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)
	July 20 - Aug 20	85.3	0.1 (0.0)	0.3 (0.1)	0.1 (0.0)
	Aug 20 - Sept 20	31.7	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)
S	May 20 - June 20	35.1	18.7 (1.3)	13.0 (1.5)	20.6 (0.9)
	June 20 - July20	61.0	16.3 (1.4)	8.4 (0.8)	15.9 (2.0)
	July 20 - Aug 20	85.3	22.3 (1.0)	8.6 (0.7)	14.8 (2.8)
	Aug 20 - Sept 20	31.7	14.4 (2.3)	7.2 (0.8)	23.5 (1.4)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 5 for each slope position
Differences among nutrient availability for a given slope position was not analyzed for the 2005 growing season

Table B.2 Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 1 for the 2006 growing season

Nutrient	Precipitation (mm)	Burial Period	Upper	Mid	Lower
	May 16 - May 30	18.2	1.4 (1.4)	4.1 (0.3)	5.4 (0.6)
	May 30-June 13	4.6	6.1 (0.5)	5.8 (0.1)	6.7 (0.7)
	June 13-June27	20.0	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
NO_3	June 27 - July 11	74.9	2.8 (0.5)	3.69 (1.0)	3.1 (0.7)
	July 11 - July 25	59.0	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	July 25 - Aug 8	22.0	1.1 (1.1)	0.0 (0.0)	1.1 (1.1)
	Aug 8 - Aug 22	12.9	1.7 (0.9)	3.1 (0.3)	3.2 (0.6)
	Aug 22 - Sept 8	6.8	4.1 (0.2)	4.9 (0.4)	4.6 (0.5)
	May 16 - May 30	18.2	1.5 (1.5)	1.4 (0.7)	0.0 (0.0)
	May 30-June 13	4.6	7.6 (0.9)	5.1 (1.2)	6.2 (0.6)
	June 13-June27	20.0	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
NH_4	June 27 - July 11	74.9	0.9 (0.9)	2.8 (0.2)	1.4 (1.4
	July 11 - July 25	59.0	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	July 25 - Aug 8	22.0	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Aug 8 - Aug 22	12.9	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Aug 22 - Sept 8	6.8	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	May 16 - May 30	18.2	2828.0 (81.0)	2983.3 (128.7)	2684.0 (22.7)
	May 30-June 13	4.6	1488.0 (27.1)	1427.7 (173.7)	1805.7 (105.2)
	June 13-June27	20.0	1892.0 (116.3)	2286.7 (228.3)	1853.7 (193.5)
Ca	June 27 - July 11	74.9	2272.7 (81.3)	1918.0 (81.4)	1971.7 (314.5)
	July 11 - July 25	59.0	2007.3 (202.8)	1870.0 (189.5)	1558.7 (213.0)
	July 25 - Aug 8	22.0	1973.7 (131.4)	2204.0 (53.9)	1924.3 (347.1)
	Aug 8 - Aug 22	12.9	1340.7 (103.7)	1092.3 (150.4)	1260.0 (115.5)
	Aug 22 - Sept 8	6.8	1499.0 (261.0)	1031.7 (206.6)	1449.0 (343.9)
	May 16 - May 30	18.2	302.7 (11.2)	345.0 (11.1)	389.3 (53.4)
	May 30-June 13	4.6	175.0 (4.0)	175.0 (9.5)	259.7 (18.5)
	June 13-June27	20.0	205.3 (15.3)	246.0 (26.5)	258.7 (66.7)
Mg	June 27 - July 11	74.9	271.0 (13.6)	239.3 (11.3)	273.7 (57.2)
	July 11 - July 25	59.0	208.0 (22.5)	217.3 (2.3)	235.0 (37.3)
	July 25 - Aug 8	22.0	225.7 (14.8)	255.7 (23.9)	276.7 (68.1)
	Aug 8 - Aug 22	12.9	167.7 (11.4)	152.7 (24.1)	188.7 (25.5)
	Aug 22 - Sept 8	6.8	152.0 (27.3)	147.3 (24.2)	204.0 (44.5)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
Values with different letters denote significant different nutrient availability at $p \leq 0.1$; values without numbers did not have any significant differences in nutrient availability

Table B.2 (cont'd) Average soil nutrient availability ($\mu g\ 10\ cm^{-2}\ 2\ wk^{-1}$) at Site 1 for the 2006 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Mid	Lower
	May 16 - May 30	18.2	10.7 (2.2)	14.0 (4.2)	16.3 (9.8)
	May 30-June 13	4.6	18.0 (4.5)	17.7 (4.9)	23.3 (10.8)
	June 13-June27	20.0	110.7 (9.7)	91.0 (27.8)	32.3 (10.7)
K	June 27 - July 11	74.9	191.0 (18.6)	214.7 (42.0)	48.3 (6.9)
	July 11 - July 25	59.0	79.3 (48.5)	37.0 (12.9)	38.0 (7.6)
	July 25 - Aug 8	22.0	79.3 (38.0)	62.3 (5.8)	33.0 (5.6)
	Aug 8 - Aug 22	12.9	62.0 (33.4)	53.7 (15.9)	28.3 (7.8)
	Aug 22 - Sept 8	6.8	54.3 (38.3)	29.3 (5.5)	26.3 (10.5)
	May 16 - May 30	18.2	1.0 (0.0)^{b}	2.7 (0.9)^{a}	0.6 (0.1)^{b}
	May 30-June 13	4.6	0.9 (0.1)^{b}	1.8 (0.4)^{a}	0.8 (0.0)^{b}
	June 13-June27	20.0	1.8 (0.7)^{b}	5.2 (2.0)^{a}	0.8 (0.1)^{b}
P	June 27 - July 11	74.9	1.1 (0.4)^{b}	7.6 (4.1)^{a}	0.4 (0.0)^{b}
	July 11 - July 25	59.0	0.7 (0.1)^{b}	1.3 (0.0)^{a}	0.5 (0.1)^{b}
	July 25 - Aug 8	22.0	1.1 (0.3)^{b}	3.5 (0.7)^{a}	0.4 (0.1)^{c}
	Aug 8 - Aug 22	12.9	0.5 (0.2)^{b}	1.0 (0.1)^{a}	0.4 (0.1)^{b}
	Aug 22 - Sept 8	6.8	0.8 (0.2)^{c}	6.1 (2.7)^{a}	3.7 (3.4)^{b}
	May 16 - May 30	18.2	988.3 (73.1)^{a}	346.3 (67.0)^{b}	1164.0 (26.0)^{a}
	May 30-June 13	4.6	272.3 (61.2)^{b}	58.0 (13.1)^{c}	578.7 (47.4)^{a}
	June 13-June27	20.0	539.0 (96.1)^{a}	131.0 (44.7)^{b}	717.7 (277.8)^{a}
S	June 27 - July 11	74.9	631.7 (62.1)^{a}	129.3 (43.2)^{b}	993.0 (249.5)^{a}
	July 11 - July 25	59.0	679.7 (161.1)^{a}	59.7 (16.2)^{b}	564.3 (199.6)^{a}
	July 25 - Aug 8	22.0	520.3 (68.6)^{a}	138.0 (25.7)^{b}	634.3 (225.2)^{a}
	Aug 8 - Aug 22	12.9	243.3 (10.9)^{a}	53.0 (7.6)^{b}	336.0 (131.9)^{a}
	Aug 22 - Sept 8	6.8	153.3 (47.1)^{b}	26.3 (5.3)^{c}	430.7 (176.7)^{a}

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
Values with different letters denote significant different nutrient availability at $p \leq 0.1$; values without numbers did not have any significant differences in nutrient availability

Table B.3 Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 2 for the 2005 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Mid	Lower
NO_3	May 20 - June 20	49.2	0.2 (0.0)	0.4 (0.1)	0.3 (0.0)
	June 20 - July20	85.0	0.1 (0.1)	0.1 (0.1)	0.0 (0.0)
	July 20 - Aug 20	54.2	0.4 (0.1)	0.4 (0.0)	0.4 (0.0)
	Aug 20 - Sept 20	35.2	0.1 (0.1)	0.1 (0.1)	0.3 (0.0)
NH_4	May 20 - June 20	49.2	1.5 (0.1)	1.2 (0.1)	1.5 (0.1)
	June 20 - July20	85.0	BDL	0.1 (0.1)	0.2 (0.1)
	July 20 - Aug 20	54.2	0.1 (0.0)	0.1 (0.1)	0.3 (0.1)
	Aug 20 - Sept 20	35.2	0.6 (0.2)	0.2 (0.1)	0.8 (0.5)
Ca	May 20 - June 20	49.2	103.6 (2.7)	108.7 (3.7)	102.2 (2.4)
	June 20 - July20	85.0	101.2 (3.0)	115.1 (2.6)	100.3 (5.5)
	July 20 - Aug 20	54.2	91.7 (6.3)	111.8 (4.2)	95.3 (8.5)
	Aug 20 - Sept 20	35.2	105.3 (4.3)	134.6 (1.8)	109.6 (7.7)
Mg	May 20 - June 20	49.2	31.8 (1.1)	24.8 (1.0)	33.7 (1.6)
	June 20 - July20	85.0	33.6 (1.5)	28.8 (1.2)	34.1 (3.1)
	July 20 - Aug 20	54.2	33.1 (2.4)	27.2 (0.7)	34.3 (3.0)
	Aug 20 - Sept 20	35.2	36.9 (1.2)	30.0 (1.4)	39.6 (2.8)
K	May 20 - June 20	49.2	0.6 (0.1)	1.5 (0.1)	0.5 (0.1)
	June 20 - July20	85.0	1.0 (0.3)	1.5 (0.1)	0.9 (0.3)
	July 20 - Aug 20	54.2	1.3 (0.4)	0.6 (0.1)	0.8 (0.3)
	Aug 20 - Sept 20	35.2	1.4 (0.4)	0.6 (0.2)	1.1 (0.2)
P	May 20 - June 20	49.2	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)
	June 20 - July20	85.0	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)
	July 20 - Aug 20	54.2	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)
	Aug 20 - Sept 20	35.2	0.1 (0.0)	0.1 (0.1)	0.1 (0.0)
S	May 20 - June 20	49.2	11.4 (3.7)	3.0 (1.1)	2.5 (0.8)
	June 20 - July20	85.0	7.7 (1.8)	2.6 (0.4)	1.5 (0.5)
	July 20 - Aug 20	54.2	4.3 (1.0)	2.7 (0.5)	1.4 (0.3)
	Aug 20 - Sept 20	35.2	4.5 (0.6)	1.9 (0.5)	1.1 (0.1)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 5 for each slope position
Differences among nutrient availability for a given slope position was not analyzed for the 2005 growing season

Table B.4 Average soil nutrient availability ($\mu g\ 10\ cm^{-2}\ 2\ wk^{-1}$) at Site 2 for the 2006 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Mid	Lower
	May 16 - May 30	18.6	0.0 (0.0)	2.4 (1.3)	0.0 (0.0)
	May 30-June 13	7.8	4.8 (0.1)	7.7 (2.6)	5.7 (0.5)
	June 13-June27	28.2	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
NO_3	June 27 - July 11	35.3	0.7 (0.7)	3.1 (0.3)	2.3 (1.4)
	July 11 - July 25	44.3	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	July 25 - Aug 8	33.3	1.1 (1.1)	0.0 (0.0)	0.0 (0.0)
	Aug 8 - Aug 22	20.9	0.7 (0.7)	2.8 (0.6)	2.7 (0.4)
	Aug 22 - Sept 8	9.5	4.2 (0.1)	4.8 (0.2)	4.6 (0.1)
	May 16 - May 30	18.6	1.8 (0.9)	4.0 (0.8)	3.2 (0.3)
	May 30-June 13	7.8	3.7 (0.9)	4.3 (0.5)	5.0 (2.5)
	June 13-June27	28.2	1.5 (0.8)	4.3 (1.1)	0.8 (0.8)
NH_4	June 27 - July 11	35.3	0.9 (0.9)	0.0 (0.0)	0.0 (0.0)
	July 11 - July 25	44.3	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	July 25 - Aug 8	33.3	2.5 (0.3)	2.7 (0.4)	1.0 (1.0)
	Aug 8 - Aug 22	20.9	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Aug 22 - Sept 8	9.5	0.0 (0.0)	0.0 (0.0)	0.7 (0.7)
	May 16 - May 30	18.6	2382.0 (305.1)	2864.0 (172.7)	2654.0 (80.4)
	May 30-June 13	7.8	1159.3 (128.7)	1420.7 (243.7)	1348.0 (261.0)
	June 13-June27	28.2	1444.7 (189.9)	1430.0 (213.4)	1408.7 (129.5)
Ca	June 27 - July 11	35.3	1083.3 (130.9)	881.3 (161.8)	896.3 (92.0)
	July 11 - July 25	44.3	1523.0 (221.4)	1518.0 (54.0)	1482.7 (271.1)
	July 25 - Aug 8	33.3	1104.0 (145.9)	1385.0 (254.8)	977.0 (103.7)
	Aug 8 - Aug 22	20.9	924.7 (151.7)	1121.7 (115.0)	766.3 (67.1)
	Aug 22 - Sept 8	9.5	637.7 (197.7)	857.0 (206.5)	505.3 (28.0)
	May 16 - May 30	18.6	474.0 (40.2)	409.7 (24.7)	513.7 (34.2)
	May 30-June 13	7.8	298.7 (43.3)	223.7 (51.5)	301.7 (56.4)
	June 13-June27	28.2	335.0 (66.6)	221.0 (13.3)	294.3 (20.3)
Mg	June 27 - July 11	35.3	262.3 (43.9)	153.0 (24.7)	203.3 (22.0)
	July 11 - July 25	44.3	337.7 (34.1)	230.3 (31.0)	306.3 (27.5)
	July 25 - Aug 8	33.3	256.0 (45.0)	228.0 (19.6)	209.3 (9.4)
	Aug 8 - Aug 22	20.9	232.0 (44.3)	205.7 (6.6)	172.7 (11.1)
	Aug 22 - Sept 8	9.5	168.3 (57.0)	154.3 (25.3)	115.7 (12.5)

Precipitation is cumulative from previous burial period measurement date

Slope position values reported as Mean (S.E.); n = 3 for each slope position

Values with different letters denote significant different nutrient availability at $p \leq 0.1$; values without numbers did not have any significant differences in nutrient availability

Table B.4 (cont'd) Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 2 for the 2006 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Mid	Lower
	May 16 - May 30	18.6	13.3 (2.0)	33.7 (11.1)	23.7 (9.9)
	May 30-June 13	7.8	29.0 (1.2)	53.3 (11.4)	59.7 (23.0)
	June 13-June27	28.2	71.7 (22.4)	153.3 (42.6)	92.0 (24.1)
K	June 27 - July 11	35.3	162.0 (22.0)	410.0 (182.3)	268.7 (69.6)
	July 11 - July 25	44.3	52.7 (25.0)	59.0 (11.0)	55.3 (12.7)
	July 25 - Aug 8	33.3	30.3 (10.3)	85.3 (25.2)	27.3 (4.4)
	Aug 8 - Aug 22	20.9	21.7 (3.2)	106.3 (44.4)	47.0 (4.5)
	Aug 22 - Sept 8	9.5	14.7 (0.9)	125.3 (55.5)	33.0 (3.6)
	May 16 - May 30	18.6	1.2 (0.2)^{b}	4.1 (1.6)^{a}	3.7 (1.0)^{a}
	May 30-June 13	7.8	1.5 (0.5)^{a}	3.9 (1.8)^{a}	3.7 (1.5)^{a}
	June 13-June27	28.2	1.7 (0.4)^{a}	4.6 (1.4)^{a}	5.0 (1.7)^{a}
P	June 27 - July 11	35.3	1.1 (0.3)^{b}	2.9 (1.3)^{ab}	5.9 (2.1)^{a}
	July 11 - July 25	44.3	0.8 (0.1)^{b}	1.7 (0.1)^{a}	1.0 (0.1)^{b}
	July 25 - Aug 8	33.3	0.6 (0.1)^{b}	1.5 (0.4)^{a}	1.3 (0.5)^{ab}
	Aug 8 - Aug 22	20.9	0.4 (0.1)^{b}	1.8 (0.4)^{a}	1.3 (0.2)^{a}
	Aug 22 - Sept 8	9.5	0.5 (0.1)^{a}	2.1 (0.8)^{a}	3.2 (1.9)^{a}
	May 16 - May 30	18.6	304.0 (52.0)	152.7 (42.5)	458.7 (135.9)
	May 30-June 13	7.8	50.7 (7.2)	48.0 (7.2)	128.0 (28.7)
	June 13-June27	28.2	79.3 (24.5)	44.3 (10.4)	70.3 (24.6)
S	June 27 - July 11	35.3	105.3 (30.6)	67.0 (20.6)	60.0 (11.1)
	July 11 - July 25	44.3	114.3 (53.1)	24.3 (7.0)	122.7 (57.7)
	July 25 - Aug 8	33.3	58.7 (12.8)	59.7 (23.3)	71.0 (25.2)
	Aug 8 - Aug 22	20.9	37.7 (9.2)	48.3 (19.9)	36.0 (10.3)
	Aug 22 - Sept 8	9.5	25.3 (7.5)	34.7 (8.3)	24.3 (3.9)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
Values with different letters denote significant different nutrient availability at $p \leq 0.1$; values without numbers did not have any significant differences in nutrient availability

Table B.5 Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 3 for the 2005 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Mid	Lower
NO_3	May 20 - June 20	33.9	3.1 (0.6)	3.1 (0.7)	2.4 (0.5)
	June 20 - July20	129.7	4.5 (0.4)	3.5 (0.7)	3.3 (0.6)
	July 20 - Aug 20	88.0	3.7 (0.7)	2.8 (0.2)	3.1 (0.4)
	Aug 20 - Sept 20	47.1	3.4 (0.4)	2.4 (0.1)	2.2 (0.3)
NH_4	May 20 - June 20	33.9	0.5 (0.1)	0.6 (0.1)	0.6 (0.1)
	June 20 - July20	129.7	BDL	BDL	BDL
	July 20 - Aug 20	88.0	0.0 (0.0)	BDL	0.0 (0.0)
	Aug 20 - Sept 20	47.1	0.3 (0.1)	0.0 (0.0)	0.0 (0.0)
Ca	May 20 - June 20	33.9	126.7 (2.9)	127.9 (2.1)	122.3 (1.9)
	June 20 - July20	129.7	131.8 (1.4)	129.1 (1.1)	132.7 (1.6)
	July 20 - Aug 20	88.0	139.4 (1.7)	142.9 (1.2)	138.3 (2.2)
	Aug 20 - Sept 20	47.1	131.9 (5.8)	142.7 (3.1)	144.1 (3.7)
Mg	May 20 - June 20	33.9	14.4 (0.5)	16.0 (1.1)	15.4 (0.4)
	June 20 - July20	129.7	14.7 (1.1)	15.6 (0.9)	16.4 (0.3)
	July 20 - Aug 20	88.0	17.0 (1.0)	18.9 (1.5)	18.7 (0.5)
	Aug 20 - Sept 20	47.1	17.8 (1.0)	20.9 (1.3)	20.7 (0.4)
K	May 20 - June 20	33.9	0.4 (0.0)	0.4 (0.0)	0.4 (0.0)
	June 20 - July20	129.7	0.3 (0.0)	0.2 (0.0)	0.3 (0.0)
	July 20 - Aug 20	88.0	0.3 (0.0)	0.4 (0.1)	0.4 (0.0)
	Aug 20 - Sept 20	47.1	0.4 (0.0)	0.4 (0.1)	0.5 (0.0)
P	May 20 - June 20	33.9	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	June 20 - July20	129.7	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	July 20 - Aug 20	88.0	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Aug 20 - Sept 20	47.1	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
S	May 20 - June 20	33.9	20.1 (1.2)	21.5 (1.8)	20.6 (1.0)
	June 20 - July20	129.7	18.1 (1.3)	18.4 (1.8)	18.6 (0.7)
	July 20 - Aug 20	88.0	15.5 (0.9)	19.3 (1.7)	19.1 (0.9)
	Aug 20 - Sept 20	47.1	18.3 (1.1)	17.0 (1.5)	19.9 (0.6)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 5 for each slope position
Differences among nutrient availability for a given slope position was not analyzed for the 2005 growing season

Table B.6 Average soil nutrient availability ($\mu g\ 10\ cm^{-2}\ 2\ wk^{-1}$) at Site 3 for the 2006 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Mid	Lower
	May 16 - May 30	18.2	105.1 (19.3)[a]	67.3 (16.5)[b]	76.7 (4.4)[b]
	May 30-June 13	4.6	28.6 (4.5)[a]	19.4 (5.9)[b]	20.9 (2.8)[b]
	June 13-June27	20.0	58.3 (8.4)[a]	26.9 (7.3)[b]	43.8 (2.9)[b]
NO_3	June 27 - July 11	74.9	125.5 (18.8)[a]	86.7 (22.5)[b]	91.7 (12.8)[b]
	July 11 - July 25	59.0	135.5 (35.5)[a]	64.4 (14.4)[b]	83.9 (14.3)[b]
	July 25 - Aug 8	22.0	172.9 (37.7)[a]	84.7 (1.1)[b]	90.1 (7.9)[b]
	Aug 8 - Aug 22	12.9	46.9 (12.1)[a]	21.1 (2.7)[b]	23.9 (4.4)[b]
	Aug 22 - Sept 8	6.8	110.9 (28.0)[a]	57.3 (14.5)[b]	82.9 (7.0)[ab]
	May 16 - May 30	18.2	2.6 (0.3)[a]	0.8 (0.8)[b]	0.8 (0.8)[b]
	May 30-June 13	4.6	6.7 (1.2)[a]	6.7 (0.5)[a]	4.9 (0.7)[a]
	June 13-June27	20.0	0.7 (0.7)[b]	2.4 (0.2)[a]	BDL[b]
NH_4	June 27 - July 11	74.9	3.1 (0.6)[a]	1.1 (1.1)[b]	1.7 (0.9)[ab]
	July 11 - July 25	59.0	2.9 (0.3)[a]	1.6 (0.8)[a]	BDL[b]
	July 25 - Aug 8	22.0	3.7 (0.4)[a]	2.9 (0.5)[ab]	1.8 (0.9)[b]
	Aug 8 - Aug 22	12.9	BDL[a]	BDL[a]	BDL[a]
	Aug 22 - Sept 8	6.8	2.3 (1.2)[a]	1.9 (1.0)[a]	BDL[b]
	May 16 - May 30	18.2	2873.3 (203.1)	2962.0 (113.8)	2766.0 (65.6)
	May 30-June 13	4.6	1476.7 (180.6)	1355.0 (68.9)	1464.0 (171.9)
	June 13-June27	20.0	3026.7 (89.7)	2849.3 (91.0)	2891.3 (152.7)
Ca	June 27 - July 11	74.9	3154.0 (44.7)	2964.0 (77.5)	3195.3 (165.3)
	July 11 - July 25	59.0	2872.0 (143.4)	2911.3 (82.2)	2839.3 (185.8)
	July 25 - Aug 8	22.0	2732.0 (119.2)	2710.0 (75.2)	2566.7 (272.2)
	Aug 8 - Aug 22	12.9	1871.0 (183.6)	1941.3 (124.4)	1744.3 (180.8)
	Aug 22 - Sept 8	6.8	2654.0 (259.3)	2700.7 (87.1)	2696.0 (53.8)
	May 16 - May 30	18.2	228.7 (5.5)	261.0 (12.5)	257.7 (11.6)
	May 30-June 13	4.6	143.7 (9.7)	140.3 (3.8)	149.0 (17.6)
	June 13-June27	20.0	222.3 (6.3)	248.0 (13.1)	240.7 (11.9)
Mg	June 27 - July 11	74.9	206.0 (5.2)	217.0 (12.0)	224.0 (19.3)
	July 11 - July 25	59.0	217.0 (11.5)	237.3 (15.0)	234.7 (20.3)
	July 25 - Aug 8	22.0	210.3 (18.9)	214.3 (15.8)	217.0 (18.1)
	Aug 8 - Aug 22	12.9	155.3 (2.0)	177.0 (20.2)	167.0 (3.8)
	Aug 22 - Sept 8	6.8	196.7 (1.7)	217.3 (20.5)	220.7 (17.6)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
Values with different letters denote significant different nutrient availability at $p \leq 0.1$; values without numbers did not have any significant differences in nutrient availability

Table B.6 (cont'd) Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 3 for the 2006 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Mid	Lower
	May 16 - May 30	18.2	15.7 (0.7)	15.3 (2.6)	16.0 (0.6)
	May 30-June 13	4.6	22.3 (0.3)	23.3 (1.8)	22.3 (0.7)
	June 13-June27	20.0	20.7 (1.9)	28.7 (3.5)	36.3 (3.2)
K	June 27 - July 11	74.9	12.3 (1.2)	13.0 (0.6)	14.0 (1.0)
	July 11 - July 25	59.0	19.7 (1.3)	17.7 (2.9)	18.7 (1.5)
	July 25 - Aug 8	22.0	29.7 (2.0)	24.7 (3.3)	21.0 (3.2)
	Aug 8 - Aug 22	12.9	18.0 (2.6)	19.3 (1.8)	20.3 (0.3)
	Aug 22 - Sept 8	6.8	16.0 (3.6)	16.7 (1.5)	11.3 (1.2)
	May 16 - May 30	18.2	0.6 (0.0)[a]	0.4 (0.0)[a]	0.4 (0.0)[a]
	May 30-June 13	4.6	0.3 (0.0)[a]	0.4 (0.1)[a]	0.5 (0.1)[a]
	June 13-June27	20.0	0.3 (0.0)[a]	0.3 (0.0)[a]	0.3 (0.0)[a]
P	June 27 - July 11	74.9	0.8 (0.2)[a]	0.4 (0.1)[b]	0.3 (0.1)[b]
	July 11 - July 25	59.0	0.4 (0.1)[a]	0.4 (0.0)[a]	0.4 (0.0)[a]
	July 25 - Aug 8	22.0	0.3 (0.0)[a]	0.2 (0.1)[a]	0.2 (0.1)[a]
	Aug 8 - Aug 22	12.9	0.1 (0.1)[b]	0.2 (0.0)[a]	0.1 (0.1)[b]
	Aug 22 - Sept 8	6.8	0.3 (0.0)[a]	0.3 (0.0)[a]	0.2 (0.1)[a]
	May 16 - May 30	18.2	923.7 (132.4)	841.3 (43.1)	970.7 (78.9)
	May 30-June 13	4.6	267.3 (35.7)	312.3 (72.1)	296.7 (49.8)
	June 13-June27	20.0	1142.3 (97.6)	1071.7 (83.0)	1332.3 (91.6)
S	June 27 - July 11	74.9	1447.7 (65.5)	1563.7 (159.5)	1495.7 (101.1)
	July 11 - July 25	59.0	1271.3 (23.1)	1280.0 (99.9)	1463.0 (48.6)
	July 25 - Aug 8	22.0	979.7 (16.8)	926.7 (155.4)	923.0 (22.3)
	Aug 8 - Aug 22	12.9	402.0 (109.7)	309.7 (51.4)	332.3 (64.8)
	Aug 22 - Sept 8	6.8	720.0 (21.9)	637.0 (131.0)	807.7 (50.9)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
Values with different letters denote significant different nutrient availability at $p \leq 0.1$; values without numbers did not have any significant differences in nutrient availability

Table B.7 Average soil nutrient availability (µg 10 cm^{-2} 2 wk^{-1}) at Site 4 for the 2005 growing season

Nutrient	Burial Period	Precipitation (mm)	Bench	Lower Slope
NO_3	May 20 - June 20	35.3	1.9 (0.3)	0.4 (0.1)
	June 20 - July20	72.9	0.1 (0.0)	0.7 (0.3)
	July 20 - Aug 20	97.0	0.4 (0.0)	0.5 (0.0)
	Aug 20 - Sept 20	57.4	0.3 (0.1)	0.3 (0.0)
NH_4	May 20 - June 20	35.3	0.7 (0.1)	0.8 (0.1)
	June 20 - July20	72.9	0.1 (0.0)	0.4 (0.2)
	July 20 - Aug 20	97.0	0.2 (0.0)	0.1 (0.0)
	Aug 20 - Sept 20	57.4	0.1 (0.1)	BDL
Ca	May 20 - June 20	35.3	104.0 (5.6)	78.0 (6.3)
	June 20 - July20	72.9	74.9 (9.0)	96.3 (7.3)
	July 20 - Aug 20	97.0	68.8 (10.5)	111.4 (12.2)
	Aug 20 - Sept 20	57.4	116.6 (5.3)	82.2 (5.7)
Mg	May 20 - June 20	35.3	28.3 (1.2)	26.0 (1.0)
	June 20 - July20	72.9	23.3 (1.8)	26.8 (2.0)
	July 20 - Aug 20	97.0	22.8 (2.5)	30.1 (2.6)
	Aug 20 - Sept 20	57.4	29.9 (1.0)	26.4 (1.0)
K	May 20 - June 20	35.3	1.3 (0.3)	4.5 (0.7)
	June 20 - July20	72.9	4.8 (0.5)	1.7 (0.5)
	July 20 - Aug 20	97.0	4.2 (0.5)	1.1 (0.4)
	Aug 20 - Sept 20	57.4	1.2 (0.5)	5.4 (1.1)
P	May 20 - June 20	35.3	0.2 (0.1)	0.3 (0.1)
	June 20 - July20	72.9	0.2 (0.0)	0.2 (0.0)
	July 20 - Aug 20	97.0	0.2 (0.0)	0.2 (0.0)
	Aug 20 - Sept 20	57.4	0.2 (0.0)	0.2 (0.1)
S	May 20 - June 20	35.3	4.0 (1.3)	2.1 (0.3)
	June 20 - July20	72.9	1.5 (0.2)	1.7 (0.3)
	July 20 - Aug 20	97.0	1.8 (0.3)	2.8 (0.6)
	Aug 20 - Sept 20	57.4	2.5 (0.4)	2.2 (0.4)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 5 for each slope position
Differences among nutrient availability for a given slope position was not analyzed for the 2005 growing season

Table B.8 Average soil nutrient availability ($\mu g\ 10\ cm^{-2}\ 2\ wk^{-1}$) at Site 4 for the 2006 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Lower
	May 16 - May 30	18.6	6.3 (1.0)	11.8 (5.6)
	May 30-June 13	7.8	6.6 (0.1)	7.7 (0.8)
	June 13-June27	28.2	1.0 (1.0)	23.3 (11.3)
NO_3	June 27 - July 11	35.3	11.5 (3.5)	26.7 (5.4)
	July 11 - July 25	44.3	0.0 (0.0)	0.0 (0.0)
	July 25 - Aug 8	33.3	1.3 (1.3)	1.7 (1.7)
	Aug 8 - Aug 22	20.9	4.1 (0.8)	3.7 (0.2)
	Aug 22 - Sept 8	9.5	5.6 (0.1)	6.5 (0.5)
	May 16 - May 30	18.6	3.7 (1.0)	3.4 (0.6)
	May 30-June 13	7.8	9.5 (1.2)	7.3 (0.9)
	June 13-June27	28.2	0.7 (0.7)	1.6 (0.8)
NH_4	June 27 - July 11	35.3	0.0 (0.0)	0.0 (0.0)
	July 11 - July 25	44.3	0.0 (0.0)	0.0 (0.0)
	July 25 - Aug 8	33.3	1.3 (0.7)	0.0 (0.0)
	Aug 8 - Aug 22	20.9	0.0 (0.0)	0.0 (0.0)
	Aug 22 - Sept 8	9.5	0.0 (0.0)	0.0 (0.0)
	May 16 - May 30	18.6	2213.0 (185.6)	1944.7 (110.5)
	May 30-June 13	7.8	514.3 (92.2)	430.7 (48.8)
	June 13-June27	28.2	1625.0 (96.3)	1811.3 (334.7)
Ca	June 27 - July 11	35.3	1988.0 (298.3)	1956.0 (150.4)
	July 11 - July 25	44.3	623.7 (75.4)	1564.3 (69.8)
	July 25 - Aug 8	33.3	1325.7 (54.6)	1613.3 (96.6)
	Aug 8 - Aug 22	20.9	731.3 (104.3)	1255.0 (71.7)
	Aug 22 - Sept 8	9.5	355.3 (39.9)	396.7 (80.7)
	May 16 - May 30	18.6	407.0 (38.1)	338.0 (31.5)
	May 30-June 13	7.8	91.3 (20.2)	72.3 (13.4)
	June 13-June27	28.2	261.7 (21.7)	268.7 (61.8)
Mg	June 27 - July 11	35.3	317.7 (28.0)	322.0 (41.5)
	July 11 - July 25	44.3	105.0 (18.0)	241.0 (10.3)
	July 25 - Aug 8	33.3	201.0 (20.5)	250.0 (17.8)
	Aug 8 - Aug 22	20.9	130.0 (17.0)	218.0 (30.0)
	Aug 22 - Sept 8	9.5	69.0 (12.1)	66.7 (15.0)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
Differences among nutrient availability for a given slope position was not analyzed for the 2006 growing season

Table B.8 (cont'd) Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 4 for the 2006 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper	Lower
	May 16 - May 30	18.6	97.7 (22.8)	52.3 (21.4)
	May 30-June 13	7.8	68.3 (22.7)	39.7 (14.2)
	June 13-June27	28.2	412.3 (233.5)	140.3 (33.8)
K	June 27 - July 11	35.3	791.3 (451.4)	189.3 (46.8)
	July 11 - July 25	44.3	207.0 (106.4)	80.0 (27.7)
	July 25 - Aug 8	33.3	172.0 (82.4)	65.0 (25.4)
	Aug 8 - Aug 22	20.9	100.3 (29.1)	57.3 (19.8)
	Aug 22 - Sept 8	9.5	62.3 (23.0)	31.0 (7.0)
	May 16 - May 30	18.6	8.7 (2.6)	4.7 (2.1)
	May 30-June 13	7.8	2.6 (1.0)	1.0 (0.2)
	June 13-June27	28.2	6.3 (1.0)	7.6 (3.6)
P	June 27 - July 11	35.3	9.7 (2.4)	6.8 (3.5)
	July 11 - July 25	44.3	1.8 (0.4)	2.5 (1.0)
	July 25 - Aug 8	33.3	2.3 (0.8)	2.0 (0.4)
	Aug 8 - Aug 22	20.9	1.4 (0.2)	1.9 (0.7)
	Aug 22 - Sept 8	9.5	1.0 (0.0)	0.8 (0.0)
	May 16 - May 30	18.6	57.0 (4.4)	47.7 (12.7)
	May 30-June 13	7.8	16.3 (1.2)	13.0 (0.6)
	June 13-June27	28.2	172.3 (57.0)	97.0 (46.2)
S	June 27 - July 11	35.3	248.3 (73.6)	52.7 (8.3)
	July 11 - July 25	44.3	14.7 (2.7)	15.7 (0.9)
	July 25 - Aug 8	33.3	60.3 (1.8)	37.3 (2.3)
	Aug 8 - Aug 22	20.9	29.0 (8.0)	26.3 (2.9)
	Aug 22 - Sept 8	9.5	14.7 (3.2)	15.0 (1.5)

Precipitation is cumulative from previous burial period measurement date
Slope position values reported as Mean (S.E.); n = 3 for each slope position
Differences among nutrient availability for a given slope position was not analyzed for the 2006 growing season

Table B.9 Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 5 for the 2005 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper
NO_3	May 20 - June 20	49.2	0.4 (0.0)
	June 20 - July20	85	0.3 (0.1)
	July 20 - Aug 20	54.2	BDL
	Aug 20 - Sept 20	35.2	0.2 (0.0)
NH_4	May 20 - June 20	49.2	0.2 (0.1)
	June 20 - July20	85	0.3 (0.1)
	July 20 - Aug 20	54.2	0.1 (0.1)
	Aug 20 - Sept 20	35.2	0.6 (0.0)
Ca	May 20 - June 20	49.2	96.1 (10.2)
	June 20 - July20	85	113.8 (7.6)
	July 20 - Aug 20	54.2	100.9 (2.3)
	Aug 20 - Sept 20	35.2	105.5 (4.7)
Mg	May 20 - June 20	49.2	32.0 (2.3)
	June 20 - July20	85	35.4 (1.5)
	July 20 - Aug 20	54.2	31.2 (1.7)
	Aug 20 - Sept 20	35.2	31.5 (0.9)
K	May 20 - June 20	49.2	1.3 (0.6)
	June 20 - July20	85	1.1 (0.5)
	July 20 - Aug 20	54.2	0.5 (0.2)
	Aug 20 - Sept 20	35.2	0.7 (0.3)
P	May 20 - June 20	49.2	0.1 (0.0)
	June 20 - July20	85	0.1 (0.0)
	July 20 - Aug 20	54.2	0.1 (0.0)
	Aug 20 - Sept 20	35.2	0.1 (0.0)
S	May 20 - June 20	49.2	9.0 (1.2)
	June 20 - July20	85	10.2 (1.8)
	July 20 - Aug 20	54.2	12.8 (1.7)
	Aug 20 - Sept 20	35.2	18.6 (1.2)

Precipitation is cumulative from previous burial period measurement date and is calculated from the weather station at Site 2
Slope position values reported as Mean (S.E.); n = 5 for each slope position

Table B.10 Average soil nutrient availability ($\mu g\ 10\ cm^{-2}\ 2\ wk^{-1}$) at Site 5 for the 2006 growing season

Nutrient	Precipitation (mm)	Burial Period	Upper
	18.6	May 16 - May 30	0.7 (0.7)
	7.8	May 30-June 13	5.4 (0.1)
	28.2	June 13-June27	BDL
NO_3	35.3	June 27 - July 11	3.8 (0.7)
	44.3	July 11 - July 25	BDL
	33.3	July 25 - Aug 8	1.4 (1.4)
	20.9	Aug 8 - Aug 22	2.7 (0.2)
	9.5	Aug 22 - Sept 8	3.5 (0.1)
	18.6	May 16 - May 30	2.3 (0.2)
	7.8	May 30-June 13	6.1 (0.5)
	28.2	June 13-June27	0.9 (0.9)
NH_4	35.3	June 27 - July 11	BDL
	44.3	July 11 - July 25	BDL
	33.3	July 25 - Aug 8	3.2 (0.6)
	20.9	Aug 8 - Aug 22	BDL
	9.5	Aug 22 - Sept 8	BDL
	18.6	May 16 - May 30	2379.3 (157.6)
	7.8	May 30-June 13	1322.0 (240.1)
	28.2	June 13-June27	1373.3 (123.9)
Ca	35.3	June 27 - July 11	1224.7 (196.6)
	44.3	July 11 - July 25	1294.3 (165.0)
	33.3	July 25 - Aug 8	1253.7 (268.1)
	20.9	Aug 8 - Aug 22	1017.7 (232.4)
	9.5	Aug 22 - Sept 8	628.0 (141.2)
	18.6	May 16 - May 30	479.0 (9.5)
	7.8	May 30-June 13	304.3 (42.2)
	28.2	June 13-June27	289.0 (12.5)
Mg	35.3	June 27 - July 11	279.3 (44.7)
	44.3	July 11 - July 25	275.3 (26.3)
	33.3	July 25 - Aug 8	271.0 (51.3)
	20.9	Aug 8 - Aug 22	253.3 (58.4)
	9.5	Aug 22 - Sept 8	162.0 (25.2)

Precipitation is cumulative from previous burial period measurement date and is calculated from the weather station at Site 2
Slope position values reported as Mean (S.E.); n = 3 for each slope position

Table B.8 (cont'd) Average soil nutrient availability (μg 10 cm^{-2} 2 wk^{-1}) at Site 5 for the 2006 growing season

Nutrient	Burial Period	Precipitation (mm)	Upper
K	May 16 - May 30	18.6	35.0 (10.1)
	May 30-June 13	7.8	47.7 (9.6)
	June 13-June27	28.2	70.0 (20.3)
	June 27 - July 11	35.3	106.3 (24.3)
	July 11 - July 25	44.3	72.3 (25.1)
	July 25 - Aug 8	33.3	60.0 (14.6)
	Aug 8 - Aug 22	20.9	61.7 (16.9)
	Aug 22 - Sept 8	9.5	36.0 (9.5)
P	May 16 - May 30	18.6	3.0 (1.0)
	May 30-June 13	7.8	2.0 (0.7)
	June 13-June27	28.2	2.2 (0.7)
	June 27 - July 11	35.3	2.4 (1.0)
	July 11 - July 25	44.3	2.3 (0.9)
	July 25 - Aug 8	33.3	1.8 (0.4)
	Aug 8 - Aug 22	20.9	2.0 (0.6)
	Aug 22 - Sept 8	9.5	0.7 (0.2)
S	May 16 - May 30	18.6	612.3 (130.9)
	May 30-June 13	7.8	169.3 (27.6)
	June 13-June27	28.2	257.0 (25.1)
	June 27 - July 11	35.3	279.3 (65.5)
	July 11 - July 25	44.3	238.7 (13.1)
	July 25 - Aug 8	33.3	232.7 (62.2)
	Aug 8 - Aug 22	20.9	115.3 (28.8)
	Aug 22 - Sept 8	9.5	44.0 (11.5)

Precipitation is cumulative from previous burial period measurement date and is calculated from the weather station at Site 2
Slope position values reported as Mean (S.E.); n = 3 for each slope position

APPENDIX C - AVERAGE SOIL TEMPERATURES

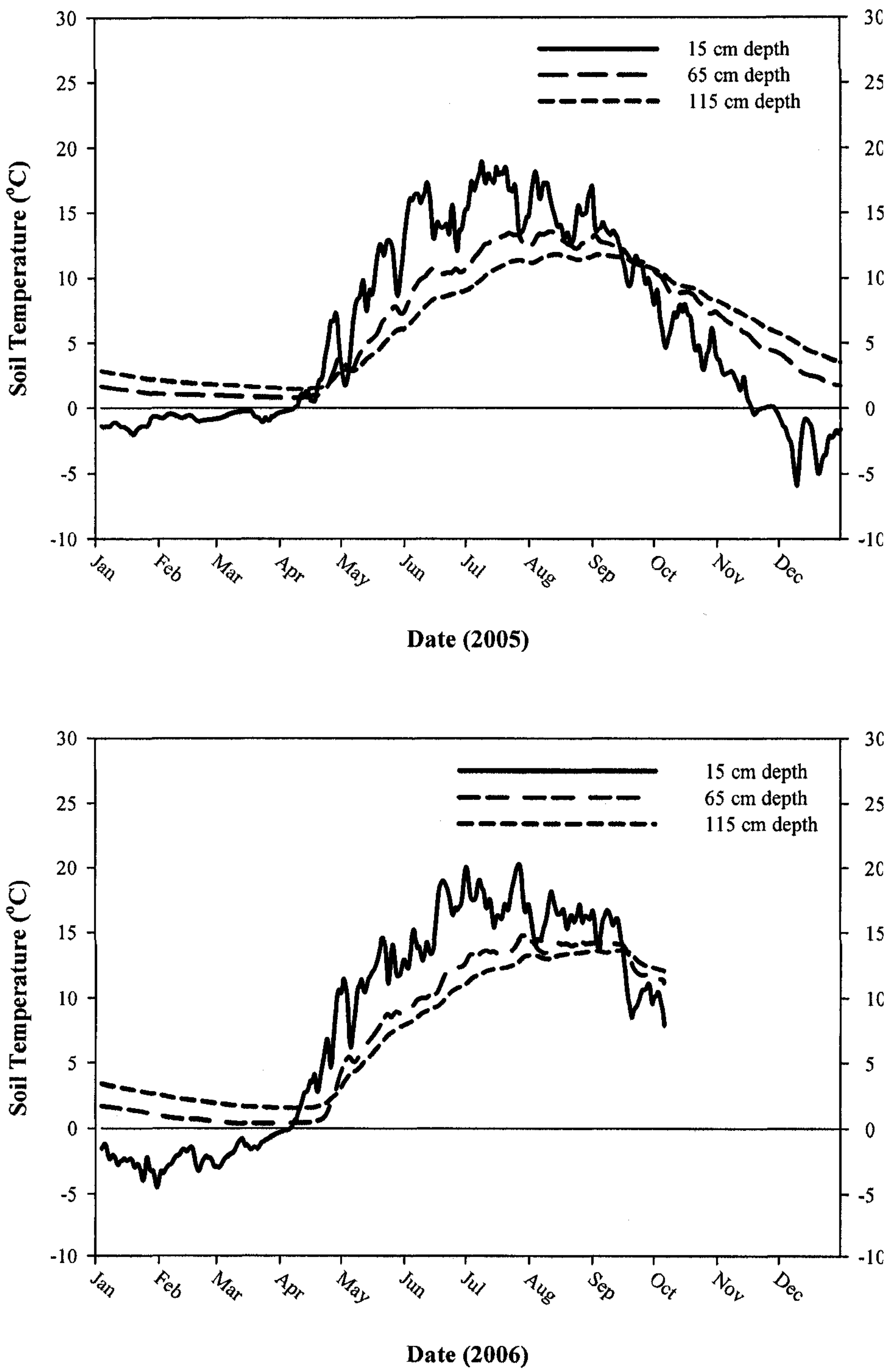
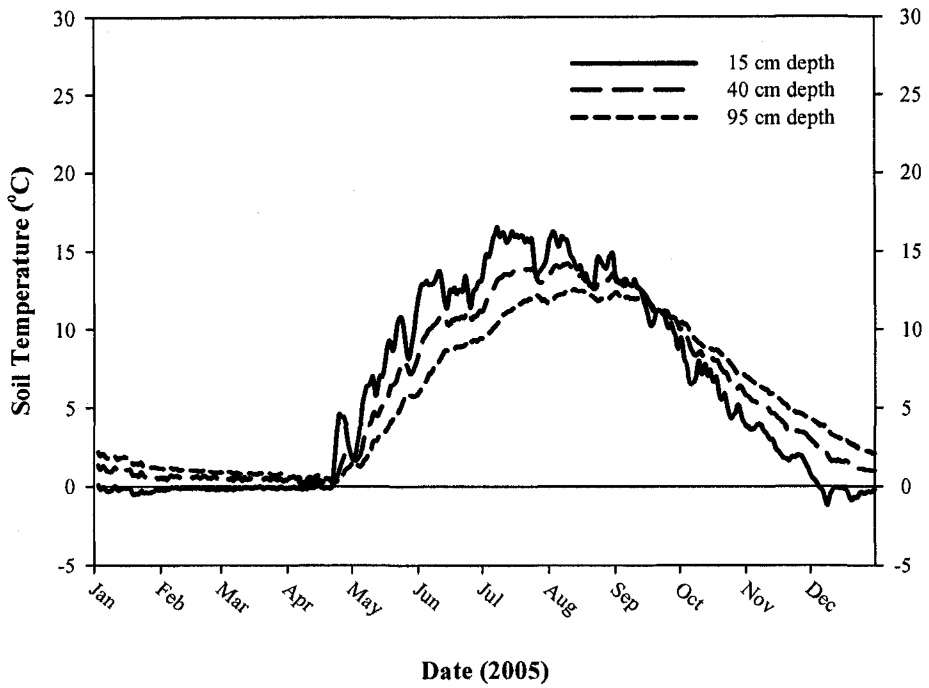


Figure C.1 Average soil temperatures for three depths at Site 1 (data past October 2006 were unavailable)



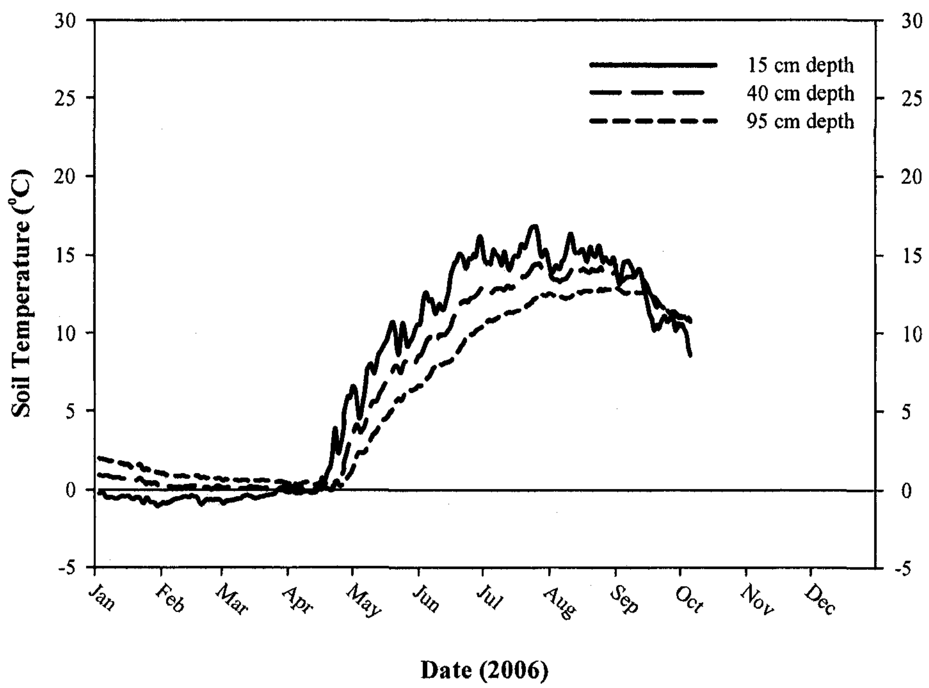
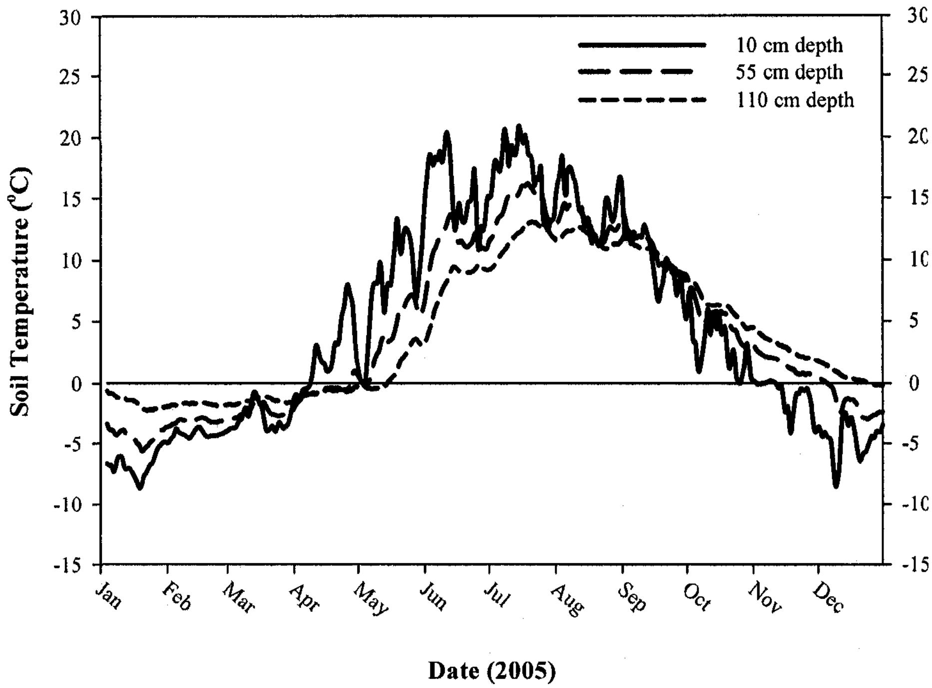


Figure C.2 Average soil temperatures for three depths at Site 2 (data past October 2006 were unavailable)



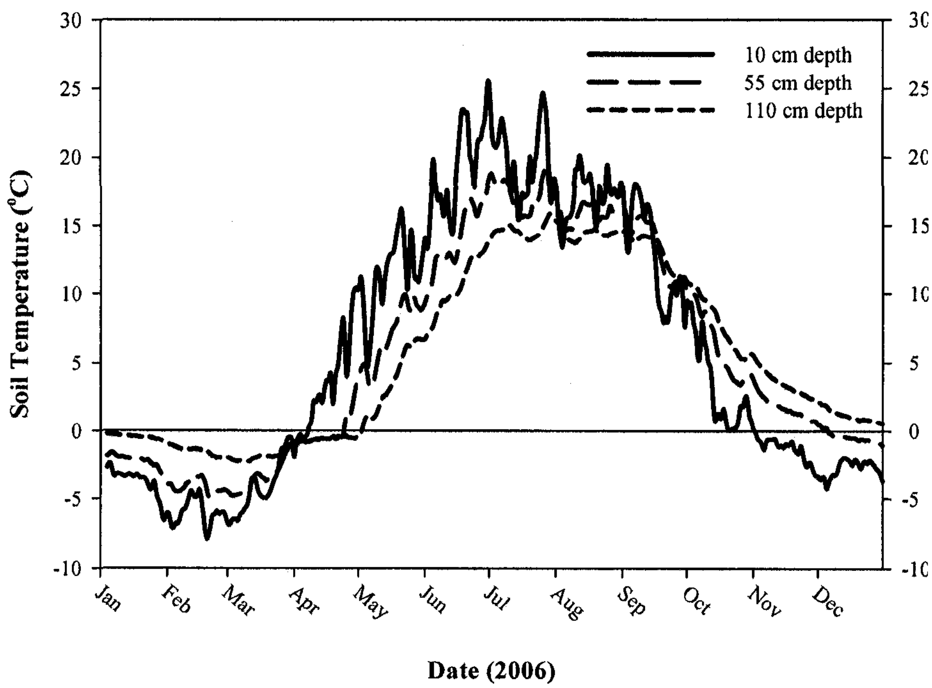
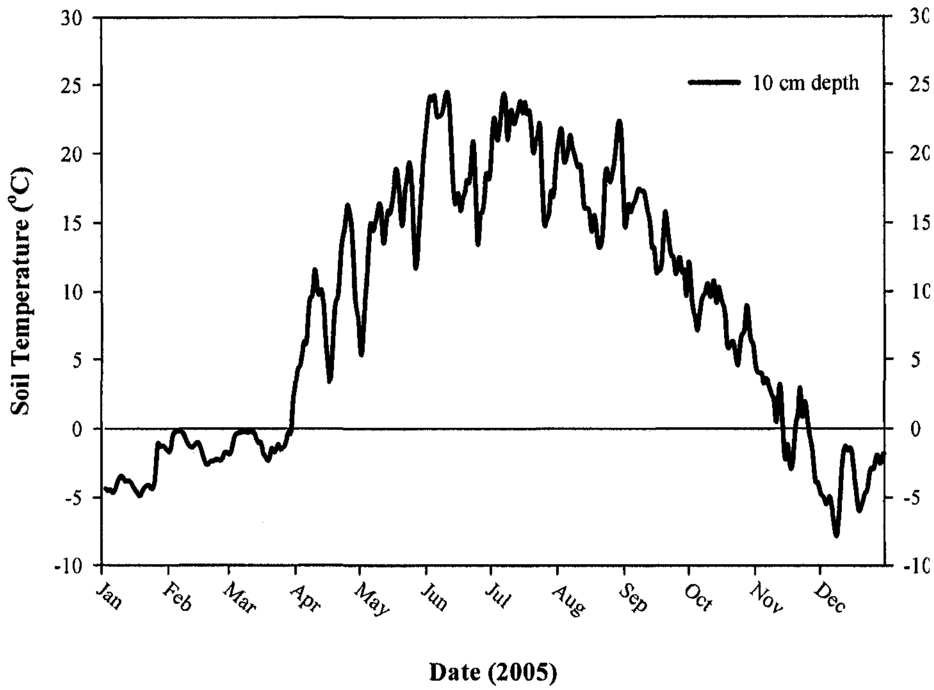


Figure C.3 Average soil temperatures for three depths at Site 3



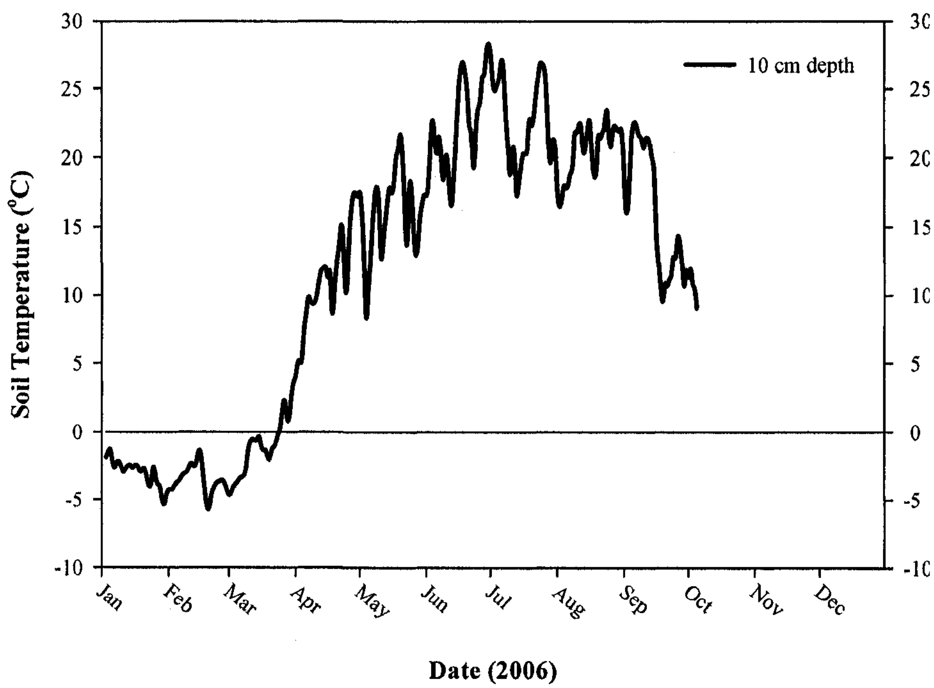


Figure C.4 Average soil temperatures for one depth at Site 4 (data past October 2006 were unavailable)