THE EFFECTS OF SURFACE DRAINAGE ON SOIL PHYSICAL AND CHEMICAL PROPERTIES IN THE BLACK SOIL ZONE OF SASKATCHEWAN

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ABSTRACT

Recent flooding of agricultural land in the northern and eastern Saskatchewan Prairies coupled with intensification of agriculture has resulted in renewed efforts to drain prairie potholes. Drainage is used to increase land available for farming, reduce costs of manoeuvring equipment around wetlands, allow for earlier seeding, and improve growing conditions. Given that low-lying areas tend to have higher nutrient and organic matter concentrations than surrounding uplands, drainage may create some of the most productive land in the province. However, agricultural drainage has been identified as a large nonpoint contributor of N and P loading to waterbodies and could result in degradation of downstream water quality in the Prairies. The objectives of this research were: 1) to determine if agricultural drainage improved growing conditions and nutrient availability in soils over time by measuring physical (i.e. structure and bulk density) and chemical properties (i.e. C, N, P and K), 2) to determine if drainage causes wetland soils to become more similar to midslope soils in terms of properties and nutrient dynamics, and 3) to investigate how forms and fates of nutrients (N and P) vary under different precipitation scenarios to reveal the potential productivity and potential nutrient loss to drainage water of drained soils. To achieve objectives 1 and 2, 42 wetlands and corresponding midslopes were selected in the Black soil zone of eastern Saskatchewan, approximately 60 km southeast of Yorkton. The drainage age of wetlands ranged from 0 to 50 years. In the fall of 2014, intact cores were collected for analysis of bulk density, aggregate stability, macronutrients, and carbon. Overall, drainage improved growing conditions and nutrient availability in soil. The field study showed greater nutrient availability, evident by greater available PO_4^{-3} and increased nitrification. These improvements were greatest in soils that had been drained from 7 to 34 years, but decreased in soils drained from 36 to 50 years. Soils that had been drained for longer durations appeared to become more similar to the midslope position. Disadvantages following drainage, such as increased bulk density and decreased quantity and quality of OC, were greatest in soils drained from 36 to 50 years. To achieve the third objective, a greenhouse study was completed using bulk soil collected from an undrained (UD), recently drained (RD), medium drained (MD), longest drained

(LD) and midslope (MS) sampling location. Wheat was planted and three different precipitation treatments (below, normal and above-normal) were applied. Nitrogen and P were analyzed in plant, soil, and leachate, and nutrient budgets were developed. The greenhouse study demonstrated that drained soils have greater plant N and P uptake, and plant yield. The greenhouse study also identified that not all soils contribute equally to nutrient losses in drainage water and that recently drained soils may be a larger contributor under below and normal precipitation, but a lower contributor under above-normal precipitation. The findings of both the field and greenhouse study are of significance because they identify that perceived benefits may decline with time. Results are useful for developing management practices that may further extend the benefits of drainage and for developing mitigation strategies to reduce N and P exports to drainage water.

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DEDICATION

To my mom, Lori, and Dad, Eugene,

I am so grateful to have such wonderful parents. Thank you for all of your love, encouragement and support.

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ABBREVIATIONS

DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
ETZ	Effective transmission zone
HF	Heavy fraction
IC	Inorganic carbon
LD	Longest drained
LF	Light fraction
MAP	Mean annual precipitation
MD	Medium drained
MS	Midslope
OC	Organic carbon
PPR	Prairie Pothole Region
RD	Recently drained
SAS	Statistical Analysis Software
SOC	Soil organic carbon
SOM	Soil organic matter
UD	Undrained
WEOC	Water extractable organic carbon

1 INTRODUCTION

1.1 General introduction

Flooding of cropland has resulted in renewed efforts to drain wetlands in southeastern Saskatchewan. The southern portion of Saskatchewan is located within the Prairie Pothole Region (PPR), which is made up of many small wetlands that typically dry up throughout summer and can be cultivated during drier years; however, at time of writing, these wetlands have been remaining wet throughout the growing season or even increasing in size. Waterlogged conditions are unfavourable for crop production since they create anoxic conditions, can increase salinity, decrease soil structure and limit nutrient availability (Nangia et al., 2013; Bedard-Haughn, 2009; Verhoef and Egea, 2013). As a result, prairie potholes are drained by connecting wetlands with open ditches, known as surface drainage (Brunet and Westbrook, 2012; Dumanski et al., 2015). Drainage increases agriculturally productive land, extends growing seasons, reduces costs associated with manoeuvering large equipment around wetlands, and increases nutrient availability (Cortus et al., 2009; Nangia et al., 2013; van Schilggaarde and Skaggs, 1999; Bedard-Haughn, 2009).

Wetlands provide many ecological services and agricultural drainage has been identified as a large nonpoint contributor of N and P loading to waterbodies leading to eutrophication (Euliss et al., 2006; Bedard-Haughn et al., 2006; Neuman and Belcher, 2011; Johnson et al., 2010; Cortus et al., 2011). As a result, draining wetlands in Saskatchewan has become a controversial topic. Agricultural drainage is common in warmer, humid locations around the world where climate, soils, and management are very different from Saskatchewan (Nangia et al., 2013; Kleinman et al., 2015b; Madramootoo et al., 2007; Montagne et al., 2009). Drainage research in Saskatchewan is lacking and other drainage research is not applicable. Furthermore, few studies have examined how drainage specifically changes soil properties over time (Montagne et al., 2009; Bedard-Haughn, 2011). A better understanding of how drainage affects key soil fertility related properties will help determine if drainage is a suitable management practice for long term soil quality and help develop management strategies that can reduce drainage related environmental consequences.

1.2 Research objectives

The first objective of this research was to determine if drainage duration affects chemical and physical properties that are important for soil fertility in the Black Soil Zone of Saskatchewan. The second objective was to determine if changes caused drained soils to become more similar to upland (midslope) soils in terms of properties, nutrient dynamics, and nutrient storage. Finally, the third objective was to determine if drainage effects on soil properties varied under below versus above-normal precipitation years.

1.3 Organization of thesis

The research presented in this thesis is organized in a manuscript format. Following the general introduction (Chapter 1) and literature review (Chapter 2), research is presented in two research chapters. The first research chapter (Chapter 3) presents the field component of this study looking at how agricultural drainage changes physical and chemical soil properties with increasing duration. This chapter provides information that satisfies the first two objectives. Chapter 4 describes a greenhouse experiment that examined fate and forms of N and P in plant, water, and soil of agriculturally drained soils under different precipitation treatments, satisfying objectives 2 and 3. Chapter 5 provides a synthesis of the two research chapters (Chapters 3-4) and general conclusions. Following a reference list (Chapter 6), the thesis also includes two appendices. Appendix A provides additional information and data that corresponds to Chapter 3 and appendix B for Chapter 4.

2 LITERATURE REVIEW

2.1 The Prairie Pothole Region

The Prairie Pothole Region (PPR) is a unique and important area covering the southern portion of Canada's three Prairie Provinces and sections of Montana, North Dakota, South Dakota, Minnesota, and Iowa, in the United States. Of the total area of 777 000 km^2, 491 000 km^2 are located in Canada, with 254 000 km^2 used for agricultural purposes (Cortus et al., 2009). The PPR has a hummocky to undulating landscape formed during the retreat of the Wisconsin ice sheet during the last glaciation (Pennock et al., 2010). Parent materials are made up of glacial till, outwash materials, or glaciolacustrine silts and clays. Since parent materials tend to consist of finer silts and clays, hydraulic conductivity is slow. Annual precipitation across the Canadian Prairies increases from southwest to northeast. The western half is drier due to dry continental air masses coming down off the Rocky Mountains (Johnson et al., 2010). Topography, parent material and climate influence prairie hydrology and soil development.

2.2 Prairie hydrology

One of the distinguishing characteristics of the PPR is the great abundance of small wetlands, also referred to as potholes or sloughs. It is estimated that the province of Saskatchewan contains 1.5 million wetlands, with 80% less than one hectare in size (Cortus et al., 2009). The wetland density can be very dense in some areas ranging between 5 to 90 km^{-2} (Brunet and Westbrook, 2012). These freshwater, mineral soil wetlands were created in depressions amongst till that was unevenly deposited (Pennock et al., 2010). They lack a well-developed drainage network and are usually seasonally connected by surface flow in spring under normal climatic periods. During spring, snowmelt runoff over frozen soils fills potholes. As wetland capacity is reached, excess water runs off and fills another nearby wetland. This is known as the "fill-and-spill" process (Spence, 2006; van der Kamp and Hayashi, 2009). Due to the semi-arid to sub-humid climate, precipitation in summer is exceeded by evapotranspiration resulting in most wetlands drying up throughout summer. These wet-dry cycles, from spring to summer, are valuable and promote nutrient cycling, vegetation growth and oxidation of soil (Anteau, 2012). These cycles also prevent development of organic wetlands, commonly referred to as peat, muck, bog, or fen soils (Bedard-Haughn, 2010).

Until recently, groundwater was assumed to be irrelevant to streamflow generation and water inputs to wetlands. However, Brannen et al. (2015) found that during very wet periods, shallow groundwater can contribute large water inputs to wetlands and extend stream flow later into the growing season than fill-and-spill processes would allow. This is due to effective transmission zone (ETZ) pathways that may form between wetlands within close proximity to one another. Due to soil macropores and fractures, an area of higher hydraulic conductivity exists underneath wetlands. The ETZs form where the water table overlaps with the area of higher hydraulic conductivity, allowing for greater subsurface flow to occur within these zones. During wetter years, the ETZ increases in size due to rising water tables (Van der Kamp and Hayashi, 2009; Brannen et al., 2015). Water can likely flow from wetland to wetland if these ETZ pathways become connected due to close proximity.

2.3 **Prairie soils**

Topography and movement of water are fundamental controls on soil genesis in Saskatchewan (Noorbakhsh et al., 2008; Pennock et al., 2014). In a hummocky prairie landscape, water moves away from and off of upper slope positions and down into depressions. These upper slopes consist of grassland soils belonging to the Chernozemic order. Chernozems have a dark surface A horizon due to high organic matter (OM) accumulation from the addition of grasses and forbs. Chernozemic soils have good structure, especially in their native state, and are high in base cations, due to glacial parent material derived from sedimentary rocks high in $Ca^{2+,}$ Mg^{2+}, K^{+} and Na^{+} (Pennock et al., 2011). Chernozemic soils have great agricultural potential due to high amounts of OM, exchangeable cations, good structure and relatively good drainage (Soil Classification Working Group, 1998).

The lower slope positions, where water accumulates and wetlands develop, are dominated by soils belonging to the Gleysolic order. The diagnostic feature of a Gleysol is presence of a reduced blue/gray matrix and mottles within 50 cm of the soil surface.

The blue/gray matrix occurs when soil is saturated long enough that anaerobic conditions cause iron oxides to be reduced. The reduced iron oxides (Fe^{2+}) are more mobile and can be removed from the profile, creating the dull coloured matrix. Mottles are orange/red spots that form when areas within the soil dry out (e.g. along root channels), allowing for oxidation of iron oxides to occur and Fe^{3+} to re-precipitate out. Anaerobic conditions also slow down decomposition, allowing for high OM to be stored in lower slope positions. Tillage translocation and water movement from surrounding cultivated upland soils can further add carbon and nutrients to these soils. The Gleysolic order has three great groups: Luvic Gleysol, Humic Gleysol, and Gleysol. These great groups are separated depending on their development of an Ah horizon and presence of a Bt horizon. The Luvic Gleysol has an illuvial, clay enriched, Bt horizon. This occurs where greater water movement leaches clay from the surface soil, creating an Ae horizon, into the Bt horizon. A Humic Gleysol has an Ah horizon similar to a Chernozemic A, which must be ≥ 10 cm and have at least 2 % organic carbon (OC) content. The Gleysol great group lacks both the Bt and developed Ah horizon (Bedard-Haughn, 2011; Soil Classification Working Group, 1998). As a result of high nutrient and organic content, Gleysols are ideal for agriculture during drier years or with agricultural drainage (Bedard-Haughn, 2011; Richardson and Arndt, 1989).

The movement and solute load of groundwater further affects soil formation within and around a wetland (Pennock et al., 2014). Generally, there are two types of wetlands in the PPR: recharge (i.e. freshwater ponds) and discharge (i.e. brackish/saline ponds) wetlands. Recharge wetlands are typically present in topographically high depressions, and discharge wetlands occur in topographically low and closed depressions (van der Kamp and Hayashi, 2009; Bedard-Haughn and Pennock, 2002). Water collects in both recharge and discharge wetlands due to precipitation, snowmelt runoff, and over-spilling of nearby ponds. Brackish/saline ponds also receive inputs from solute-rich groundwater. In recharge wetlands, water percolates downwards dissolving and leaching out soluble salts and carbonates. This creates an underlying carbonate-free zone. Due to low permeability of underlying clay-rich parent material, movement of water to and from deep aquifers is very slow. As a result, water moves laterally out towards pond edges due to higher hydraulic conductivity of surface materials, capillary rise, and uptake of surrounding vegetation (Pennock et al., 2014; van der Kamp and Hayashi, 2009; Naschon et al., 2013). Water is then drawn upwards and soluble salts precipitate out creating a “saline ring” around the wetland. This can also be referred to as a discharge ring, due to upwards movement of water, or a rego ring, representing the likely Regosolic soil order (or Rego subgroups) present. The Regosolic order of soils represents undeveloped soils that lack a well formed B horizon. In discharge wetlands, dominant movement of water is vertically towards the surface and laterally out towards the edges. This upward movement restricts formation of a B horizon in these underlying Gleysols. Both the lateral and upslope movement of water with salts around wetlands, and hillslope hydrological processes influence soil distribution. This creates the commonly observed prairie catena of less developed thin Regosolic soils or Rego subgroup from the Chernozemic order on the convex knoll position, to Calcareous or Orthic Chernozems on midslopes, to Eluviated Chernozems in concave footslopes, followed by a Rego/Calcareous ring surrounding Gleysols located in depressions, where standing water persists.

2.4 Wetland importance and agricultural potential

Prairie potholes provide many ecosystem services. Wetlands provide habitat for wildlife and are vital breeding grounds for migratory birds (Anteau, 2012; Brunet and Westbrook, 2012). They are also important for flood control, water quality, groundwater recharge, carbon storage, and recreational purposes (Euliss et al., 2006; Bedard-Haughn et al., 2006; Neuman and Belcher, 2011; Johnson et al., 2010; Cortus et al., 2011). Wetlands in the PPR are interspersed amongst prime agricultural land, and may be some of the most agriculturally productive land due to naturally high fertility, organic matter content, and plant available moisture holding capacity (Richardson and Arndt, 1989). Since settlement of the Prairies, many potholes have been cleared of their natural vegetation and cropped in drier regions or during drier years (Bedard-Haughn et al., 2006). During wetter periods, farmers may install drainage ditches to permanently remove water in order to increase agricultural land.

2.5 **Soil fertility**

Soil fertility refers to the soil's ability to grow and produce optimal crop yields. Various factors can affect soil fertility such as climate, parent material, topography, nutrients, and water supply. Moisture and nutrient availability are the greatest limiting factors of crop growth (Havlin et al., 2014a). Roots of plants are responsible for water and nutrient uptake. Any factor limiting root growth, and ability of water and nutrients to move throughout soil to roots, will affect soil fertility (Stockdale et al., 2013). Therefore, soil fertility should not be based solely on a soil's potential to supply nutrients, but also on the ability to provide moisture and suitable structure favorable for root growth. Both physical and chemical properties should be considered when investigating soil fertility.

2.6 **Physical properties**

2.6.1 Porosity, bulk density and soil structure

Porosity refers to pore spaces within soil that can hold or transmit water and air; pores are created by packing and arrangement of soil aggregates, and biological action by roots and burrowing organisms. Soil structure is strongly influenced by development of soil aggregates, which are masses of sand, silt, and clay bound together by organic material. Both porosity and structure affect the rate of permeability within soils and influence movement of air, water, and nutrients. Increased aggregation often equates to an increase in pore spaces and permeability, which provide aerobic conditions for plants and allow space for root growth (Kay, 1998; Bedard-Haughn, 2009). Texture can also influence porosity. Finer textured soils, rich in silts and clays, have a greater proportion of micro-pores and are good at retaining moisture, but movement of air and water is more restricted. Sandy soils have a greater presence of macro-pores that cause water to move quickly through the profile (Kay, 1998). Bulk density, which is the mass of soil per unit volume of soil that has not been disturbed, is also strongly related to porosity. A very low or high bulk density is unfavourable for plant growth since a low bulk density would not offer the support that plants need and a high bulk density would have fewer pore spaces, limiting root growth, water movement, nutrient uptake, and gas exchange (Baker et al., 2004, Havlin et al., 2014a).

Aggregate stability, a measure of structure, is also useful as an indicator of organic matter, biological activity, and nutrient cycling within soil. Aggregate stability is measured by applying some form of disruption to a soil sample and separating that sample into different aggregate fractions or sizes. The presence of larger aggregates indicates better structure since this equates to an increase in pore spaces and a decrease in bulk density. Greater aggregation is also favourable because aggregates offer protection to SOM. Microaggregates (<250 μm) are more stable and made up of older, more recalcitrant forms of organic material. This fraction is critical for long term storage of soil C. Macroaggregates (>250 μm) are larger, newly formed aggregates, which are composed of more labile organic matter, making them less stable. New microaggregates are created within macroaggregates as the more labile OM of the macroaggregate begins to break down. When macroaggregates break up, any microaggregates formed within the macroaggregates remain, resulting in greater proportions of microaggregates. Since macroaggregates consist of microaggregates, held together by organic binding agents like roots and polysaccharides, the C concentration increases with aggregate size (Six et al., 2000). However, a short macroaggregate turnover time, due to some kind of disturbance, can decrease new microaggregate formation and reduce C sequestration (Six et al., 2004).

Draining soils has potential to improve soil structure via biological activity due to increased aeration, and wet-dry cycles that create cracks in finer textured soils (Montagne et al., 2009). This improved aggregation can help further reduce standing water in saturated soils due to greater infiltration associated with more pore spaces (Bedard-Haughn, 2009). Some studies have found that subsurface drainage can increase soil macropores and lower bulk densities (Baker et al., 2004; Montagne et al., 2009). However, greater biological activity following drainage would result in greater organic matter decomposition, with potential to decrease structure, porosity, and increase bulk density (Hao et al., 2008). Additionally, the use of agricultural equipment and intensive management practices can be detrimental to structure. Intensive agriculture, such as tillage and compaction from heavy equipment, disrupts aggregation, decreases porosity, and increases bulk density (Tan, 2005b; Abdollahi et al., 2014). It is well known that aggregation increases in less disturbed soils (Kay, 1998; Stockmann et al., 2013; Denef et al., 2001), and cultivated soils have greater SOC held within microaggregates relative to macroaggregates due to the susceptibility of macroaggregates to breaking up with cultivation (Bajracharya et al., 2008). Although drainage may improve structure, subsequent use of equipment and management can degrade structure, porosity, and bulk density.

2.7 **Chemical properties**

2.7.1 Carbon

Carbon is the driving force of nutrient cycling and plays a central role in soil structure (Blair et al., 2001) . It supplies microorganisms with the energy needed to carry out various tasks, such as breaking down compounds into more usable and plant available forms. Carbon can contribute to nutrient supply, improve water holding capacity, increase soil aggregation, and buffer movement of nutrients, pesticides, and herbicides (Kimble et al., 2001). Soil organic carbon (SOC) refers to elemental C held in soil that has originated from organic materials. Soil organic matter (SOM) is a mixture of organic materials, humus, charcoal, plant roots and living microorganisms (Stockmann et al., 2013).

Prairie soils are rich in SOC with C content increasing along the southwest to northeast moisture gradient. Soil organic C also varies across landscape features and is higher in depressions and convergent positions where water accumulates. Carbon increases with moisture due to greater vegetation and SOM transformations. Gleysols have even larger stores of C due to anaerobic conditions that slow down decomposition. In addition to protection offered by soil aggregates, soil minerals protect SOM through calcium carbonate coats and chemical bonding with clay (Stockmann et al., 2013). The SOC content across a cultivated landscape is also highly influenced by water, wind, and tillage erosion. Tillage translocation and erosion results in removal of C and nutrient rich surface soil from upper slope positions down into lower slope positions, further increasing C and nutrient concentrations of soils in lower slope positions (Vandenbygaart et al., 2012; Noorbakhsh et al., 2008; Pennock et al., 2011).

Agricultural drainage and cultivation has great potential to alter SOC. Changes in SOC occur when land management or environmental factors change SOM inputs and rates of decomposition (Gregorich and Beare, 2008). Drainage can increase biological activity, which can increase aggregation and protection of C; however, an increase in biological activity equates to increased decomposition of C by organisms. Other agricultural management practices following drainage may further decrease C stocks through crop removal, and tillage operations that reduce protection offered by aggregates (Denef et al., 2001). Tillage can also transfer C and other nutrients from upslope soils down into drained depressions. Although this would increase C within drained soils, it removes C from upper slope positions and may reduce productivity. Reduced tillage may be a better option for drained soils in order to promote formation of macroaggregates and C storage. Minimal tillage may also slow down decomposition of SOM in drained soils since residues will collect on the surface and decrease contact between soil microorganisms (Six et al., 2000). Although drainage has potential to improve structure and offer protection of C, agricultural production followed by crop removal will result in losses of C and the use of different agricultural practices can further increase C decomposition.

There are various fractionation techniques that divide SOM into groups used to describe quality of C in terms of how labile and available it is to microorganisms (Pennock et al., 2011). Dissolved organic carbon (DOC) and light fraction (LF) represent more available, labile forms of C (Gregorich et al., 2006; Stockmann et al., 2013). Dissolved organic carbon is soluble organic carbon, which is operationally defined as the fraction passed through a 0.45 µm filter. Although it is a relatively small fraction, it is believed to be one of the most active fractions due to its mobility and labile nature (Chantigny et al., 2008). Light fraction is a commonly measured type of physically uncomplexed organic matter, representing “free” C that is minimally associated with the mineral fraction. This fraction tends to be more sensitive to cultivation and conservation management, responding quickly to management changes (Kumar et al., 2014). Light fraction is mainly affected by residue input, soil temperature, and moisture (Six et al., 1998; Gregorich et al., 2006).

2.7.2 Nitrogen

Amounts of N vary across the Prairies depending on soil type and land use. Greater N exists in Chernozems of the Black soil zone, compared to other soil zones, and lower slope positions due to greater moisture allowing for greater organic matter accumulation. Soils that have been cultivated tend to have less N than uncultivated soils (Bedard-Haughn et al., 2006). Nitrogen is an essential macronutrient for plants. The major N input to Saskatchewan soils are inorganic and organic fertilizers (Bedard-Haughn et al., 2006). Other inputs include N fixation, crop residues, and even atmospheric pollution. Generally, plant available forms of N are inorganic ammonium (NH_4^+) and nitrate (NO_3^-). To a lesser extent, plants are capable of directly taking up dissolved organic N (DON) (Haygarth et al., 2013; van Kessel et al., 2009). Since most soil N is present in the organic form, N needs to be converted to an inorganic form through the process of mineralization before it can be used by plants. Mineralization is stepwise reaction completed by microorganisms that convert DON into NH_4^+. Following mineralization, nitrification converts NH_4^+ into nitrite (NO_2^-) followed by NO_3^-. Immobilization occurs simultaneously with mineralization and nitrification; soil microorganisms use available N, making it temporarily unavailable. Denitrification is also carried out by microorganisms, but under anaerobic conditions. Denitrification results in a loss of N, typically to the atmosphere, due to reduction of NO_3^- to N_2 and nitrous oxide (N_2O) gases (Havlin et al., 2014b). Mineralization, nitrification and denitrification all influence quantity and forms of N in a system.

Environmental conditions and land use affect N processes, influencing quantity and fate of N within a system. As mentioned, some processes require aerobic conditions while others require anaerobic conditions. Mineralization, which is perceived to be the critical flux in the N cycle controlling plant availability (Isaac and Timmer, 2007), has many controls including pH, temperature, moisture, and texture. Acidic soils, cooler temperatures, too dry or too wet environments, and finer textures can all decrease N mineralization (Booth et al., 2005). Although wetland soils are high in nutrients, excess water conditions reduce plant available N, which is the most critical nutrient for plant growth. Anaerobic conditions decrease available N due to reduced mineralization, losses of N_2O due to denitrification, and NO_3^- leaching (Bedard-Haughn, 2009). Draining excess water can create aerobic conditions resulting in increased mineralization and nitrification, decreased denitrification, and greater available N (Venterink et al., 2002). Other management practices like fertilizer applications, following drainage, are also believed to be responsible for increases in nutrient availability (Ewing et al., 2012; Streeter and Schilling, 2015). Additionally, crop removal with harvest and losses of N to drainage water can lead to a decline in N over time.

2.7.3 Phosphorus

Most Saskatchewan soils are inherently rich in soil P, originating from glacially-derived parent material. Soil P in Saskatchewan increases from 300 mg kg^{-1} for sandy parent materials up to 800 mg kg^{-1} in clayey material (Anderson, 1988). Other inputs of soil P include fertilizer, manure and crop residues. Phosphorus can be broadly subdivided into organic P and inorganic P. Inorganic orthophosphate ($H_2PO_4^-$ and HPO_4^{2-}) in soil solution is the main form of P available to plants and microorganisms (Tan, 2005a; Condron et al., 2005). Soil solution P is low and represents < 1% of total soil P (Pierzynski et al., 2005). As inorganic P is removed from soil solution, it must be continually replenished in order to sustain plant growth. This is accomplished by further desorption and dissolution of inorganic P and mineralization of organic P (Condron et al., 2005). Phosphorus is strongly sorbed or precipitated to soil minerals. Phosphate binds to Fe^{3+} or Fe^{2+} and Al^{3+} in acidic soils, and to Ca^{2+} and Mg^{2+} in neutral, calcareous soils, such as those present in the Prairies, creating compounds with low solubility that limit plant and microbial uptake (Newman and Pietro, 2001; Stewart and Tiessen, 1987). In native grasslands, more P is continually held in the organic form and recycled, maintaining a higher level of P availability. Conversely, agricultural systems have intermittent crop growth with more opportunities for precipitation or P adsorption to the mineral fraction, which reduces P availability (Stewart and Tiessen, 1987). Organic P is greater in depressions due to greater weathering associated with higher moisture content, increased organic matter, and greater biological activity (Noorbakhsh et al., 2008; Manning et al., 2001). Across the Prairies, P availability increases from upper slope to lower slope positions, following similar trends of soil movement.

Various factors influence P availability. Increased moisture and flooding can increase plant available P due to the conversion of Fe^{3+}-P to Fe^{2+}-P, which is a more soluble form. Greater moisture can enhance P diffusion to roots (Clarke et al, 1990; Turner and Gillam, 1976), mineralization, and solubility of Ca-P in calcareous soils (Venterink et al., 2002). In more Ca-P dominated soils, P availability is unaffected by drying (Venterink et al., 2002; Havlin et al., 2014d), whereas P solubility would be expected to decrease in more $Fe^{3+,2+}$ and Al^{3+} dominated soils. Mineralization of organic material can also increase as flooded soils become drier due to greater aerobic conditions. However, this microbial activity can also be a disadvantage and result in temporary decreases of available P due to immobilization. Since both increases and decreases in moisture content can improve P availability, depending on initial circumstances, it is no surprise that wet-dry cycles are thought to increase plant available P. Extractable P can increase following rewetting of dry soil due to water dissolving Ca-P and flushing out newly mineralized P (Venterink et al., 2002).

The effects of flooding and soil drainage on soil P have varied across studies and are likely due to differences in soil type, climate and drainage practices (King et al., 2015; Kamiri et al., 2013; Venterink et al., 2002). Drainage of prairie potholes has potential to increase P availability due to aerobic conditions, increased biological activity, and greater wet-dry events, and, like N, some studies suggest greater P availability results from fertilizer inputs (Ewing et al., 2012; Streeter and Schilling, 2015). Since P solubility is greatest at a neutral pH, fertilizer additions in drained calcareous soils have potential to lower pH and make Ca-P complexes more soluble, increasing plant available P (Turner et al., 2003). However, with time in cultivation, available P may decrease due to crop exports and greater opportunities for precipitation of inorganic P to the mineral fraction, instead of being recycled into organic P (Stewart and Thiessen, 1987).

2.8 **Climate change**

Temperature and moisture strongly influence soil properties and affect plant growth. The PPR is described as having a semi-arid to sub-humid climate; however, the earth is currently experiencing a warming trend with varying predicted outcomes. Due to distance from a large water body (i.e., no lake effect precipitation) and location on the leeward side of the Rocky Mountains, southern Saskatchewan is prone to droughts (Bonsal et al., 2012) and with a temperature increase, is expected to experience greater drought conditions (Parry et al., 1990; Cutforth et al., 1999; Akinremi et al., 2001). However, the northern Prairie region is expected to experience wetter conditions in the future. Historical weather data show Prairie temperatures have increased by 1.6°C over the last century (Bonsal et al., 2012) and precipitation across the PPR has increased by 9% between 1906 and 2000 (Millet et al., 2009; Johnson et al., 2010). Recent weather events such as the 1999 to 2005 drought in the Prairies, described as possibly one of the worst to hit over the last 800 years, as well as historic flooding that occurred in the province of Saskatchewan in 2010 and 2011, show how variable and unpredictable Canadian Prairie climate is (Brimelow et al., 2014).

Advantages associated with warmer temperatures and increased precipitation include an increase in agriculturally productive land in the north, longer growing seasons, and increased crop yields. Currently, northern agriculture is constrained due to low temperatures. In some areas, a 1°C increase has potential to advance the thermal limit of cereal crops by 150 to 200 km. With increased temperatures, growing seasons may last longer as frost free days increase and earlier seeding is possible (Parry et al., 1990; Cutforth et al., 1999). Greater precipitation will be advantageous for areas that currently experience moisture deficits, and coupled with greater atmospheric CO_2, may experience increased crop yields.

Disadvantages due to climate change include increased pests and diseases, drought, and flooding. Under warmer conditions, pests and diseases thrive because they can establish themselves earlier in the growing season. Additionally, the geographical range of some species will likely expand (Parry et al., 1990). Warmer temperatures and decreased precipitation in Western Canadian Prairies can cause further moisture stress to areas already experiencing moisture deficits (Johnson et al., 2010). Alternatively, the eastern PPR could expect wetter conditions like ones currently being experienced since 2010 (Johnson et al., 2010; Bedard-Haughn, 2009; Brimelow et al., 2014). Wet soils can prevent farmers from accessing their fields since movement of large agricultural equipment is difficult in saturated soils. This can delay or prevent seeding in spring and harvest in fall (Cortus et al., 2009). The Canadian Wheat Board estimated that 2011 flooding resulted in almost 5.5 million hectares of agricultural land not producing crops (Brimelow et al., 2014). Increased precipitation can also lead to greater nutrient leaching and soil erosion (Parry et al., 1990). As climate changes, farmers will need to adjust and make adaptations to their farming practices. Due to inter-annual variability and variability in model predictions, having an understanding of how to be prepared for both scenarios – drought and flooding – is equally important.

2.9 **Agricultural drainage**

Drainage is a large scale management practice used to combat issues associated with flooding and saturated soils. Drainage is an essential agricultural practice in more humid regions like the Great Lakes and St. Lawrence lowland region of Ontario and Quebec (Nangia et al., 2013; Kleinman et al., 2015b), whereas the Prairie region of Saskatchewan is located in a drier climate where past agricultural issues have traditionally revolved around droughts. The main purpose of drainage is to create favorable growing conditions for crops and soil management (van Schilfgaarde and Skaggs, 1999). Surface and subsurface drainage are the two major drainage methods that can be implemented. The type of drainage used depends on a variety of variables such as topography, crop species, soil characteristics, and suitable outlets (Fangmeier et al., 2006).

2.9.1 Surface drainage

Surface drainage is the removal of water from the uppermost area of the soil profile by installing open drains and channels that connect to ditches. Surface drainage is the oldest and easiest method of choice. Ditches, or field drains, are shallow graded channels created using equipment such as excavators. These channels are directed to larger ditches that transfer the water to an outlet point (Robinson and Rycroft, 1999). Surface drainage is the common drainage method used in Saskatchewan since it is most ideal for flat areas with low permeability and is the best method for draining scattered depressions (Fangmeier et al., 2006; Bedard-Haughn, 2009; Cortus et al., 2009; Robinson and Rycroft, 1999).

2.9.2 Subsurface drainage

Subsurface drainage, often referred to as tile drainage, involves installing plastic perforated pipes of varying depths, pipe sizes and spacing depending on intensity. The depth of drainage is usually less than 1 m if ephemeral (flows only at certain times of year) and deeper if flows are perennial (flows consistently throughout year) (Kleinman et al., 2015b). Unlike surface drainage, subsurface drainage increases infiltration within the soil profile because pipes are located underground and require water to percolate through soil before collection. This method is more costly and is ideal for soils that have a higher hydraulic conductivity so water can be moved fast enough to drains (Bedard-Haughn, 2009).

2.9.3 Benefits of drainage

Drainage of Prairie wetlands can be beneficial because it increases the area of arable land and reduces machine operating costs associated with navigating around saturated soils (Cortus et al., 2009). Better drainage of soil helps extend the growing season by making the field more accessible to equipment in spring, allowing for seeding to take place sooner (Nangia et al., 2013). Drainage lowers the water table creating better aeration conditions for plants, increasing root activity and nutrient uptake (van Schilfgaarde and Skaggs, 1999). When the water table is close to the surface, roots remain close to the surface as plants avoid anaerobic conditions. This puts plants at a disadvantage for assessing nutrients and responding to drought later in the growing season if the water table recedes. Excessive water can also hinder the plants ability to take up nutrients, even if present in soil, as nutrient uptake by plants requires energy inputs from aerobic respiration (Bedard-Haughn, 2009). Aerobic conditions can also increase nutrient availability due to increased mineralization. Public health can also benefit by removal of stagnant water, limiting breeding grounds for mosquitoes and other parasites that can spread diseases. Finally, agricultural surface drainage is relatively inexpensive (Nangia et al., 2013).

2.9.4 Disadvantages of drainage

Many disadvantages of agricultural drainage stem from the consolidation and increased connectivity of wetlands. Consolidation refers to the draining of smaller, shallow wetlands into larger wetlands, which is very common since small wetlands are easier to drain (Anteau, 2012). Increased connectivity has potential to reduce groundwater recharge, increase magnitude and frequency of flood events, and increase transport of sediment, nutrients, pesticides, and salts into lower basins (Anteau, 2012; Brunet and Westbrook, 2012). Greater connectivity also creates opportunities for invasive species to spread and reduces wet-dry cycles of isolated wetlands that drive productivity and abundance of aquatic invertebrates. Amphipods, which are a good indicator of water quality, have decreased across the PPR, with declines linked to sedimentation and predation by invasive fish. The PPR is a major migratory pathway and prairie potholes are responsible for production of over half of the continent's waterfowl each year (Brunet and Westbrook, 2012). Wetland consolidation decreases food availability for water fowl and also destroys breeding ground habitat. Some may argue that bigger wetlands are better, but seasonal temporary wetlands support more pairs of breeding ducks than larger permanent wetlands. Additionally, drainage is believed to be responsible for more stable water levels that decrease shorebird habitat due to growth of dense emergent vegetation along wetland margins (Anteau, 2012). The tension between environmental impacts and agricultural benefits associated with drainage has potential to lead to conflict.

The largest disadvantage associated with agricultural drainage is water quality. Agricultural drainage has been identified as a large contributor to N and P loading to downstream waterbodies. N and P loading leads to eutrophication of water that can cause hypoxia, toxic algae blooms and disrupt recreational use of water (Randall and Goss, 2008; Haygarth et al., 2013; Westbrook et al., 2011). The impact drainage has on water quality varies and depends on drainage type, land use, management practices, topography, soils, and climate (Skaggs et al., 1994; Sharma et al., 2015). Nutrients can move from soil to water in dissolved or solid forms. Solid nutrient losses occur when nutrients are bound to sediment and erosional processes suspend the material in the water. Surface drainage is thought to contribute large sediment losses of P, especially during the construction phase, whereas subsurface drainage may reduce P losses due to decreased surface runoff. However, more recent research has found that subsurface P losses are not as negligible as once thought and can even contribute to P losses of surface drained soils. Factors promoting subsurface P losses include finer textured soils with preferential flow paths created by earthworms, roots, and cracks, low P sorption capacity, reducing conditions, and excessive P fertilizer application (King et al., 2015; Kleinman et al., 2015b; Gburek et al., 2005). Most drainage N losses occur in the dissolved form of NO_3^- and are a larger issue with subsurface drainage due to increased interaction of water with soil before reaching the drainage system (Skaggs et al., 1994; Bedard-Haughn, 2009; Tan et al., 1998). Soil factors promoting N loss to drainage water include high N mineralization rates, and preferential flow paths (Randall and Goss, 2008). Both agronomically and environmentally, NO_3^- is often the nutrient of greatest concern in drainage water since it can occur in large concentrations due to its high mobility. Agronomically, P is not a concern in drainage waters, but, ecologically, it is a great concern since eutrophication can occur at very low concentrations of P in water.

Research on effects of agricultural drainage to water quality in Saskatchewan is limited. In eastern Saskatchewan, Brunet and Westbrook (2012) found that all nutrients held within pond water (in solution or suspension) were exported out of drainage ditches immediately following drainage. Studies outside of the province have found ditch soils can behave as a sink or source of N and P by sedimentation/resuspension, sorption/desorption, plant or microbial uptake, and microbially mediated mineralization and nitrification processes (Skaggs et al., 1994; Sharpley et al., 2007). Although not measured, Brunet and Westbrook (2012) suggested biotic and abiotic processes that occur in ditches would not contribute to removal or addition of nutrients to drainage water due to cooler spring or fall temperatures restricting mineralization, nitrification, sorption and diffusion rates, and plant uptake. Therefore, all nutrients in drainage water would likely be exported downstream since streamflow occurs in the spring, following snowmelt, and drainage construction typically occurs in the fall when soils are frozen, restricting infiltration and soil water interactions. However, Brunet and Westbrook's (2012) study did not account for ditch or drainage age, and cultivation after drainage that likely changes conditions of both wetlands and ditches. These changes, such as cropped ditches, can influence nutrient exports (Skaggs et al., 1994; Sharpley et al., 2007) in subsequent years. Furthermore, greater streamflow throughout the growing season, linked to greater rainfall runoff and shallow groundwater connectivity during wet periods (Dumanski et al., 2015; Akinremi et al., 2001; Brannen et al., 2015), suggests that there is potential for greater soil water interaction and greater streamflow generation events, which could contribute to nutrient losses.

2.10 **Drainage policy**

Drainage needs to be designed in a way that considers both agricultural and environmental needs. It is critical for the government to have a policy in place to help avoid conflicts. The planning and legislation of agricultural drainage in the past has been minimal in Saskatchewan. Previous policies allowed property owners to drain land as long as water drained did not affect surface flows to surrounding properties. If water was going to affect surrounding properties, a permit was required. Often drainage was completed without permits, leading to conflicts between landowners and complaints to the Water Security Agency, the agency responsible for provincial water resources. This ultimately caused a backlog preventing timely approval of new permits (Water Security Agency, 2015; Briere, 2015). More recently, there has been growing awareness in the province of negative downstream effects of drainage and recognition that drainage is an important water management tool. Extensive consultations over the past two years, involving over 500 public participants and 15 industry and environmental groups, helped to develop new regulations that were announced September 1, 2015 by the Water Security Agency. The key changes include: allowing landowners to sign agreements without acquiring easements, simplifying the application approval process, having compliance of all drainage works including those installed prior to 1981, allowing consultants to help design higher risk drainage works, and addressing impacts related to flooding, water quality, and habitat loss during the approval process. New regulations are meant to improve the approval process in order to increase compliance of landowners, reducing unauthorized drainage and mitigating downstream damage (Water Security Agency, 2015; Briere, 2015). However, there are still concerns over lack of official monitoring and what types of mitigation will be used (Briere, 2015).

2.11 Previous drainage research

Agricultural drainage related research has been conducted around the world including British Columbia (Chieng and Hughes-Games, 1995) and Ontario (Tan et al., 1998; Tan and Zhang, 2011) in Canada; Florida (Newman and Pietro, 2001), Ohio (Baker et al., 2004; Kumar et al., 2014; Fisher et al., 1999), North Carolina (Hayes and Vepraskas, 2000; Ewing et al., 2012), and Iowa (Streeter and Schilling, 2015) in the United States; Sweden (Venterink et al., 2002; Andersson et al., 2013); and East Africa (Kamiri et al., 2013). There is an extensive list of research on subsurface drainage in countries outside of North America in a review by Montagne et al. (2009) who discusses the impact of drainage on soil evolution. Most research available involves subsurface drainage, different soil types, and is located in more humid climates, with a focus on water quality. Few studies address changes to soil quality. Montagne et al. (2009) highlight that although there have been many drainage studies around the world, there is a lack of quantitative data to accurately describe how drainage specifically affects soil properties. Additionally, other scientists stress that there is still a need of field studies to help understand nutrient fate and transport within soils to help develop models (Kleinman et al., 2015a, 2015b; King et al., 2015).

Drainage research in the Canadian PPR is particularly lacking. Brunet and Westbrook (2012) have investigated water quality impacts associated with surface drainage in the Smith Creek Watershed in Saskatchewan, and Bedard-Haughn et al. (2006) have studied effects of non-drained cultivated wetlands on fundamental N processes. Madramootoo et al. (2007) provide an overview of drainage management, quality and disposal issues in Canada and the United States. They state that some surface drainage is practiced in combination with irrigation in Southern Saskatchewan and some surface drainage, although not very extensive, occurs in the more northern wetter region of the province (Madramootoo et al., 2007). However, this is not necessarily true as some areas of Saskatchewan, like the Smith Creek Watershed, have experienced extensive drainage and loss of wetlands, and with renewed efforts to drain more wetlands, more research would be beneficial in Saskatchewan.

3 EFFECTS OF DRAINAGE DURATION ON MINERAL WETLAND SOILS IN A PRAIRIE POTHOLE AGROECOSYSTEM

3.1 Preface

Agricultural drainage is a necessary and expanding management practice in the northern and eastern extent of the Saskatchewan prairies; it is used to improve growing conditions of flooded cropland as well as increase land for crop production. This involves connecting prairie potholes by ditching and is referred to as surface drainage. To date, drainage research has been primarily based in tile drained agroecosystems in humid regions of the world, but drainage conditions are quite different in the PPR. Due to drainage concerns regarding water quality and downstream flooding, research has also been more focused on the water component of agricultural drainage. Research on how drainage specifically affects soil properties is lacking and knowledge of long term effects of drainage are almost nonexistent. Since the aim of drainage is to improve soil fertility for crop production, understanding how drainage affects soil properties is a knowledge gap that needs to be filled. Therefore, research described in this chapter identifies physical and chemical changes caused by surface drainage over time in southeastern Saskatchewan. This chapter also discusses similarities between these drained soils and their typically cultivated midslope counterparts.

3.2 **Abstract**

Recent flooding of agricultural land in the northern and eastern Saskatchewan Prairies has resulted in increased agricultural drainage. Drainage is used to improve growing conditions and increase the amount of land that can be cultivated. The aim of this study is to determine if duration of agricultural drainage improves growing conditions and nutrient availability, by measuring physical (i.e. structure and bulk density) and chemical properties (i.e. C, N and P). Sampling was completed following harvest in fall of 2014. Forty-two wetlands and paired midslopes were selected in the Prairie Pothole Region in the Black soil zone of southeastern Saskatchewan. Drainage duration of wetlands ranged from 0 to 50 years. Intact cores were collected to a depth of 60 cm for analysis of bulk density, macronutrients, C, and aggregate stability. Results suggest that drainage does improve growing conditions and nutrient availability for agricultural production, but these changes vary across wetlands that have been drained for different durations of time. Improvements were greatest in soils drained from 7 to 34 years, but decreased with increasing duration, becoming more similar to cultivated midslope positions. Some drainage benefits include increased nitrification and greater available PO_4^{-3} at a depth of 0-15 cm. Initially, SOC remained relatively consistent and even increased slightly in wetlands drained from 7 to 34 years. Drainage did not have an effect on water extractable organic carbon. Longer-term drainage implications, particularly in soils drained for 36 to 50 years, included increased bulk density, and decreased quantity and quality of OC. Both light fraction (LF) and microaggregates were found to decrease with drainage duration. It is likely that other agricultural practices used in conjunction with drainage, such as tillage, fertilizer additions, and crop removal are affecting how these soil properties change over time. For instance, tillage translocation may be gradually moving soil from upslope positions into drained wetlands and soils that have been drained the longest may appear to become more similar to the MS not due to drainage, but because surface soil in the wetland is the same soil from upslope. This study provides quantitative results that can help develop suitable management strategies to improve nutrient use efficiency and reduce losses to the environment. The changes in properties across wetlands and midslopes may be a potential avenue to explore precision agriculture.

3.3 Introduction

The Prairie Pothole Region (PPR) is a valuable agricultural region that covers the southern half of Saskatchewan and extends into Alberta, Manitoba, and the United States (Fig. 3.1; Cortus et al., 2009). One of the distinguishing characteristics of the PPR are millions of small mineral wetlands, also known as sloughs or potholes, located within depressions of the hummocky landscape. Potholes provide many ecological services such as wildlife habitat, flood control, improving water quality, groundwater recharge, and carbon sequestration (Euliss Jr et al., 2006; Bedard-Haughn, 2011; Neuman and Belcher, 2011; Brunet and Westbrook, 2012). These wetlands are usually only hydrologically connected during spring following snowmelt, when they fill up and then spill into another nearby wetland (Spence, 2006; van der Kamp and Hayashi, 2009). Over the course of a growing season many of the smaller wetlands dry up and may even be cultivated during drier years. However, since 2010 to time of writing, northern and eastern Saskatchewan Prairies have been experiencing a wet period where these wetlands are remaining wetter for longer, expanding in size, and encroaching onto valuable farmland.

Saturated soils are unfavourable for plant growth due to anoxic conditions, restricted root growth, reduced nutrient availability, and increased salinity (Nangia et al., 2013; Bedard-Haughn, 2009; Verhoef and Egea, 2013). Waterlogged soils are also difficult to navigate large agricultural equipment through, which can delay seeding. Agricultural drainage is a common management practice used in more humid regions of the world to improve soil for crop production (Nangia et al., 2013; Kleinman et al., 2015b; Madramootoo et al., 2007; Montagne et al., 2009). Drainage removes excess water from the soil creating aerobic conditions and warmer soil temperatures, which can increase decomposition. This has potential to change key soil fertility related physical and chemical properties, such as structure, bulk density, infiltration, and nutrient availability, ultimately increasing crop yields (Ewing et al., 2012; Streeter and Schilling, 2015; Kumar et al., 2014; Hundal et al., 1976; Sullivan et al., 1998). Saturated soils and agricultural intensification in Saskatchewan have resulted in renewed efforts by farmers to drain wetlands (Brunet and Westbrook, 2012; Dumanski et al., 2015).

Surface drainage is the common type of drainage installed in south-eastern Saskatchewan since it is the most ideal method for flat areas with a low hydraulic conductivity and for draining scattered depressions. Surface drainage is also less costly than subsurface tile drainage (Fangmeier et al., 2006; Bedard-Haughn, 2009; Cortus et al., 2009; Robinson and Rycroft, 1999). Surface drainage involves excavating open ditches between isolated wetlands that move water from one wetland to the next (Brunet and Westbrook, 2012). Unlike subsurface drainage that removes water from throughout the soil profile, surface drainage only removes water from the very surface of soil (Bedard-Haughn, 2009).

The greatest concerns regarding agricultural drainage are effects on water quality and downstream flooding. Drainage water can transport nutrients (ie. N and P), salts, sediment, and bacteria that can contaminate drinking water, put stress on fish communities, and contribute to eutrophication. Eutrophication leads to hypoxia, toxic algae blooms and disruption to recreational use of water (Tan and Zhang, 2011; Montagne et al., 2009; Randall and Goss, 2008; Kleinman et al., 2015b; Haygarth et al., 2013; Westbrook et al., 2011; Bedard-Haughn, 2009). Downstream flooding is a concern, as modelling projects have shown that drainage can increase magnitude and frequency of flood events (Brunet and Westbrook, 2012; Dumanski et al., 2015). As a result of these concerns, focus of drainage research in Saskatchewan and globally has been on the water aspect of drainage. Research focusing on how drainage specifically affects soil physical and chemical properties is limited and studies looking at long term effects of drainage are almost nonexistent (Montagne et al., 2009; Bedard-Haughn, 2011). Since drainage is used to improve soil fertility and agricultural production, research on how drainage directly affects soil properties is a knowledge gap that needs to be filled. Not only would this information be beneficial for determining if drainage is a suitable management practice for long-term soil quality, but it would also be beneficial for developing management strategies that could help minimize negative impacts associated with drainage.

Drainage research in Saskatchewan is limited and research from elsewhere is not directly applicable due to drier climate, drainage type (i.e. surface drainage), unique hydrology, and soils of the PPR. Agricultural drainage is necessary in these regions and given that low-lying areas tend to have higher nutrient and organic matter concentrations than surrounding uplands, drainage may create some of the best agricultural land. Since these wetland soils are so very different from upland soils, understanding how drainage may change these poorly drained soils in comparison to upland soils is important from a management perspective and can help improve nutrient planning. The objectives of this study were to: (1) determine how drainage affects physical and chemical properties in the Black Soil Zone of Saskatchewan over time; and (2) determine if these drained soils become more similar to upland (midslope) soils in terms of properties and nutrient dynamics.

3.4 **Materials and methods**

3.4.1 Site and sampling design

This research was conducted in the northern portion of the Smith Creek Watershed (50º50’4”N 101º34’48”W), approximately 60 km southeast of Yorkton, Saskatchewan in the Prairie Pothole Region (Fig. 3.1). The average wetland density is approximately 20 km^{-2} (Brunet and Westbrook, 2012). This area is located within the Black soil zone and has a loamy glacial till parent material (Oxbow and Yorkton associations). Sites ranged from gentle to moderate slopes (2.5 to 10 %) on hummocky terrain (Saskatchewan Soil Survey, 1991). The Yorkton region has a semi-arid to sub-humid climate with mean annual precipitation (MAP) (1981 to 2010) of 449 mm (Government of Canada, 2015). Sampling occurred following harvest in the fall of 2014. This was a wet year where flooding occurred due solely to rainfall, which is unusual because greatest streamflow in the prairies is usually snowmelt driven (Dumanski et al., 2015). Total precipitation for 2014 was 582 mm, with 235 mm occurring in June alone (Government of Canada, 2015). Due to wet conditions, some drained wetlands had been too wet to seed in spring and many undrained wetlands still had standing water during fall sampling. Wheat and canola were the main crops harvested from the study sites, except for one field that had been cropped with soybeans. Wetland vegetation predominantly consisted of grasses, sedges, rushes, and willow (Westbrook et al., 2011).

Figure 3.1 Study site location indicated by the star. The dashed area represents the Prairie Pothole Region.

Quarter sections, tracts of land 800 m by 800 m, were selected to represent nine sites grouped into three drainage categories based on drainage duration: recently drained (RD) (7-15 years; sites 1-3), medium drained (MD) (20-34 years; sites 4-6), and longest drained (LD) (36-50 years; sites 7-9) (Fig. 3.2). Class intervals were determined by dividing the nine sites into three groups, each containing 3 sites, and assigning the groups lowest drainage age as the minimum and the oldest age as the maximum. Duration of time since drainage was determined with air photos, satellite imagery, and communication with landowners. Due to a limited selection of undrained (UD) wetlands at each site, zones were created around groupings of sites to ensure that UD wetlands selected would be representative of all sites and spread throughout the study area.

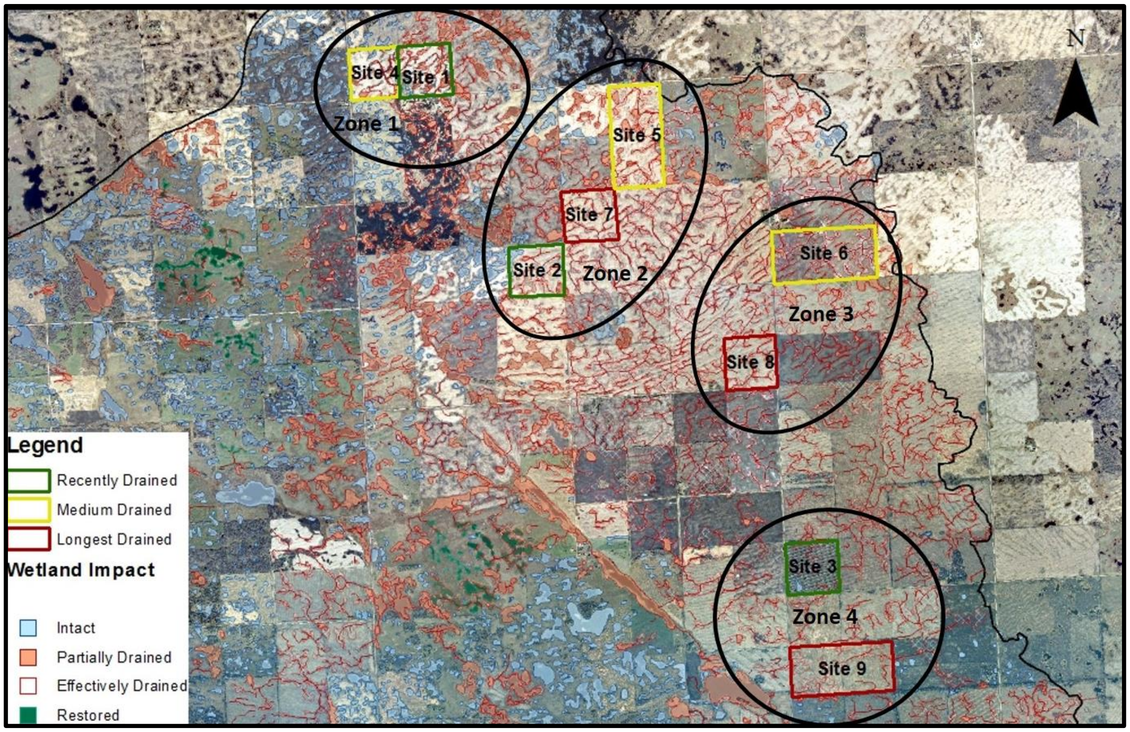

Figure 3.2 Location of sites within the study area in the northern portion of the Smith Creek Watershed. The recently drained sites range in drainage duration of 7 to 15 years, medium drained: 20 to 34 years and longest drained: 36 to 50 years. Undrained wetlands were selected for each zone, except for zone 3 where no undrained wetlands remain. Wetland impact was determined by Ducks Unlimited Canada. Geospatial data was provided by Saskatchewan Geospatial Imagery Collaborative and Ducks Unlimited Canada (Ducks Unlimited Canada, 2016).

Prior to fieldwork, 142 potential wetlands were identified throughout the sites and zones using air photos, satellite imagery, and soil maps. Potential wetlands were selected based on nature of ditch network, similar size, shape, wetland class, and parent material. Wetlands with one exiting ditch were selected over wetlands with multiple ditches or ditches that transected multiple sides of the wetland. Wetland area was determined by digitization using ArcGIS 10.1 (ESRI, 2012). Wetland area ranged between 2000 to 6000 m^2 with an average of approximately 3800 m^2. Potential wetlands were skewed to right with a greater number of small wetlands. Any large wetlands selected were due to limited availability of wetlands that fit the selection criteria.

During the wetland screening process, prior to sampling, wetlands were identified in field using GPS coordinates, landscape features, and presence of mottling. To determine suitability, soils were examined to a depth of 1 m using a hand auger. Suitable wetlands had to have mottling within 50 cm, have similar parent material and lack evidence of infill. Evidence of infill was identified as complete mixing of horizons (Appendix Fig. A.1), out of place horizons (e.g. C horizon overlying an A horizon), and inconsistent effervescence throughout the profile. Undrained wetlands were selected that fell within class I, II or III (ephemeral, temporary or seasonal) according to Stewart and Kantrud's wetland classification (1971). These wetlands are more likely to dry up and be tilled through for agricultural purposes and are more likely to be drained. The midslope was required to have a B horizon present. When a suitable wetland was identified, a brief soil description was completed using the hand auger excavated soil. Horizon depths, depth to calcium carbonates, colour, mottles, and hand texture were recorded (Appendix Table A.1). At least three drained wetlands were selected per site. Four undrained wetlands were selected in zone 1 and 2, but only 2 wetlands were selected in zone 4, due to a limited selection, and 0 wetlands at zone 3 because all wetlands had been drained in this area. In total, 42 wetlands (11 RD, 10 MD, 11 LD and 10 UD) and 42 paired midslopes were sampled.

Soil sampling occurred at the boundary of the depression and foot slope (Fig. 3.3). If the wetland was a recharge wetland, the sample was taken before the discharge ring. If the wetland was a discharge wetland, the sample was taken at the boundary of the depression and footslope. This sampling location was selected to avoid infill, and was drier allowing for the use of a truck mounted hydraulic corer (Giddings Machine Company Ltd., Windsor, CO). The midslope position was located upslope of the depression and outside of the discharge ring (Fig. 3.3). Sampling was completed to a depth of 60 cm using a 5 cm diameter core that was then divided into three depth increments (0-15, 15-30 and 30-60 cm). Three cores were collected per sampling location for bulk density, aggregate stability and chemical analyses. WD-40® (WD-40 Company Ltd., San Diego, CA) was used to prevent compaction and keep soil from sticking to the corer. During sampling, any signs of compaction resulted in resampling. Aggregate cores were loosely broken up and placed in plastic containers. All other samples were placed in sealed and doubled plastic bags. All samples were placed in coolers, transported to the lab, and stored at 4ºC until sample processing.

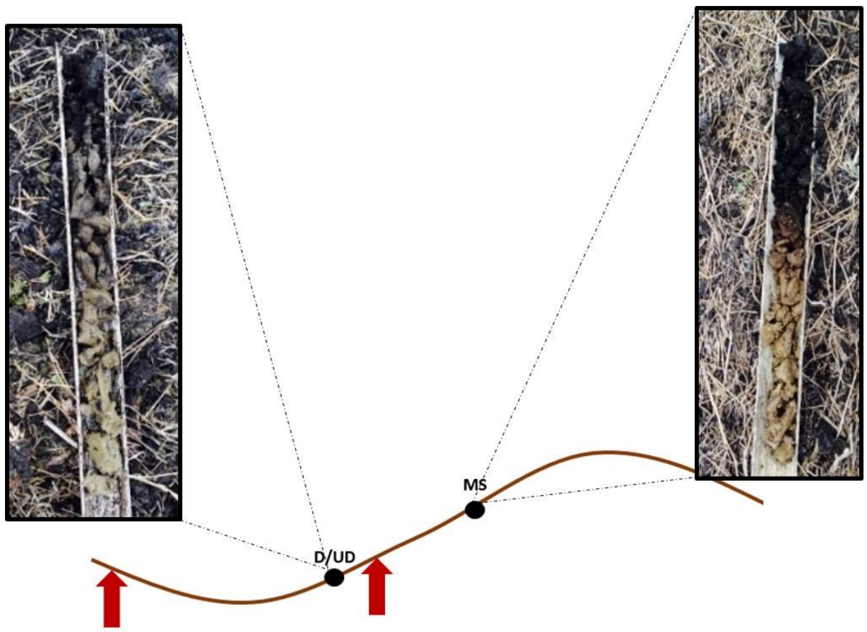

Figure 3.3 Sampling location of wetland and midslope soil. Either drained (D) or undrained (UD) was selected on the edge of the wetland before the discharge ring (red arrows). The midslope (MS) soil was selected upslope on the other side of the discharge ring and had to have a B horizon present. The pictures show an example of a paired wetland and midslope soil.

3.4.2 Sample processing and laboratory procedures

Field samples were weighed for bulk density and subsampled to determine moisture content. Remaining soil was further divided into four subsamples for handling and storage according to analysis requirements: 1) air-dried and stored for light fraction (LF) and heavy fraction (HF) analysis; 2) air-dried, ground, and passed through a 2 mm sieve for pH, EC, phosphorus sorption/desorption, available P and K; 3) air-dried and ground finely with a ball mill grinder for total C and N; and 4) frozen until further analysis for available N, mineralization, nitrification and water extractable organic carbon (WEOC). Containers containing soil for aggregate analysis were stored at 4ºC and analyzed as soon as was possible.

Samples were analyzed for pH, electrical conductivity (EC), texture, macronutrients and bulk density. These analyses were completed for all three depths (0-15, 15-30 and 30-60 cm). Soil pH and EC were measured in a 1:2 ratio of soil: water (Hendershot et al., 2008; Miller and Curtin, 2008). A representative subset of 29 wetlands and 9 midslopes were selected across the study area for texture analysis using the modified pipette method (Indorante et al., 1990). Available N was determined by a KCl extraction, and NH_4^+ and NO_3^- were analyzed by colorimetry using a Technicon Auto Analyzer (Technicon Industrial Systems, Tarrytown, NY, USA) (Maynard et al., 2008). Available P and K were determined using modified Kelowna extractions (Ashworth and Mrazek, 1995). Phosphorus was then analyzed by colorimetry for PO_4^{-3} with a Technicon Auto Analyzer and K was analyzed by flame atomic absorption using a Varian Spectra 220 Atomic Absorption Spectrometer (Varian Inc., Palo Alto, CA). Bulk density was determined by the standard core method (Hao et al., 2008).

Structure

Wet aggregate size distribution was used to characterize changes in soil structure size and strength. Field moist aggregates were gently crumbled to pass an 8 mm sieve. Duplicate subsamples of 30 g were added to the top of a set of sieves (2000, 250, and 53 μm). Soil was allowed a 2 min slaking period before sieves were oscillated using a wet-sieving apparatus (3 cm, 50 times). Floating debris was removed with vacuum suction, dried, and subtracted from total weight. Aggregates were backwashed from each sieve and dried at 105°C (Angers et al., 2008). Samples were weighed and proportions for each aggregate size were determined. Duplicates were combined and ground finely using a ball mill grinder.

Carbon

Carbon analyses included total C, inorganic carbon (IC), and OC for all three depths; OC was also determined for each of the aggregate size fractions. Water extractable organic carbon, LF, and HF were determined for the 0 to 15 cm depth. Total C was determined by combustion at 1100ºC with a LECO C632 carbon combustion analyzer (LECO Corporation, St. Joseph, MI). For OC, a separate sample was pretreated with HCl to remove carbonates and then analyzed the same way as total C. Inorganic C was determined by difference (Skjemstad and Baldock, 2008). Carbon equivalency values were determined based on fixed mass using bulk density for better comparisons among wetlands (Ellert and Bettany, 1995). For WEOC, soils were thawed and sieved to pass 4.5 mm. A slurry was created by mixing a 5 mM $CaCl_2$ solution with a subsample of soil. Slurries were filtered through a 0.45 µm Millipore filter (Whatman Inc., Piscataway, NJ) and analyzed for dissolved organic C using a Shimadzu TOC-VCPN analyzer (Shimadzu Scientific Instruments, Columbia, MD) (Chantigny et al., 2008). The LF was determined by adding dried, unground subsamples to a dense liquid solution of NaI. Samples were shaken for 1 h and transferred to beakers at room temperature for 2 d. This allowed for LF to settle out in the top 25 mL of solution where it could be aspirated and then filtered through a 0.45 µm Millipore filter. After NaI was removed from HF by filtering, HF was washed and collected. Both LF and HF were dried, weighed, finely ground, and analyzed for total C and total N by combustion with a LECO TruMac CNS Analyzer (Six et al., 1998; Gregorich and Beare, 2008). Due to small sample sizes, LF samples were combined per site prior to C and N analysis.

Nitrogen

Additional N analyses included total N, net mineralization, and potential nitrification for the 0 to 15 cm depth. Total N was determined by combustion as described for LF above. Net mineralization was determined using a short-term aerobic incubation. Frozen samples were thawed and sieved to pass 4.75 mm. A subsample of 5 g was extracted with KCl to determine inorganic N at time=0. Another subsample was added to polypropylene containers that were covered with pierced Parafilm M® (Bemis Company Inc, Neenah, WI). Containers were placed in trays containing water and covered with plastic in order to maintain high humidity. Soils were incubated at 20ºC for 28 d and were weighed daily to ensure field moist conditions were maintained. Final inorganic N was determined again at the end of the incubation (Curtin and Campbell, 2008). Net mineralization was calculated as the difference between final and time=0 inorganic N and then divided by 28 d. Potential nitrification was determined using the shaken soil-slurry method. Frozen samples were thawed and sieved to pass 4.75 mm.

Soil samples were added to bottles that were covered with pierced Parafilm M® (Bemis Company Inc, Neenah, WI) in order to allow for gas diffusion. A working solution was added to each bottle with an ample supply of NH_4^+, and bottles were shaken while incubated at 20ºC. Subsamples were collected at 2, 6, 20, and 24 h, and analyzed for NO_3^- by colorimetry. The NH_4^+ was also measured to ensure it did not become limiting (Drury et al., 2008). Potential nitrification was calculated by multiplying the slope of NO_3^- measured throughout the experiment by 24 h.

Phosphorus

Phosphorus sorption and desorption was measured for the 0 to 15 cm depth. This analysis gives an idea of the soils ability to hold onto and release P. A KCl solution containing 50 mg P L^{-1} was added to soil. Two drops of toluene were added to inhibit microbial activity and tubes were shaken for 24 h. Tubes were centrifuged and supernatant filtered. Residual material was washed twice with 95% alcohol solution to remove free PO_4^{-3}. A KCl solution containing no P was added to tubes containing residual material and shaken again for 24 h. Samples were centrifuged and supernatant filtered. Samples were then analyzed for PO_4^{-3} by colorimetry (Nair and Reddy, 2013).

3.4.3 Statistical analysis

Statistical analyses were performed using SAS version 9.4 (SAS Institute, 2014). One-way ANOVAs were performed to determine differences in soil properties across different drainage categories. Additionally, paired comparisons were completed for SOC, available N, and available P: wetland values were subtracted from their paired midslope, and ANOVAs were run on differences. Tukey Kramer test was used for mean comparisons. If data were not normally distributed, a log transformation was applied to make data more normal. Statistical significance was deemed to be too conservative at the 0.05 probability level for this study. Although great effort was put forward to obtain suitable replicates that fit the developed criteria, finding exact replicates of hydrological and pedological features is impossible (Bedard-Haughn et al., 2006). Due to inherent variability of wetlands soils, statistical significance was declared at $p<0.10$.

3.5 **Results**

3.5.1 General soil properties

Figure 3.4 provides an overall summary of the soil profile descriptions from the 84 sampling locations. The majority of wetland soils were classified as Humic Luvic Gleysols or Orthic Humic Gleysols. Midslopes were classified as Calcareous Black Chernozems or Orthic Black Chernozems. All 0 to 15 cm depth increments fell within an A horizon, whereas 15 to 30 cm and 30 to 60 cm increments had varying proportions of A, B, and C horizons. MS soils had greater proportions of C horizon within samples collected for analysis. The average A horizon depth varied across drainage categories (UD: 24.2 cm, RD: 28.0 cm, MD: 33.5 cm, LD: 32.0 cm and MS: 24.1 cm). Soil pH and EC were consistent across all sites and depths (Table 3.1). The pH was basic (ranging from 7.6 to 8.4), and EC values were considered non-saline (<2000 µs cm^{-1}) (Saskatchewan Soil Survey, 1991). Bulk density was similar across categories at lower depths, but increased with duration of drainage at 0 to 15 cm. At 0 to 15 cm, bulk density was significantly lower in UD than drained soils and MS (p=0.0004). Glacial till parent material was present across all sites and the dominant soil texture was clay loam.

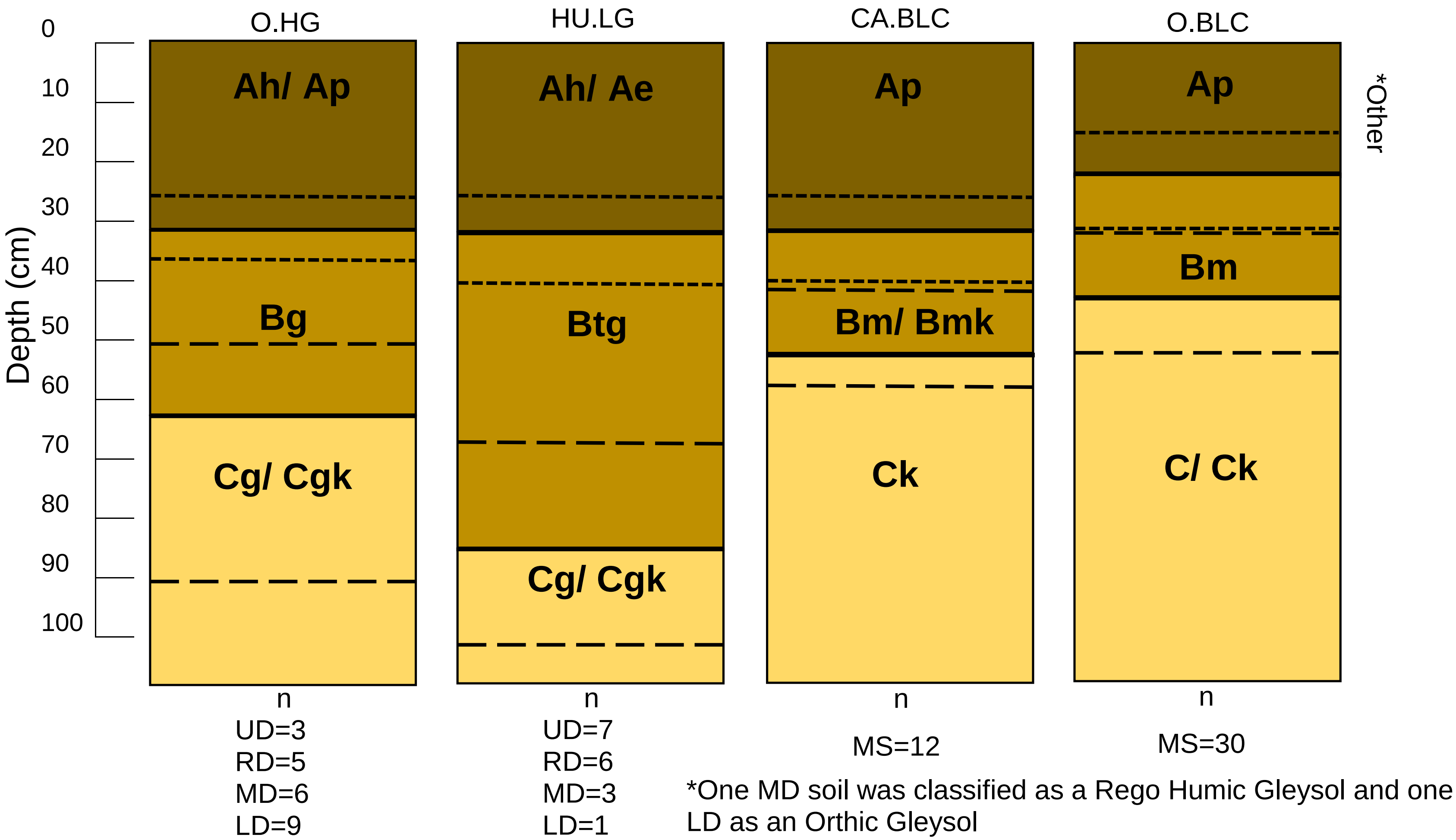

Figure 3.4 Soil profile description summaries of the 42 wetlands and midslopes sampled. The solid line represents the median depth. The dashed lines represent the 25th and 75th percentile lower depth of the A (- - -) and B (— —) horizon. Profile descriptions were completed to a depth of 100 cm. Classifications are based on the Canadian System of Soil Classification. O.HG=Orthic Humic Gleysol, HU.LG=Humic Luvic Gleysol, CA.BLC=Calcareous Black Chernozem and O.BLC=Orthic Black Chernozem. UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained and MS=midslope.

Table 3.1 Basic soil properties across wetlands drained for different durations of time and corresponding midslopes.

Depth (cm)	Drainage category†	pH		EC (μS cm^{-1})	Bulk density (g cm^{-3})	Texture (%)			
							Sand	Silt	Clay
		N	Mean	Mean	Mean	N	Mean		
0-15	UD	10	7.8 (0.1)‡	590.0 (532.5)	1.20 (0.27)	10	39 (5)	32 (5)	29 (3)
	RD	11	7.7 (0.3)	430.8 (341.3)	1.38 (0.16)	7	39 (8)	33 (6)	28 (3)
	MD	10	7.7 (0.2)	715.1 (589.2)	1.39 (0.11)	5	36 (8)	33 (5)	31 (4)
	LD	11	7.8 (0.3)	625.5 (691.7)	1.42 (0.10)	7	34 (9)	37 (14)	29 (7)
	MS	42	7.7 (0.3)	338.8 (626.0)	1.46 (0.13)	9	42 (5)	26 (6)	32 (4)
15-30	UD	10	7.9 (0.1)	346.3 (261.2)	1.61 (0.23)	10	39 (7)	30 (6)	31 (5)
	RD	11	7.7 (0.5)	229.3 (168.7)	1.72 (0.21)	7	40 (14)	31 (8)	29 (9)
	MD	10	7.6 (0.3)	635.1 (344.3)	1.65 (0.28)	5	27 (9)	39 (7)	34 (6)
	LD	11	7.8 (0.3)	656.4 (671.1)	1.62 (0.25)	7	31 (8)	37 (7)	32 (2)
	MS	42	8.1 (0.2)	288.3 (481.2)	1.62 (0.14)	9	41 (6)	28 (4)	31 (4)
30-60	UD	10	8.0 (0.2)	273.6 (179.4)	1.73 (0.18)	10	39 (13)	24 (7)	37 (9)
	RD	11	7.7 (0.3)	250.1 (188.2)	1.78 (0.07)	7	43 (13)	26 (11)	31 (6)
	MD	10	7.7 (0.3)	530.1 (337.9)	1.78 (0.09)	5	28 (15)	33 (11)	39 (7)
	LD	11	7.8 (0.3)	517.5 (433.4)	1.72 (0.11)	7	28 (12)	34 (13)	38 (6)
	MS	42	8.4 (0.2)	430.6 (540.7)	1.66 (0.10)	9	41 (7)	27 (3)	32 (5)

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Mean (SD) are reported for each drainage category.

3.5.2 Aggregate size distribution

Wet aggregate size distribution was used as a measure of size and strength, as well as an indicator of C quality (Fig. 3.5A). All soils had greater proportions of macroaggregates (250-2000 and >2000 μm) than microaggregates (<53 and 53-250 μm). Proportion of macroaggregates increased in drained soils compared to UD, but these increases were not significant (Fig. 3.5A). The MS was significantly different ($p<0.0001$) from all wetland categories with a lower proportion of >2000 μm aggregates and a greater proportion of 250 to 2000 μm aggregates. The opposite trend occurred for microaggregate fractions and was significant ($p<0.0001$ and $p=0.0005$). Proportion of microaggregates decreased in drained soils compared to UD. For the 53 to 250 μm fraction there were no significant differences between MS and UD. The MS was only similar to drained soils for the <53 μm fraction.

The finest fraction (<53 μm) had the highest concentration of OC but when proportion of soil within aggregate fractions was considered (Fig. 3.5A), the greatest OC was held in the >2000 μm fraction (Fig. 3.5B). In this fraction, there were no significant differences between drained and undrained soils, but MS had less OC ($p<0.0001$). The lowest amount of OC was held in the finest aggregate fraction with UD having greater OC than drained soils and MS ($p=0.0003$).

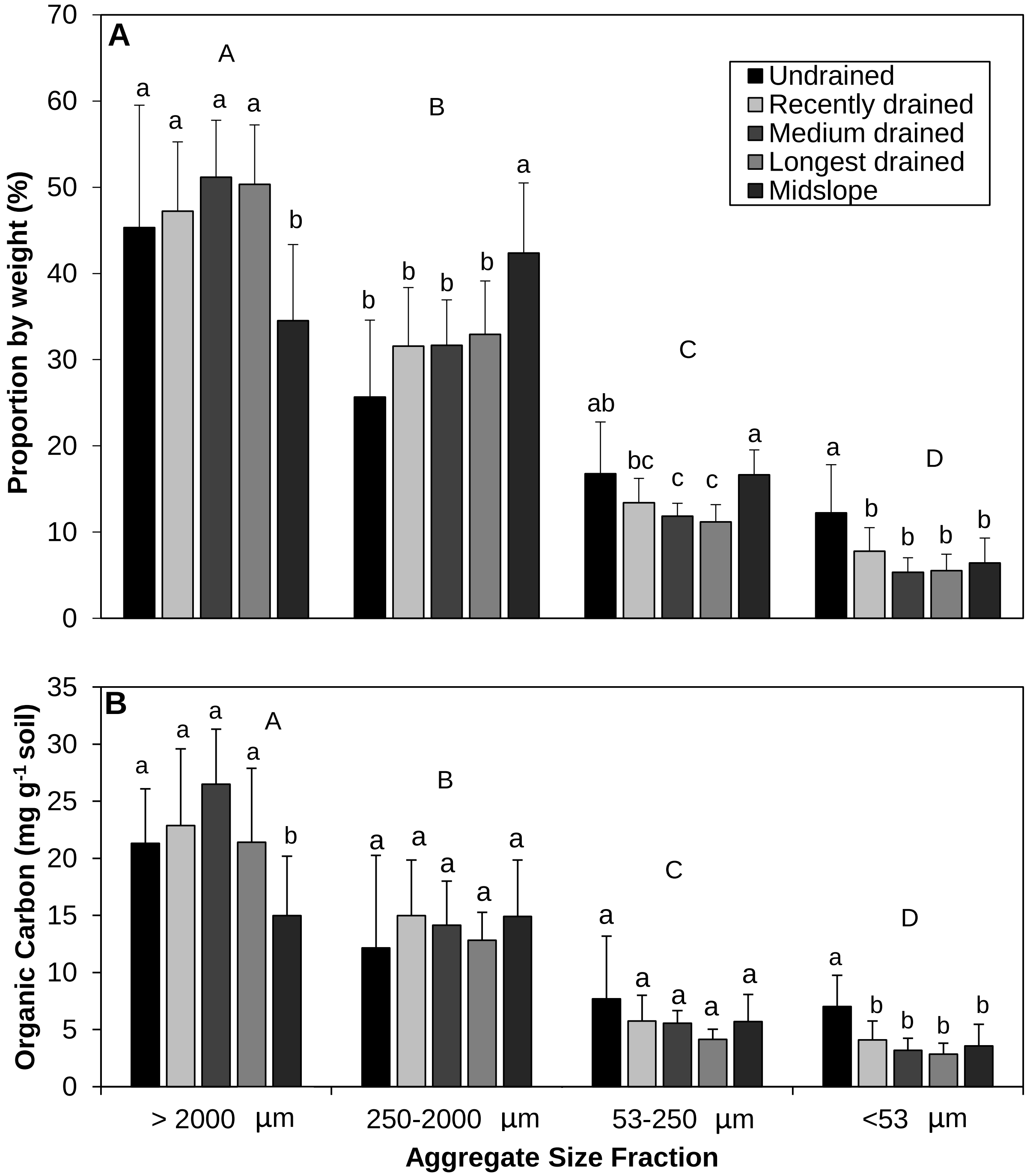

Figure 3.5 A) Comparison of wet aggregate size distribution and B) organic carbon within the size fractions in surface soil (0-15 cm) across drained wetlands and paired midslope soils. Error bars represent standard deviation and letters represent significant difference according to Tukey Kramer test ($p<0.10$). Upper case letters represent significance across the different fractions. Lower case represent significance of drainage categories within each fraction.

3.5.3 Carbon

Various fractions and forms of C were analyzed (Table 3.2-3.4). Carbon decreased with depth except for IC, which increased at 30 to 60 cm and was significantly greater in the MS ($p<0.0001$) (Table 3.2). At 0 to 15 cm, all forms of C were greater in wetland soils compared to MS. Organic C remained consistent following drainage in RD and MD categories but decreased in LD, becoming more similar to MS ($p=0.0005$). At 30 to 60 cm, LD and MS had significantly higher amounts of OC than RD. However, variability was much higher for the LD compared to other categories. Soil OC based on fixed mass was further separated into more precise drainage categories for the 0 to 15 cm depth (Table 3.3). Here it appears SOC increases initially rather than remains consistent, with the exception of the RD site drained for 7 years. This initial increase (or consistency for OC) in RD and MD soils followed by a decrease in LD soils is a trend across some properties measured in this study and will be referred to throughout the remainder of the chapter as the increasing-decreasing trend. Water extractable organic carbon did not differ among wetland soils, but all were significantly greater than MS ($p<0.0001$).

Low amounts of LF were collected (≤1.02%) (Table 3.4). Light fraction was greatest in UD, and lowest in MS ($p=0.0050$). The opposite occurred for HF. It appears that HF increased with drainage while LF decreased. The UD and MS were significantly different, but there were no statistical differences among drained wetlands. The C: N ratios were higher in LF than HF. There were no significant differences for % C, % N or C: N for LF, but significant differences occurred for HF. Within the HF, MD had significantly higher C than MS, and RD and MD had significantly higher N and lower C: N ratio than MS.

Table 3.2 Carbon fractions of drained wetlands and paired midslopes.

Depth (cm)	Drainage category†	N	Total C (g kg^{-1})	Inorganic C (g kg^{-1})	Organic C (g kg^{-1})	Organic C fixed mass (Mg C ha^{-1})	WEOC (mg C kg^{-1})¶
		N	Mean				
0-15	UD	10	48.8^{a} (13.2)‡	3.5^{ab} (3.0)	45.2^{a} (11.2)	49.2^{a} (12.1)	46.1^{a} (18.9)§
	RD	11	48.6^{a} (13.1)	1.4^{bc} (2.5)	47.2^{a} (12.5)	51.3^{a} (13.6)	41.9^{a} (12.9)
	MD	10	49.8^{a} (8.1)	2.3^{abc} (3.0)	47.5^{a} (6.7)	51.6^{a} (7.3)	45.3^{a} (13.4)
	LD	11	43.6^{ab} (6.7)	5.4^{a} (10.8)	38.1^{ab}(11.2)	41.5^{ab}(12.2)	41.6^{a} (11.8)
	MS	42	36.8^{b} (8.3)	0.8^{c} (2.0)	36.0^{b} (8.7)	39.1^{b} (9.5)	27.1^{b} (11.4)
15-30	UD	10	20.4 (16.7)	1.1 (1.1)	19.3 (15.7)	29.4 (23.9)	ND
	RD	11	16.9 (12.8)	0.9 (2.7)	16.0 (10.7)	24.3 (16.3)	ND
	MD	10	26.7 (23.2)	1.0 (2.9)	25.7 (21.3)	39.2 (32.5)	ND
	LD	11	24.6 (15.0)	1.6 (2.4)	23.0 (13.1)	35.1 (19.9)	ND
	MS	42	20.1 (8.8)	3.7 (5.8)	16.4 (8.0)	24.9 (12.2)	ND
30-60	UD	10	8.9^{b} (6.1)	3.7^{b} (6.5)	5.2^{ab} (0.9)	20.4^{ab} (3.5)	ND
	RD	11	7.7^{b} (8.5)	2.8^{b} (8.7)	4.9^{b} (0.9)	19.2^{b} (3.6)	ND
	MD	10	6.7^{b} (3.8)	0.9^{b} (3.1)	5.8^{ab} (2.8)	22.9^{ab}(11.1)	ND
	LD	11	12.8^{b} (9.5)	5.0^{b} (8.1)	7.9^{a} (5.3)	30.9^{a} (20.8)	ND
	MS	42	25.6^{a} (9.1)	18.9^{a} (9.2)	6.6^{a} (1.8)	26.1^{a} (7.3)	ND
			P values				
0-15			<0.0001	0.0006	0.0005	0.0005	<0.0001
15-30			0.4397	0.1872	0.3403	0.3403	ND
30-60			<0.0001	<0.0001	0.0129	0.0129	ND

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Mean (SD) are reported for each drainage category.
§Means with same letter in same column and depth are not significantly different according to Tukey Kramer test (P>0.10).
¶WEOC=water extractable organic carbon. WEOC was only determined for surface soil (0-15 cm)

Table 3.3 Soil organic carbon (SOC) in surface soils (0-15 cm) of drained wetlands for different durations of time and paired midslopes.

Drainage category†	Drainage age‡ (yr)	n	SOC equivalent mass (Mg C ha^{-1})
UD	0	10	49.2 (12.1)§
RD	7	4	41.7 (11.8)
	14	4	59.6 (9.6)
	15	3	53.0 (16.0)
MD	20	3	49.6 (7.9)
	34	7	52.5 (7.4)
LD	36	3	41.0 (7.8)
	42	4	47.0 (3.7)
	50	4	36.3 (19.2)
MS	N/A¶	42#	39.1 (9.5)

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Each drainage age represents one site of the study with the exception of 2 sites that have both been drained for 34 years.
§Mean (SD) are reported for each drainage category.
¶MS category have never been drained.
#A MS was selected for each wetland and includes samples from all sites.

Table 3.4 Density fractionation and % carbon and nitrogen within fractions of drained wetlands and corresponding midslopes.

Drainage category†	N	Density		LF				HF			
		% HF‡	% LF	n	% C	% N	C:N	N	% C	% N	C:N
UD	10	99.0^{b} (0.009)	1.02^{a} (0.281)	3	21.2 (3.3)	1.1 (0.2)	20.2 (2.6)	10	4.8^{a} (1.3)	0.33^{a} (0.1)	14.8^{abc} (0.9)
RD	11	99.3^{ab}(0.003)	0.70^{ab}(0.010)	3	22.2 (4.5)	1.2 (0.2)	18.8 (0.4)	11	4.7^{ab}(1.3)	0.35^{a} (0.1)	13.9^{c} (1.5)
MD	9	99.2^{ab}(0.007)	0.82^{ab}(0.020)	3	23.1 (2.2)	1.3 (0.1)	17.6 (0.6)	10	4.9^{a} (0.8)	0.36^{a} (0.1)	13.8^{bc} (0.8)
LD	11	99.4^{ab}(0.003)	0.56^{ab}(0.009)	3	19.7 (2.3)	1.1 (0.1)	18.0 (1.3)	11	4.4^{ab}(0.7)	0.29^{ab}(0.1)	15.8^{ab} (2.8)
MS	37	99.6^{a} (0.002)	0.44^{b} (0.015)	12	18.4 (5.1)	1.1 (0.1)	18.5 (1.3)	41	3.8^{b} (0.8)	0.25^{b} (0.1)	15.8^{a} (1.8)
P value		0.0050	0.0050		0.3672	0.2003	0.2018		0.0012	0.0005	0.0016

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡HF=heavy fraction soil, LF=light fraction soil.
§Mean (SD) are reported for each drainage category.
¶Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.10)

3.5.4 Macronutrients

Available N, P and K all decreased with depth (Fig. 3.6; Appendix Table A.3). Soil NH_4^+ (mg kg^{-1}) was low throughout the profile except for UD at 0 to 15 cm, which was approximately three times greater than other drainage categories (p=0.0006). At 30 to 60 cm, UD had significantly lower PO_4^{-3} (p=0.006) than all other drainage categories. At all depths, wetland soils had approximately twice as much soil K as the MS (p<0.0001). Similarly, K (p<0.0001), PO_4^{-3} (p<0.0001), and NO_3^- (p=0.2636) followed the increasing-decreasing trend at 0 to 15 cm and became more similar to MS (Fig. 3.6).

Paired comparisons were used to better understand differences between wetland soils and their paired MS (Fig. 3.7). At 0 to 15 cm, significant differences were present for SOC (p=0.0205) and available P (p=0.0262). The SOC of LD soil appeared to be most similar to MS, whereas MD soils had a greater amount of SOC than their paired MS. Soil PO_4^{-3} of UD was most similar to MS. The MD had significantly greater PO_4^{-3} than their MS pair. Drained wetlands had very similar amounts of NH_4^+ and NO_3^- compared to their MS pairs. For NH_4^+, the median of UD was similar to MS, but there was high variability with some UD wetlands having much greater concentrations of NH_4^+ than their MS. There were no other significant differences at lower depth increments (not shown) except between UD and LD for NO_3^- at 30 to 60 cm (p=0.0270). The UD had lower concentrations of NO_3^- than MS with difference decreasing between drained soils and MS with drainage duration. The LD was most similar to MS.

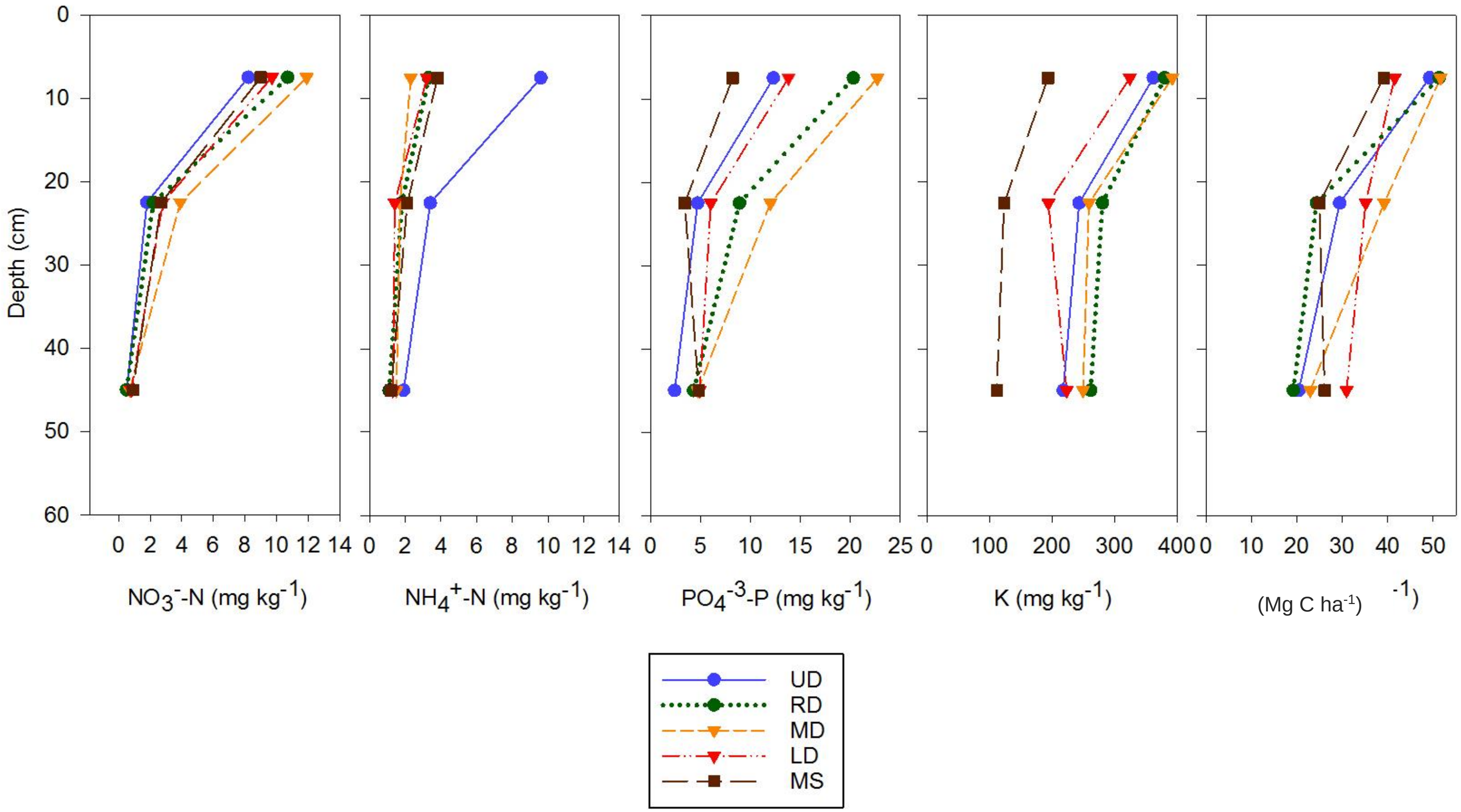

Figure 3.6 Mean profile comparison (representing depths 0-15, 15-30, and 30-60 cm) of available N, P, and K, and SOC based on fixed mass for drainage categories and paired midslopes. UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.

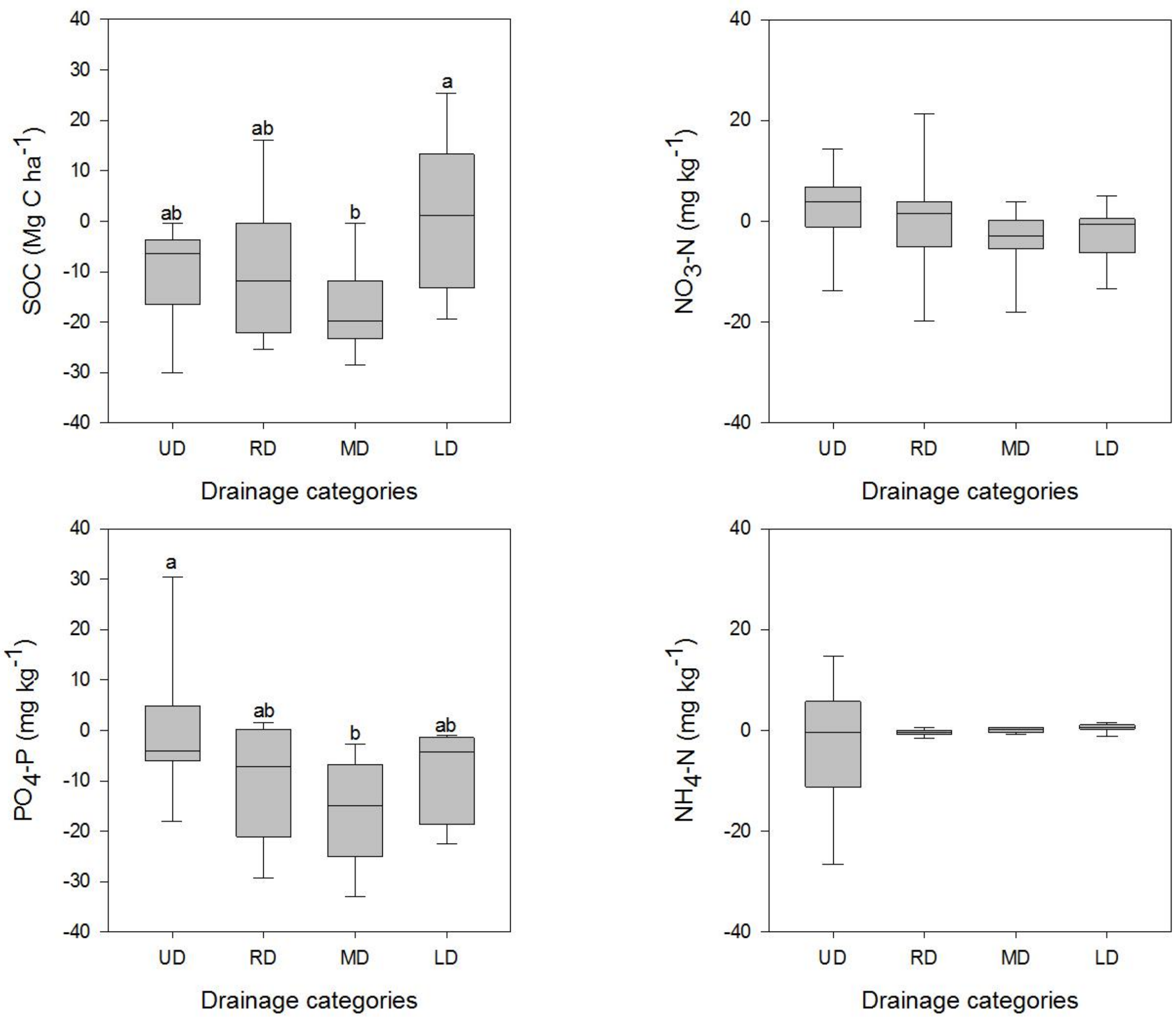

Figure 3.7 Paired comparisons of SOC, PO_4^{-3}, NO_3^-, and NH_4^+ in surface soils (0-15 cm) of drained wetlands compared to midslope pairs. Values close to 0 indicate wetland soil is similar to paired MS. Positive values indicate MS is greater than wetland soil, and negative values indicate wetland soil is greater than MS. Letters above boxplots represent significance according to Tukey Kramer test (P<0.10). UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained and MS=midslope.

3.5.5 Nitrogen processes

Total N was significantly higher in wetland soils compared to the MS, except for LD, which decreased and became more similar to MS (p=0.0001; Table 3.5). Net mineralized N was higher in wetland soils than the MS with MD being significantly higher than MS (p=0.0011). Field moist conditions used for net mineralization varied across drainage categories (UD: 44 ± 15; RD: 29 ± 6; MD: 30 ± 3; LD: 30 ± 7; MS: 25 ± 5) (mean % ± standard deviation). Potential nitrification followed the increasing-decreasing trend (p<0.0001). The UD soil had the highest available NH_4^+, but lowest available NO_3^- and potential nitrification. The MD had the highest available NO_3^-, mineralized N, and potential nitrification.

Table 3.5 Nitrogen properties of drained wetlands and corresponding midslopes.

Drainage category†	n	Total N (g kg^{-1})	Available NH_4^+-N (mg kg^{-1})	Available NO_3-N (mg kg^{-1})	Net Mineralized N (mg kg^{-1}d^{-1})	Potential Nitrification (mg kg^{-1}d^{-1})
UD	10	3.3^{a} (1.0)‡§	9.6^{a} (9.9)	8.2 (6.4)	0.25^{ab} (0.39)	35.0^{c} (16.0)
RD	11	3.5^{a} (1.2)	3.3^{b} (1.1)	10.7 (7.8)	0.18^{ab} (0.12)	46.7^{bc} (17.3)
MD	10	3.5^{a} (0.6)	2.3^{b} (0.3)	11.9 (5.9)	0.38^{a} (0.30)	74.4^{a} (29.4)
LD	11	2.9^{ab}(0.7)	3.2^{b} (1.1)	9.7 (5.9)	0.24^{ab} (0.15)	54.7^{ab} (14.5)
MS	42	2.4^{b} (0.8)	3.8^{b} (3.1)	9.0 (5.2)	0.11^{b} (0.17)	38.9^{c} (16.2)
P value		0.0001	0.0006	0.2636	0.0277	<0.0001

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Mean (SD) are reported for each drainage category.
§Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.10).

3.5.6 Phosphorus processes

The UD soil had greatest P sorption compared to drained soils and MS (p=0.0181). The P desorption varied among drainage categories and followed a similar trend as available PO_4^{-3} (Table 3.6). Desorption was greatest for MD and significantly different from UD, LD, and MS (p<0.0001). The UD and MS soils had the lowest desorption.

Table 3.6 Phosphorus properties of drained wetlands and corresponding midslopes.

Drainage Category†	n	Available PO_4^{-3}-P (mg kg^{-1})	P sorption (mg PO_4^{-3}-P kg^{-1})	P desorption (mg PO_4^{-3}-P kg^{-1})
UD	10	12.3^{bc} (9.2)‡§	597.1^{a} (50.6)	44.1^{c} (8.4)
RD	11	20.3^{ab} (12.8)	586.9^{ab} (44.7)	55.7^{ab} (11.7)
MD	10	22.7^{a} (11.5)	571.4^{b} (36.3)	61.1^{a} (12.6)
LD	11	13.8^{ab} (8.5)	573.6^{b} (26.7)	46.0^{bc} (5.4)
MS	42	8.2^{c} (6.8)	569.8^{b} (23.2)	45.0^{c} (7.0)
P value		<0.0001	0.0181	<0.0001

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Mean (SD) are reported for each drainage category.
§Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.10).

3.6 **Discussion**

3.6.1 General soil properties

Agricultural surface drainage appears to change soil properties over time. Some of these changes may be beneficial, while others may be undesirable. At 0 to 15 cm, drainage appears to increase bulk density (Table 3.1). A British Columbia study found drainage to decrease bulk density, whereas other studies in Ohio found no differences (Baker et al., 2004; Hundal et al., 1976). These latter studies and more have found increases in porosity or improvements in structure, which could be expected to equate to a decrease in bulk density (Montagne et al., 2009; Kumar et al., 2014). A study in the Dark Brown soil zone found undrained, cultivated wetlands to have a higher mean bulk density of 1.2 g cm^{-3} compared to uncultivated wetlands bulk density of 0.7 g cm^{-3} (Bedard-Haughn et al., 2006). It may be possible that other factors are counteracting benefits of improved structure and porosity on bulk density. Lower bulk densities are usually associated with higher organic matter. The increase in bulk density in our study may be a result of greater decomposition associated with improved aerobic conditions, followed by a removal of C with crop harvest. The equipment used on these still relatively wet, fine-textured soils can also increase bulk density due to compaction (Hamza and Anderson, 2005).

3.6.2 Aggregate size distribution

Tillage operations may be responsible for the lack of statistical difference in macroaggregates and the decline in microaggregates following drainage (Fig. 3.5A). During wet years, tillage of whole fields, drained wetlands, or ditches occurs in an attempt to allow soil to dry out before seeding the following year. It is well understood that tillage reduces aggregation, increases aggregate turnover times, and increases decomposition of SOM due to loss of physical protection offered by aggregates (Six et al., 1998; Denef et al., 2001; Stockmann et al., 2013; Kumar et al., 2014; Six et al., 2004; Tan et al., 2007). Although drainage can increase macroaggregates (Kumar et al., 2014), tillage disruption in this area may be counteracting any increases in macroaggregate formation. Subsequent tillage that can occur following drainage may be increasing macroaggregate turnover time compared to UD, which is not cultivated as often as the drained wetlands. Quicker turnover time could explain the decline in microaggregates with drainage duration due to greater losses of SOC, less protection offered from macroaggregates, and decreased formation of new microaggregates. Since C held within microaggregates is considered to be more stable and recalcitrant, the decline in proportion of microaggregates could be problematic in terms of carbon storage. A study in Southwestern Ontario found that conventional tillage combined with tile drainage is more disruptive to soil structure than no tillage combined with tile drainage (Tan et al., 1998). In order to slow down macroaggregate turnover and reduce loss of microaggregates, it may be wise to avoid tillage of drained soils. Reducing tillage operations can also improve structure due to reduced compaction, and increase infiltration further improving drainage (Bedard-Haughn, 2009; Bedard-Haughn, 2011).

Since macroaggregates consist of microaggregates, bound together by organic material like roots and polysaccharides, C concentration increases with aggregate size (Six et al., 2000). Previous research in tropical and temperate regions suggest that areas of natural vegetation or pasture have greater proportions of SOC in macroaggregates (500 µm or larger) versus cultivated land or fallow fields that would have a greater proportion of SOC in finer aggregates. Cultivated fields are expected to have greater OC within microaggregates due to lower proportions of macroaggregates, which have been disrupted by cultivation (Bajracharya et al., 2008). However, this research shows greater proportions of OC to be held within macroaggregates and also shows a decrease in microaggregate SOC with time (Fig. 3.5B). This may suggest that these soils are not disrupted enough to see the transformation of a more macroaggregate dominance to a microaggregate dominance. Our results may differ from these other studies due to the high clay content and OM of these wetland soils.

3.6.3 Carbon

Quantity and quality of whole soil C are major factors that influence other soil properties. At 0 to 15 cm, all fractions of C were greater in wetland soils than MS (Table 3.2). The anaerobic conditions that exist in wetlands allow for an accumulation of SOM due to slower decomposition rates (Bedard-Haughn, 2009; Neuman and Belcher, 2011). Organic C remained consistent, with even a small increase in RD and MD soils, but decreased in LD soils. However, when drainage categories are divided into individual drainage ages, SOC at the site drained for 7 years is as low as LD and MS categories (Table 3.3). This suggests that there may be some other factor influencing SOC at this particular site, and SOC may actually be greater in the RD category. The landowners had indicated, after sampling, that this quarter section of land had experienced recent flooding.

Overall, SOC decreased after 34 years of drainage in this region. Other studies have also measured lower SOC in drained wetlands versus undrained (Kumar et al., 2014; Sullivan et al., 1998; Streeter and Schilling, 2015). This decrease in SOC is likely a result of increased decomposition due to aerobic conditions and removal of C due to annual cropping (Ewing et al., 2012). The slight increase in SOC may have resulted due to ploughing in and burning of wetland vegetation during the drainage process, since burning and cultivation can increase SOC through incorporation of ash and remaining unburned material (Nelson et al., 2007).

Interestingly, OC at depth is greater in MD, LD, and MS than UD and RD soils, with LD and MS being significantly greater than RD (Table 3.2). Previous studies have found greater C can be stored with depth in cultivated soils due to increased infiltration allowing for OC to be transported deeper (Cihacek and Ulmer, 1998). However, a more likely explanation for these drained soils may be erosion associated with tillage translocation leading to an accumulation of C-rich soil at the surface. Across Canadian agroecosystems, erosion of soil from upslope landscape positions is transferred downslope where it is deposited, causing A horizons to thicken. In Prairie Provinces this erosion is largely caused by tillage operations, with depositional locations tending to have similar surface OC concentrations to the upslope where the soil originated from (Vandenbygaart et al., 2012). The MD and LD soils that have been in continuous agricultural production longer have thicker average A horizons; MD and LD averages are 5.5 cm and 4.0 cm greater than RD average. Since sampling for this project was based on depth and not horizons, the 30 to 60 cm sampling depth is likely capturing more A and B horizons that have greater OM than less developed parent material C horizons. Although most soil is redistributed close to the source within the same field, rates of OC deposition in off field and riparian soil profiles have also been found to be similar to depositional positions within field, suggesting that water and wind are also contributing to redistribution of soil (Vandenbygaart et al., 2012). However, the MS has a similar average depth of A horizon as UD, but has greater OC at depth. Increased infiltration may be responsible for greater OC at depth in the MS. The higher slope position and sand content of the MS can allow for greater water movement across and down through the soil allowing for increased infiltration. Translocation by water movement and burial by tillage erosion may help to store SOM at depth due to reduced decomposition and mineralization as a result of increased anaerobic conditions, greater compaction, cooler temperatures, and lower abundance and decreased activity of microorganisms (Bedard-Haughn et al., 2006; Vandenbygaart et al., 2012).

The more labile fractions of SOC are useful for determining changes in carbon quality and are more responsible for affecting C and N fluxes in soil. These fractions are also more sensitive to land use changes (Tan et al., 2007; Kumar et al., 2014). There were no significant differences between drained soils and undrained soils for WEOC suggesting that drainage is not affecting this fraction of C over time (Table 3.2). There are higher amounts of this labile OC fraction in wetland soils versus MS soil. This may once again be due to high SOM that had accumulated in wetlands prior to drainage. Light fraction carbon is believed to be very sensitive to cultivation. The HF is proportional to the LF and represents a more mineral associated, recalcitrant form of C

(Kumar et al., 2014; Tan et al., 2007). Although low amounts of LF were measured, there was still a statistically significant decrease in LF with drained soils becoming more similar to MS (Table 3.4). The higher C: N ratio of the LF would be expected as LF is partially decomposed plant material and contains higher concentrations of C than HF (Tan et al., 2007; Vandenbygaart et al., 2012). There were no significant changes of C and N within LF, but the increasing-decreasing trend, which was noted previously with OC, occurs with both C and N for HF.

Organic C decreased with depth, but IC increased at 30 to 60 cm (Table 3.2). There was no difference between drained soils and UD, but MS had higher concentrations at lower depths. The carbonates present in the PPR originate from Paleozoic limestone in clay rich parent material that was deposited during the last glaciation (Pennock et al., 2014; Naschon et al., 2013). As water slowly percolates downwards, water dissolves carbonates and other soluble salts and moves them to lower depths (Pennock et al., 2014; van der Kamp and Hayashi, 2009). Wetland soils are located in depressions within the landscape where greater water accumulates and moves downwards, thus allowing carbonates to be leached to lower depths than the MS. Almost all wetland soils sampled in this study are believed to be within recharge zones where water moves vertically downwards, with exception of the discharge ring surrounding the wetland edge. The few discharge wetlands would have carbonates throughout due to movement of water bringing soluble salts and carbonates to the surface (Pennock et al., 2014; van der Kamp and Hayashi, 2009; Bedard-Haughn and Pennock, 2002; Pennock et al., 2011). These wetlands could account for some of the variability across soil properties measured. Since location of sampling was at the wetland edge, the slightly higher concentrations of IC at the surface of wetland soils may be due to cultivation and translocation of soil from the surrounding discharge zone. Carbonates at surface could also be evidence of slight infill during drainage construction, however, there were no significant differences between UD and drained soils.

3.6.4 *Macronutrients*

All macronutrients were higher at the surface and decreased with depth, with minimal differences among drainage categories at lower depths (Fig. 3.6). In contrast, Ewing et al. (2012) found that greater nutrients were present deeper in the profile as drainage duration increased, with changes occurring as deep as 1 m after 30 years of drainage. Although drainage duration for our study was up to 50 years, there were no significant differences between UD and duration of drained wetlands at lower depths except for PO_4^{-3}, which was significantly greater in drained soils and MS at 30 to 60 cm. However, available PO_4^{-3} did not increase with drainage duration, suggesting there is not an accumulation with time due to leaching. Ewing's study was located in a warmer, wetter climate with sandier soils, whereas here there is a cooler climate, low hydraulic conductivity, high clay content, and less precipitation, which would likely result in less water movement downwards and less leaching of nutrients. However, paired comparisons at 30 to 60 cm indicated that NO_3^-, a very mobile nutrient, did increase and became more similar to MS with drainage duration. This finding suggests that drainage duration could cause changes in lower depths with time.

Nitrogen

Nitrogen pools differed among drainage categories (Fig. 3.6). Soil NH_4^+ was likely higher in UD soils due to anaerobic conditions preventing conversion of NH_4^+ to NO_3^- through nitrification. Drained soils and MS had greater NO_3^- and lower NH_4^+ due to greater aerobic conditions. Changes in processes, such as mineralization and nitrification, can affect availability of NH_4^+ and NO_3^-. Since mineralization occurs faster under warmer and more aerobic conditions (Booth et al., 2005), drainage would be expected to increase mineralization, resulting in greater NH_4^+ substrate. This could then lead to increased nitrification due to greater substrate and aerobic conditions (Venterink et al., 2002). Previous studies have found that drying of wetland soils increases inorganic N and DON, and triples mineralization rates, with increases of inorganic N availability largely due to greater mineralization (Venterink et al., 2002). Although there were no clear differences between drained and undrained wetlands in this study for net mineralization, potential nitrification was greater in drained soils suggesting the greater proportion of NO_3^- over NH_4^+ is due to increased nitrification (Table 3.5). Some studies have also suggested higher extractable nutrients in drained versus undrained soils to be a result of fertilizer application following drainage (Ewing et. al., 2012; Streeter and Schilling, 2015). This could be contributing to the greater presence of NO_3^- observed in our study. Denitrification was not measured in this study but conversion of NO_3^- to N gasses is likely diminished under drainage.

Moisture, quantity and quality of substrate, and microbial communities are major influencing factors of mineralization, nitrification, and availability of inorganic N. As discussed, flooded soils can decrease mineralization, but very dry conditions can also slow down mineralization. Shoulder positions in a hummocky landscape are usually drier and have lower SOC. As a result, mineralization is reduced in these upslope positions and available N decreases (Noorbakhsh et al., 2008). However, these upper slopes typically have higher rates of nitrification compared to lower slopes (Bedard-Haughn et al., 2006). Although MS had low net mineralization and potential nitrification in our study, available NO_3^- was still comparable to levels in wetland soils. Since field moist soils were used for net mineralization, some mineralized N rates may have been over and underestimated. The UD soils had a higher water content (average 44% field moisture) than drained soils, and MS had the lowest water content (average 25% field moisture). Consequently, UD net mineralization may have been overestimated because nitrification was restricted, while MS may appear lower because greater NH_4^+ was consumed by nitrification. Drained wetland soils may have higher net mineralization rates than MS due to greater SOM. Quantity and quality of SOC may also explain lower potential nitrification rates measured in MS soils, since SOC, WEOC, and LF were all lowest in MS. Higher WEOC available in wetland soils can increase mineralization of DON and lead to greater nitrification (van Kessel et al., 2009). Additionally, the slight decrease in mineralization and nitrification in LD soils may also be due to observed decrease in SOC.

Quality of SOM (i.e. C: N ratios) affects microbial communities and N processes by influencing immobilization by organisms. High C: N ratios result in greater immobilization as organisms need to take up more mineral N to maintain their own C: N ratio. Soils with a high C: N are believed to support larger populations of heterotrophs that assimilate NH_4^+ and put nitrifiers at a disadvantage (Booth et al., 2005). Although nitrification is primarily controlled by mineralization, this competition for NH_4^+ is a secondary control since substrate available for nitrification is reduced (Booth et al., 2005; Bedard-Haughn et al., 2006). Light fraction has a high C: N ratio that typically decreases in soils that have been disturbed due to increased decomposition of SOM associated with increased N mineralization (Booth et. al. 2005; Tan et al., 2007). A loss of LF lowers C: N and affects microbial N immobilization by reducing NH_4^+ assimilation by heterotrophs. This benefits nitrifiers and increases nitrification rates. In agricultural soils, C becomes depleted and N is added in the form of fertilizer, exceeding C inputs resulting in a lowering of C: N ratios. As C: N decreases, agricultural soils shift from an NH_4^+ to NO_3^- based inorganic N economy because nitrifiers are able to better compete against heterotrophs (Booth et al., 2005). This is evident in our study, as there is lower available NH_4^+ and increased nitrification in drained soils compared to UD.

In addition to the potentially large heterotroph population, previous anaerobic conditions may have restricted the population and activity of nitrifiers. There are various microbial communities that are responsible for different N processes that have different niches (Wessen et al., 2011; Norton and Stark, 2011). When environmental conditions change, like quality of SOM or aerobic conditions, a lag time may occur where the microbial populations change (Norton and Stark, 2011). This lag time may have been captured in the potential nitrification experiment. Oxygenated conditions and abundant substrate was maintained throughout the course of the experiment, but potential nitrification was lowest in UD suggesting the nitrifying microbial community was not as present or active as drained soils.

Phosphorus

There are various factors that might contribute to the observed increasing-decreasing trend of available P following drainage. Firstly, in more acidic soils, available P would be expected to increase with moisture due to the reduction of Fe^{3+}-P to Fe^{2+}-P, which is a more soluble form, but this is not as important in more basic soils (such as those in our study region) where Ca-P complexes are more common. Studies have found that P availability is unaffected following drying in soils with a greater dominance of Ca-P complexes (Venterink et al., 2002; Havlin et al., 2014d).

Fertilizer additions are another factor that can affect P availability. Solubility of Ca-P complexes can increase as pH decreases in basic soils (Newman and Pietro, 2001; Stewart and Tiessen, 1987). Increased fertilizer application following drainage can decrease pH and make Ca-P complexes more soluble (Turner et al., 2003). In this study, pH across drainage categories was consistent and is unlikely to be a factor affecting P availability, but fertilizer may be contributing to increased P availability in drained soils due to addition of P with increased fertilizer applications (Ewing et al., 2012; Streeter and Schilling, 2015).

Thirdly, dry wet cycles can influence P availability. Increases in extractable P following rewetting of a dried soil can occur due to water dissolving Ca-P and an increase in mineralized organic material (Venterink et al., 2002). Wetlands in this study undergo drying with drainage, yet are not always effectively drained. During wet years, water may still collect in these drained depressions creating dry wet cycles.

Landscape position is a fourth factor that can control available PO_4^{-3}. In the Brown soil zone of Saskatchewan and the Black soil zone of Manitoba, greater available P has been measured in lower slope, convergent positions due to translocation of P from upper slopes to lower slopes (Noorbakhsh et al., 2008; Manning et al., 2001). Higher P availability measured in wetland soils compared to MS could be a result of erosion and translocation of P with water and tillage from upper slopes to lower slopes.

Duration of drainage and agricultural production may explain the decrease of available PO_4^{-3} in LD soils. Wetlands that are disturbed and have an outflow have reduced capacity to act as a P sink (Sharpley et al., 2007). Ditches associated with these wetlands provide a conduit allowing for removal of nutrients with water to an even lower landscape position. Soil P reserves may be decreasing with duration of drainage due to losses in drainage water. Finally, declines in available P may also be due to P removed with crop export (Stewart and Tiessen, 1987).

Phosphorus processes can further help explain why available PO_4^{-3} was greater in drained soils compared to UD and lowest in MS (Table 3.6). It appears that UD has the greatest capacity to retain available P as it has the highest sorption and lowest desorption. The more recently drained soils (RD and MD) have greatest potential to supply P to crops, but also to lose nutrients downstream due to high available PO_4^{-3} and higher desorption. However, compared to P sorption of ditch soils in other agroecosystems, soils of this region appear to have a greater capability of holding onto P due to high clay content (Reddy et al., 2005). Sharpley et al. (2007) looked at differences between ditch sediments and their capacity to hold onto P and found agricultural ditch sediments had a maximum P sorption of 362 mg kg^{-1}, which were higher than a forest and mixed land use ditch (194 and 277 mg kg^{-1}). The higher sorption capacity was attributed to finer clay sized material that correlates well with P sorption. Clay-sized soils that have a higher sorption capacity can hold sorbed P more tightly. Other research into nutrient flows along ditches fed by tile drains have found that some agricultural ditches, especially shallow, finer textured ditches, can have a high retention of N and P due to retention and sorption capacities (Brunet and Westbrook, 2012; Sharpley et al., 2007). So although there is potential for nutrient losses from wetlands out through ditches, losses may not be as large as those experienced in other drained agroecosystems.

Potassium

Drainage did not have a significant effect on K. This lack of change may be the result of Saskatchewan soils having inherently high K, especially those that have a high clay content. Decreases over time associated with crop uptake likely do not exist as most K remains in the stems or straw of crops resulting in little losses with seed (Government of Saskatchewan, 2012). Finer textured soils adsorb and fix K preventing loss through leaching. The MS had significantly lower available K, which can be expected as extractable K has been found to have an inverse relationship with elevation across a prairie landscape (Noorbakhsh et al., 2008; Manning et al., 2001); as elevation increases, extractable K decreases. Potassium can be greater in depressions due to an accumulation of eroded clay minerals, and a high rate of weathering due to moisture. Extractable K was greater at the surface in our study, which is likely due to greater weathering (Noorbakhsh et al., 2008). Although there were no differences in extractable K, drainage may still be improving growing conditions. Although soil tests may show adequate levels of K for crops, some crops will still respond to addition of K due to other factors such as cool temperatures, soil compaction, shallow rooting depth, and poor drainage, which interfere with crop uptake (Government of Saskatchewan, 2012).

3.6.5 Influence of different agricultural practices

Drainage may begin the process and contribute to some of the increases in nutrient availability and structural changes due to aerobic conditions and greater decomposition, but decomposition of C over time, and nutrient uptake and removal by crops is likely contributing to declines in wetland soils to levels similar in MS soils that have been in cultivation longer. It is difficult to distinguish between which agricultural practice is contributing more to the observed changes. Nevertheless, there are some changes such as NO_3^- and NH_4^+ becoming more similar to MS that may be a direct result of drainage. As mentioned NO_3^- became more similar to MS with drainage duration at the 30 to 60 cm depth and although there was no significant difference across drainage categories of NH_4^+ levels between wetlands and paired MS, variability was large for UD (Fig. 3.7). Interestingly, levels of NH_4^+ did not only vary in UD soils but also in MS, with some MS soils having higher NH_4^+ than the paired UD. This indicates that NH_4^+ in some paired MS and UD landscapes may be very different, and drainage can remove this variability of NH_4^+.

It could be argued that the perceived transformation of wetland soils becoming more similar to the MS is not due to drainage. More likely, tillage, which appears to be a reoccurring theme, is likely influencing soil properties in drained wetlands. Surface soil of drained wetlands may actually be soil that used to belong to the surface A horizon of the MS and has been moved to that position as a result of tillage translocation. Since the UD soils have been cultivated during drier years it is likely that they have also experienced some of the effects of tillage, but not to the same degree as wetlands that have been drained and are cultivated on a more annual basis. Many prairie studies have examined tillage erosion and how it causes removal of upslope soil down into depressions where it accumulates (Vandenbygaart et al., 2010; Noorbakhsh et al., 2008; Bedard-Haughn, 2009; Bedard-Haughn, 2011; Pennock et al., 2011; Papiernik et al., 2005). Over time this redistribution of soil can begin to level out the topography of an area (Bedard-Haughn, 2011). This was observed in this study as it was harder to distinguish drained wetlands in LD sites from the typically cultivated upslope positions because these fields had less topographic variability. Unfortunately, if a similar future drainage study were to try and eliminate the confounding factor of tillage, it would be extremely difficult or impossible since all drained wetlands have likely been tilled at some point.

3.7 **Conclusions**

Historically, drainage policy has been minimal in Saskatchewan, but renewed interest by farmers to drain flooded cropland and growing concern over increased nutrient loads reaching eutrophic Lake Winnipeg, downstream flooding, and loss of waterfowl habitat, efforts have been put in place to establish better policy and legislation (Bedard-Haughn, 2009; Water Security Agency, 2015; Briere, 2015). Having a better understanding of how drainage affects soil fertility properties over time can be very beneficial for helping make future drainage management decisions that can help lessen drainage concerns. Drainage overall improves growing conditions and nutrient availability for agricultural production. Nutrient availability improved following drainage with changes depending on drainage duration. Greatest benefits appear to be with RD and MD soils that have been drained for 7 to 34 years, but this decreases with LD soils becoming more similar to cultivated midslope positions. This is not necessarily a negative thing as midslopes are very productive cropland, but prolonging benefits associated with higher nutrient and SOM of wetland soils would be desirable. Although other studies have observed increasing nutrient concentrations at depth with time following drainage, there was no hard evidence in this study that suggests the same. Hydrology and C appear to be major factors influencing soil properties. Aerobic conditions allowed for increased biological activity and a change in processes that allow for increased nutrient availability. However, increased biological activity results in increased decomposition of C that, with time, results in a decrease of nutrient availability. Although there is concern for long term soil C storage due to decreases in SOC at the surface, tillage translocation from upslope positions may protect C at depth. It is likely that other agricultural practices coinciding with drainage are also affecting soil properties over time. Therefore, long term quality of these drained soils depends on these other management practices. Since mitigation projects are likely to have higher success rates if the area of interest, which includes soil, is properly assessed (Ewing et al., 2012), this quantitative data for this particular region is an excellent resource for planning suitable management practices. Finally, differences in properties across drained wetlands and midslopes may be a potential avenue to explore precision agriculture that could improve nutrient use efficiency and reduce nutrient losses to the environment.

4 FATE AND FORM OF N AND P IN DRAINED PRAIRIE SOILS UNDER DIFFERENT PRECIPITATION SCENARIOS: A GREENHOUSE EXPERIMENT

4.1 Preface

The previous chapter identified that drainage of agricultural land in the Smith Creek watershed of Saskatchewan can improve growing conditions and nutrient availability for agricultural production with greatest benefits occurring in soils drained from 7 to 34 years (RD and MD) and decreasing afterwards, becoming more similar to the cultivated MS. Drainage of agricultural land has been identified as a large nonpoint contributor of N and P loading, resulting in degradation of downstream water quality. Although some water quality research in the Smith Creek Watershed has been completed, that study did not investigate soil as a factor influencing nutrient exports in drainage water and did not explore how duration of drainage may affect nutrient losses. Using a subset of wetlands from the previous chapter, this chapter examines how drainage duration may affect forms and fate of nutrients in soil, plant, and water. Since fate and form of nutrients can vary drastically depending on moisture, three different precipitation scenarios were applied to assess how these results may change in one of the most variable climates in North America.

4.2 **Abstract**

In Saskatchewan, renewed interest in draining prairie potholes occurs during periods of greater flood events and excess soil moisture, with drainage projects increasing without a clear understanding of effects on soil itself in this particular environment. Additionally, draining wetlands through ditching increases hydrological connectivity and allows previous non-contributing areas to contribute to stream flow. Drainage of agricultural land has been identified as a major nonpoint contributor to N and P loading to downstream water bodies, degrading water quality. As a result, drainage of prairie potholes has great potential to contribute to downstream nutrient loading. The aim of this study was to determine how drainage duration may affect forms and fate of N and P in soil, plant, and water. This was accomplished with a 5 x 3 factorial greenhouse experiment. Five different bulk soils were collected from Eastern Saskatchewan representing soils drained for 0, 14, 20, and 42 years, and a midslope soil. Three different precipitation treatments were applied: below, normal and above-normal, and fertilizer was applied at a rate of 300 kg N ha^{-1} and 20 kg P ha^{-1}. Pots were seeded with wheat and leachate collected once per week. Leachate analyses included determination of total dissolved N, dissolved organic N, NO_3^-, NH_4^+, and PO_4^{-3}. Above ground biomass and total N and P were determined for plants. Soil analyses included total N and P, available NO_3^-, NH_4^+ and PO_4^{-3}, and net mineralized N. Soils drained for different durations of time had differing nutrient losses, nutrient availability, and above ground biomass. Drained soils had greater N and P uptake, above ground biomass, and remaining soil P; however, these properties appear to decline in the longer drained soil. Nutrient availability, mineralization, sorption capacity, soil water holding capacity, and vegetation all appear to affect nutrient losses. Greater availability of NH_4^+ and PO_4^{-3} translated into greater NH_4^+ and PO_4^{-3} leachate losses. Longer drained soils (20 and 42 years) had the greatest field capacity, plant growth and lowest cumulative losses of nutrients under below and normal precipitation treatments. These outcomes varied under different precipitation treatments. The above-normal treatment resulted in drastic increases of NO_3^- leachate losses compared to the normal treatment; losses at least tripled for most soils, but resulted in a 16 fold increase in the 20 year drained soil. Finally, quantity and timing of nutrient leaching responded differently depending on

precipitation treatment. Most nutrient losses occurred at the beginning of the experiment when plant demand was lower and water additions greatest. This research provides valuable information highlighting both risks and benefits associated with agricultural drainage that can be used to make sound management decisions to prolong soil fertility and reduce environmental consequences.

4.3 Introduction

The Prairie Pothole Region of Saskatchewan is comprised of prime agricultural land that is vital to Saskatchewan's economy and helping meet global food demands (Government of Saskatchewan, 2015). However, since 2010, the northern and eastern extent of the Saskatchewan PPR has been experiencing an ongoing wet period that has been restricting agricultural production (Bedard-Haughn, 2009; Brimelow et al., 2014). The PPR is made up of many small wetlands (prairie potholes) that typically dry up throughout the growing season during more normal climatic conditions. During drier years, these wetlands can be cultivated; however, more recently these wetlands are remaining wet late into the growing season, increasing in size, and encroaching onto surrounding farmland. Anaerobic conditions are unfavorable for crop growth and wet soils are difficult to manoeuver large agricultural equipment through. Agricultural drainage is a solution that is typically used in more humid regions of the world (Montagne et al., 2009; Tan and Zhang, 2011; Baker et al., 2004; Kumar et al., 2014; Madramootoo et al., 2007; Streeter and Schilling, 2015; Randall and Goss, 2008). Drainage creates aerobic conditions that increase biological activity and decomposition of OC, which in turn improves key soil fertility properties such as structure, infiltration and nutrient availability (see chapter 3) (Ewing et al., 2012; Streeter and Schilling, 2015; Kumar et al., 2014; Hundal et al., 1976; Sullivan et al., 1998; Verhoef and Egea, 2013; King et al., 2015). Intensification of agriculture coupled with an ongoing wet period has resulted in extensive drainage of Prairie Pothole wetlands (Brunet and Westbrook, 2012).

Plant available nutrients are taken up in soil solution and occur in various forms. Some of these nutrients are more labile than others and as a result have a greater likelihood of being transported with excess water. Plant available forms of nitrogen include NH_4^+ and NO_3^- (Havlin et al., 2014b), with NO_3^- being the nutrient of greater concern of losses to drainage water due to its high mobility. Dissolved organic N (DON) is another labile form of N that, to a much lesser extent than NO_3^-, can be taken up directly by plants. Dissolved organic N is also of importance since it is mineralized by microorganisms increasing NH_4^+ and NO_3^- availability (Haygarth et al., 2013; van Kessel et al., 2009). However, agricultural studies often overlook DON losses when constructing nutrient budgets. Studies should consider including DON measurements since DON has been estimated to have leachate losses equivalent to 1/3 of NO_3^- losses in some agricultural systems (van Kessel et al., 2009). Plant available P occurs in the form of orthophosphates ($H_2PO_4^-$ and HPO_4^{2-}) in soil solution (Tan, 2005a). Phosphate (PO_4^{-3}) is strongly sorbed or precipitated and as a result is relatively immobile (Havlin et al., 2014d). Although present in lower concentrations than NO_3^- in drainage water, PO_4^{-3} is still a significant contributor to total-P enrichment of waterbodies (Smith et al., 2015). Farmers apply N and P fertilizers in order to meet crop demands and produce optimal yields. Although great efforts can be made to optimize nutrient use efficiency, nutrient losses still occur.

Drainage of agricultural land has been identified as a large nonpoint contributor to N and P loading to downstream water (Tan and Zhang, 2011; Montagne et al., 2009; Randall and Goss, 2008; Kleinman et al., 2015b; van Kessel et al., 2009). Nitrogen and P loading from drainage waters can lead to: economic losses for farmers due to fertilizer loss, contamination of drinking water, stress on fish communities, and eutrophication that can lead to hypoxia, toxic algae blooms and disrupt recreational use of water (Randall and Goss, 2008; Haygarth et al., 2013; Westbrook et al., 2011).

Soil has the potential to serve as a sink or source for N and P leaching depending on nutrient availability, sorption/desorption characteristics, ability to maintain anaerobic conditions, depth and time of soil/water interaction, and presence of preferential flow paths (Smith et al., 2015; Andersson et al., 2015; Withers et al., 2005). Greater nutrient availability and low sorption capacity can cause soils to behave as a source of nutrients (King et al., 2015; Andersson et al., 2015). A deeper soil/water interaction can increase contact of P in soil water to adsorption sites, causing the soil to behave as a sink. Subsurface soils generally have a high sorption capacity, especially finer textured soils, due to presence of Fe^{2+}, Fe^{3+}, Al^{3+}, and Ca^{2+} that can bind with P (Andersson et al., 2015; King et al., 2015). However, preferential flow paths can reduce interaction of water with soil, bypassing adsorption sites, and decreasing the ability of soil to sorb P (Smith et al., 2015; Andersson et al., 2015). Anaerobic conditions can decrease NO_3^- through conversion by denitrification into N gases, and limit nitrification, which converts NH_4^+ into NO_3^-. Additionally, anaerobic conditions can increase P availability due to the conversion of Fe^{3+}-P to a more soluble form of Fe^{2+}-P in acidic soils. In more basic soils, saturation can increase available P due to a greater capacity to dissolve Ca^{2+}-P and by flushing out newly mineralized P from previous drying (Venterink et al. 2002; Reddy et al., 2005; King et al., 2015). Depending on soil properties, a soil may contribute to or reduce nutrient losses.

Much drainage research has focused on tile drained agroecosystems in wetter regions of the world (Montagne et al., 2009; Tan and Zhang, 2011; Baker et al., 2004; Kumar et al., 2014; Madramootoo et al., 2007; Streeter and Schilling, 2015; Randall and Goss, 2008). Soils, climate, and management are different in semi-arid to sub-humid Saskatchewan and previous results are likely not transferable to a surface drained PPR agroecosystem. Fortunately, research on drainage effects on prairie stream hydrology and water quality have been investigated in the Smith Creek Watershed (Fang et al., 2010; Westbrook et al., 2011; Brunet and Westbrook, 2012), but these studies have not addressed the soil aspect of drainage or how drainage duration may affect results. This is surprising considering that the amount and quality of drainage water that leaves a landscape is highly dependent on climate and soil properties (Randall and Goss, 2008).

Traditionally, hydrological connectivity in the region has been thought to be at a maximum during snowmelt, which is considered to be the only event that contributes to streamflow (Fang et al., 2010; Westbrook, et al., 2011; Brunet and Westbrook, 2012; van der Kamp and Hayashi, 2009) and resulting nutrient export. Since snowmelt runoff occurs over frozen soils, any potential for soils to behave as a sink or source of nutrients is limited due to reduced infiltration and interaction of water with soil (Brunet and Westbrook, 2012; Dumanski et al., 2015; Cade-Menun et al., 2013). However, due to increasing temperatures, there has been a shift in form of precipitation, with more falling as rainfall and less as snow. There has also been an increase in multiple-day rain events. These changes have resulted in less snowmelt and greater rainfall runoff (Dumanski et al., 2015; Akinremi et al., 2001; Brannen et al., 2015), likely increasing infiltration and soil water interaction. Furthermore, Brannen et al. (2015) have proposed that shallow groundwater can play a larger role in streamflow generation and wetland connectivity than previously thought. Therefore, under an increasingly variable climate, water may have greater opportunity to interact with soils in these drained landscapes, which may in turn affect nutrient losses downstream.

Even though annual precipitation across the whole PPR increased by 9% between 1906 and 2000 (Millet et al., 2009), the Canadian Prairies have one of the most variable climates in North America (Brimelow et al., 2014). A moisture surplus or deficit can negatively affect crop yields, reducing N and P uptake throughout the growing season and increasing potential for applied nutrients to be lost to drainage water (Andersson et al., 2015). Wetter years can also increase anaerobic conditions that can reduce NO_3^- but increase PO_4^{-3}. Both timing and amount of precipitation can create different nutrient loss scenarios from year to year. For example, greater cumulative NO_3^- losses have occurred in tile drained systems during years of higher precipitation, whereas dry conditions with low flows can result in accumulation of nutrients in soil (Randall and Goss, 2008). As a result, research that integrates potential year to year variability is necessary to accurately predict nutrient losses (Randall and Goss, 2008). Additionally, it is important to consider drainage duration as it has been identified that soil properties differ in soils drained for different periods of time (Chapter 3). Since soil properties can affect nutrient losses, differences in soil properties could result in differing nutrient losses. Having a better idea of how drained soils may behave under different precipitation scenarios can help us estimate nutrient losses, residual soil nutrients, and crop yields under different scenarios.

The objectives of this study were to: 1) Determine the nutrient balance of soils of varying drainage age under different precipitation treatments, 2) Determine whether forms of N and P respond differently to precipitation treatments in these soils, and 3) Determine whether quantity and timing of nutrient leaching from these soils responds differently to precipitation treatments.

4.4 **Materials and methods**

4.4.1 Study area and sample design

The objectives of this study were addressed with a greenhouse study using bulk soils collected from the Smith Creek Watershed. Soils were collected from the north-eastern extent of the Smith Creek Watershed. The Smith Creek watershed, in south-eastern Saskatchewan, is an area that has experienced a >50% loss of wetlands, covering 24% of the watershed in 1958 to 10% in 2009 (Dumanski et al., 2015). This watershed is a tributary to the Assiniboine River flowing into the Red River, eventually making its way to eutrophic Lake Winnipeg (Brunet and Westbrook, 2012). Since prairie potholes are storage zones that accumulate nutrients, salts, and bacteria from surrounding agricultural land, increased connectivity of wetlands via open drainage ditches, may adversely affect downstream water quality and add to the already problematic nutrient loading of Lake Winnipeg (Brunet and Westbrook, 2012). This area is approximately 60 km southeast of Yorkton in the Black soil zone of Saskatchewan in the PPR. Parent material is glacial till and slopes range from gentle to moderate (2.5 - 10%) on an overall hummocky terrain (Saskatchewan Soil Survey, 1991). The region has a semi-arid to sub-humid climate with a MAP (1981-2010) of 449 mm (Government of Canada, 2015).

In November 2015, bulk soils were collected from five sites representing an undrained (UD), recently drained (RD), medium drained (MD), longest drained (LD), and midslope (MS) soil, which will be referred to as drainage categories. The UD wetlands had been previously cultivated in dry years, but were not cultivated during sampling year. The RD, MD, and LD had been drained for approximately 14, 20, and 42 years, as determined by air photos. These sites were selected from 42 wetlands that were sampled for the field component of this study (Chapter 3). Wetlands that had been extensively tilled or burned following field sampling, but before soil collection for the greenhouse experiment, were excluded from the selection. The selection process involved reviewing soil profile descriptions (Appendix Table A.1) and choosing wetlands that did not have carbonates to a depth of 100 cm. The exception was for UD sites that had carbonates at a depth of 70 cm or had minimal effervescence at the surface. Wetlands selected were mid-size for the area, with areas of 1,984, 1,559, 3,147, and

2,638 m^2. Each wetland was drained by a single ditch. The MS corresponding to the LD site was selected to represent the MS soil. Bulk soil was collected by removing surface vegetation and excavating soil to a depth of 15 cm. Large roots in UD soil were removed. Soil was stored in large plastic containers, transported back to lab, and stored at 4°C. Once temperatures outside remained below 0°C, soil was stored outside until two weeks prior to the start of the greenhouse experiment; they were then thawed at 4°C. Table 4.1 provides basic properties of soils used. All soils have a neutral to basic pH, are non-saline (<2000 µS cm^{-1}), and have a loam to clay loam texture. The MS has a texture higher in sand with less silt. The RD and LD varied slightly across basic soil properties and had higher SOC and TN.

Table 4.1 Basic soil properties of each soil used in greenhouse experiment.

Drainage Category†	pH	EC (µS cm^{-1})	Texture (%)			SOC (%)	Total N (%)
			Sand	Silt	Clay		
UD	7.8	311	30	41	29	3.4	0.3
RD	8.1	186	40	34	26	5.4	0.4
MD	7.7	345	29	38	33	3.7	0.3
LD	7.2	297	31	37	32	4.1	0.4
MS	7.7	143	46	16	38	3.5	0.3

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.

The treatment design is 5 x 3 factorial RCBD with three replicates. There were five different drainage categories (UD, RD, MD, LD, and MS), three precipitation treatments (below-normal, normal, and above-normal) and fertilizer was applied to all pots. The experiment was also completed on pots with no fertilizer additions. Non-fertilized results can be found in appendix B (Tables B.2, B.3, B.4, B.5, B.8, and B.9). Only the fertilized results are presented since these agricultural systems would typically receive fertilizer applications. The experiment was set up in a greenhouse, and blocking was used to address potential differences of temperature and lighting over the bench. The experiment took place over six weeks throughout February and March 2015. Daytime greenhouse temperature was set to 26°C and nighttime to 20°C.

4.4.2 Greenhouse experiment preparation

The dry equivalent of 1.2 kg of field moist soil was added to each pot and packed to ensure similar bulk density (0.75 g cm^{-3}). Soil was broken up and mixed gently by hand to homogenize soil and to try and maintain some inherent soil structure. Paper filters were added to the bottom of each pot to prevent soil loss (Fig. 4.1). Surface soil was removed and 300 kg N ha^{-1} and 20 kg P ha^{-1} of fertilizer were added in granular form of urea and monoammonium phosphate. Fertilizer was covered with removed surface soil and eight Waskada (Agriculture and Agri-Food Canada) wheat seeds were added above fertilizer. The form and placement of fertilizer helped minimize volatilization losses of N. Pots were brought to field capacity by filling trays under pots with water and waiting for the wetting front to reach the surface of soil. Remaining water in trays was emptied and each pot weighed. These weights were averaged for each soil type. The % moisture at field capacity of these soils was high and increased in order of UD, MS, RD, MD, and LD at values of 39, 46, 48, 49, and 52% respectively. Pots were weighed daily to monitor moisture and were not allowed to drop below 70% of their field capacity during germination. One week after seeding, pots were thinned to five plants and brought back up to field capacity. The seedlings were removed, dried and added to total plant mass at the end of the experiment. White plastic beads were added to soil surface of pots to minimize evaporative losses.

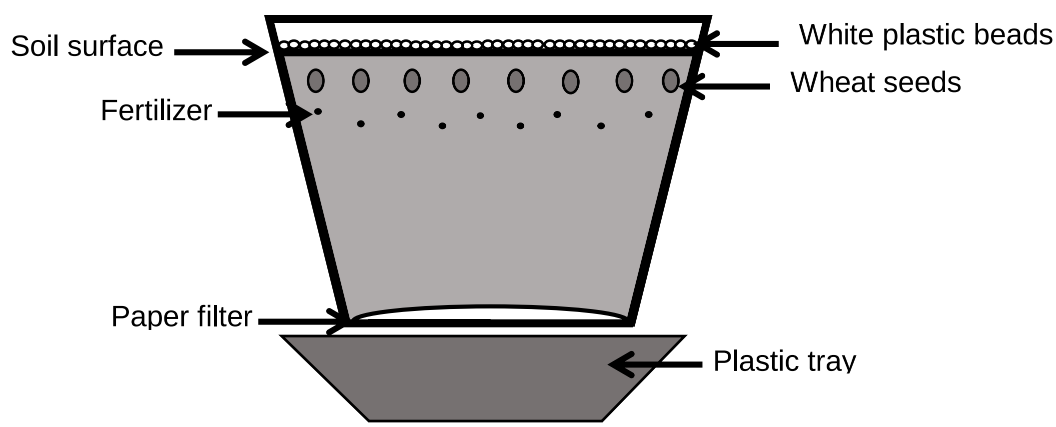

Figure 4.1 Diagram of pot set up. A paper filter was inserted into the bottom of the pot to prevent soil loss before the addition of soil. Surface soil was removed and fertilizer applied. The surface soil was reapplied and wheat seeds were pushed into soil above the fertilizer. After seedlings emerged, white plastic beads where added to help minimize evaporative losses. Water was added to the surface of the pot and leachate was collected from the plastic trays that pots rested on.

In order to develop a precipitation treatment that would simulate a below, normal and above-normal year, precipitation data was downloaded from the Yorkton weather station for the months of June and July for the previous 20 years (1994-2013). Precipitation totals for these months had a mean of 150.7 mm and standard deviation of 61.24 mm. Mean was used to represent the normal precipitation treatment and below and above-normal precipitation treatments were determined as one standard deviation above and below mean (89.46 mm and 211.94 mm). Years were selected that had the best matched total precipitation amounts to the determined precipitation treatments for June and July. This resulted in 1997 representing below-normal precipitation (92 mm), 2013 representing normal (146 mm) and 2012 representing above-normal (214 mm). A watering schedule was developed that mimicked precipitation patterns for June and July. Adjustments were made so below-normal precipitation would consistently have the lowest precipitation and above-normal would have the highest precipitation added each day.

4.4.3 Greenhouse experimental procedure

Precipitation treatments began once pots had been thinned. For the remainder of the study, pots were weighed daily to determine moisture content. As soon as moisture dropped below 60% of field capacity, water was added to bring moisture to 70% field capacity. The watering schedule was followed and on watering days, pots were weighed before and after. Once per week, leachate was collected from pot trays. Water was left in trays on non-collection days. Plants were also checked daily for pests and diseases. Aphids were controlled by hand and elemental sulfur was applied once during the experiment to control powdery mildew. Weeds were pulled and left on the soil surface.

Towards the end of the experiment, some adjustments were made to amount of water added to pots because plants began showing symptoms of moisture stress. When pots dropped below 60% of the soils field capacity on week 5 (day 27), they were brought up to 70% field capacity and an additional 100 mL (equivalent to 5.7 mm) of water was added. For the final week (day 32-34), the precipitation treatment was adjusted again so that when pots fell below 60% field capacity they were brought to 70% of field capacity and 0, 100, and 150 mL (equivalent to 0, 5.7, and 8.5 mm) of additional water was added to below, normal, and above-normal treatment respectively. This was deemed necessary because the below-normal treatment was consistently drying out and required more water additions than the normal and above for plant survival. This adjustment maintained necessary differences between the precipitation treatments for total water added (Fig. 4.2).

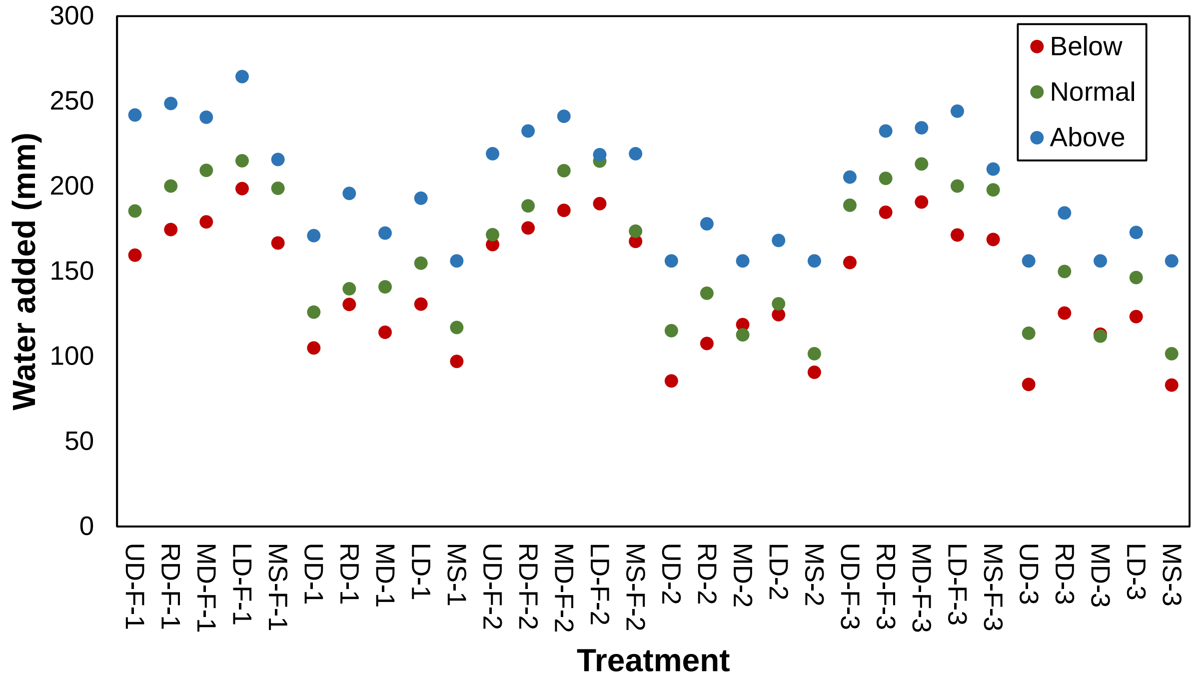

Figure 4.2 Total water added from precipitation treatments and additional water adjustments deemed necessary to prevent plant death. UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope, F=fertilized treatment, 1, 2, 3=replicate.

4.4.4 Sample processing and laboratory procedures

Plants were harvested six weeks after the start of the experiment when wheat plants were in the heading or flowering stage. Plants were cut at the base of the stem. Soil was air dried and crowns of plants were picked out. Seedlings, crowns, and above ground plant matter were dried at 60°C and weighed to determine total above ground biomass for each pot. Plants and soil were ground to pass a 2 mm sieve. Sulfuric acid digestions were used to determine total N and P contents of plant and soil (Thomas et al., 1967). Available N and P were determined for soil samples using KCl and modified Kelowna extractions (Maynard et al., 2008, Ashworth and Mrazek, 1995). All three extractions were analysed using a Technicon Auto Analyzer (Technicon Industrial Systems, Tarrytown, NY, USA) for NH_4^+, NO_3^-, and PO_4^{-3}. Mineralized N was estimated using the unfertilized treatment and was calculated by subtracting initial NO_3^- and NH_4^+ from remaining NO_3^- and NH_4^+, leachate NO_3^- and NH_4^+, and plant N.

Leachate was immediately filtered through a Whatman 42 filter paper (Whatman Inc., Piscataway, NJ) and frozen. Prior to analysis, samples were thawed and filtered through a 0.45 um Millipore filter (Whatman Inc., Piscataway, NJ). Samples were analyzed for total dissolved N (TDN) using Shimadzu TNM-1 equipment (Shimadzu Scientific Instruments, Columbia, MD), and NH_4^+, NO_3^-, and PO_4^{-3} by colorimetry using a Technicon Auto Analyzer. Dissolved organic N was determined by difference of NH_4^+ and NO_3^- (including NO_2^-) from TDN (Qualls, 2013).

4.4.5 Statistical analysis

Statistical analyses were performed using SAS version 9.4 (SAS Institute, 2014). The SAS mixed model procedure was used to test the effects of moisture and duration of drainage on P and N uptake and losses. Blocks were considered a random effect and moisture and drainage duration fixed effects. Fertilized and unfertilized treatments were analyzed separately. Least square means were compared using Tukey Kramer test and significance was declared at $P<0.05$. It was not possible to transform some of the data to normality. Two way ANOVAs were run on nontransformed data despite non-normality. This was done so that the same statistical approach was used for all data and to explore interaction effect of moisture and duration of drainage on all properties. Separate one way ANOVAs were used to determine differences between drainage categories and precipitation treatments for nutrient budgets. Any correlations were determined using Pearson product-moment correlations with significance declared at $P<0.05$.

4.4.6 Study limitations

Unfortunately, it was not possible to account for runoff or subsurface flow, separate surface and subsurface leachate losses, maintain field soil structure and preferential flow paths, or maintain field temperature and light conditions. However, by optimizing temperature, light, and fertilizer additions, and controlling weeds and pests, a better comparison among soils was possible due to these factors not interfering. It is also easier to apply different precipitation treatments and collect leachate for multiple reps in a greenhouse setting. However, the need to apply water in order to generate leachate was a major limitation and consistently high daytime temperatures and long daylight hours made it difficult to follow the developed precipitation schedule. This project is intended as a first step to understanding how drained soils in this region may affect nutrient losses under different precipitation scenarios.

4.5 **Results**

4.5.1 Above ground biomass

Plant mass varied across drainage categories (UD: 15.99, RD: 16.75, MD: 20.63, LD: 18.59, and MS: 17.67 g pot^{-1}) and was significantly higher for MD soil (p=0.0017). Plant mass was also significantly higher (p=0.0019) under normal and above-normal precipitation treatments (below: 16.07, normal: 18.54, and above: 19.17 g pot^{-1}) (Appendix Table B.1).

4.5.2 Nutrient budgets

Nutrient budgets summarize overall findings of the greenhouse experiment. Soils had different initial starting points with drained soils having greater N (Table 4.2). Drained soils had significantly higher plant N uptake than UD and followed an increase-decrease trend, where increases occurred in RD and MD but decreased with LD; this trend is most evident under below-normal and normal precipitation treatments (below p=0.0010, normal p=0.0001, above p<0.0001). Plant N uptake was greater under normal and below-normal treatments for all drainage categories except for RD, which had lower uptake under normal conditions. Under below-normal precipitation, TDN leachate losses only occurred in UD soils. Under normal precipitation, TDN losses were highest for MS ($p<0.0001$). The TDN leachate losses were much higher in above-normal, but were not significantly different among drainage categories. Unaccounted losses of N occurred for all treatments except below-normal UD. Some of the greatest unaccounted losses were with the above-normal treatment; however, MD had greater unaccounted losses for the below treatment and LD for the normal treatment.

Initial P varied with drained soils having greater P than UD or MS (Table 4.3). Except for MS, plant P uptake was greater during normal and above-normal precipitation treatments and was significantly higher under above-normal conditions for RD soil. Like N uptake, plant P uptake increased in RD and MD, followed by a decrease in LD (below $p=0.0002$, normal $p<0.0001$, above $p<0.0001$). Losses of PO_4^{-3} in leachate were low overall, but increased with increasing moisture. The UD had highest losses ($p<0.0001$) for below-normal and all wetland soils had greater losses than MS ($p=0.0101$) for above-normal. The lowest losses occurred with MS. Total soil P remaining also followed the increasing-decreasing trend. Unaccounted gains in P occurred for all categories under below precipitation treatment and for all UD soils.

4.5.3 Soil nutrient pools and losses

There were no differences across drainage categories for NO_3^- loss in leachate, but MD had double the loss of UD for above-normal (Fig. 4.3). Losses increased with increasing moisture for NO_3^- , NH_4^+, DON, and PO_4^{-3}(Fig. 4.3-4.6). Losses of NO_3^- at least tripled from normal to above-normal precipitation. The MD had losses of less than 5 mg pot^{-1} under the normal treatment and losses of almost 80 mg pot^{-1} in above-normal treatment. Additionally, UD had some of the highest losses of NO_3^- for below and normal precipitation treatments, but had lowest losses for above-normal (Fig. 4.3). Correspondingly, all nutrient pools remaining in soil decreased with increasing moisture. Of the wetland soils, UD had the lowest soil NH_4^+ remaining and had significantly higher NH_4^+ losses ($p<0.0001$) than all other categories across precipitation treatments (Fig. 4.4) with means for UD, RD, MD, LD and MS being 0.27, 0.15, 0.08, 0.08 and 0.09 mg pot^{-1} respectively(Appendix Table B.4). A significant (p value: below<0.0001, normal=0.0017, above=0.0002) positive relationship was present between initial available NH_4^+ and leachate NH_4^+ across all precipitation treatments (r: below=0.97, normal=0.74, above=0.81). Remaining soil NO_3^- was highest in MS compared to wetland soils with no significant difference in NO_3^- remaining across drained wetlands and UD (Table 4.4). The NO_3^- remaining in MS was much greater in below and normal treatments than all other drainage categories and precipitation treatments. Similar to NO_3^-, there were no differences of DON losses among wetland soils, but MD lost twice as much as UD for above-normal precipitation. Overall MS had higher losses of DON than wetland soils (Fig. 4.5). Mineralized N increased with drainage duration and moisture inputs. Both MS and UD had the lowest mineralized N, and longer drained MD and LD had the highest mineralized N (Table 4.4).

Leachate PO_4^{-3} losses were low in all soils (Fig. 4.6), but there was a significant difference among drainage durations (p=0.014) with means for UD, RD, MD, LD and MS being 0.10, 0.13, 0.09, 0.06, and 0.02 mg pot^{-1} respectively (Appendix Table B.5). Losses of PO_4^{-3} were greatest in UD and RD, but decreased in LD. The LD had significantly lower losses than RD, but was not statistically different from MS, which had the lowest losses of PO_4^{-3}. A significant (p=0.0013) positive correlation between initial available PO_4^{-3} and leachate PO_4^{-3} only existed for above-normal treatment (r=0.75). Unlike N, moisture did not affect remaining soil P, but there was a drainage category effect. Soil P remaining was greater in drained soils compared to UD and MS. Soil P and PO_4^{-3} remaining increased in RD and MD and then decreased in LD. There was a strong significant (p<0.0001) positive correlation between initial and remaining soil PO_4^{-3} across all precipitation treatments (r: below=0.97, normal=0.91, above=0.95).

Leachate losses of all nutrients began earlier in the experiment as moisture increased (Fig. 4.3-4.6); leachate losses began on day 15 for below, day 6 for normal, and day 3 for above. Most of the NO_3^- and PO_4^{-3} losses occurred during the first three weeks, with largest single day losses occurring on day 15, after consecutive days of large water additions. For DON, MS had a large spike in leachate losses on day 6 for both normal and above-normal treatments.

Table 4.2 Nitrogen nutrient budget of fertilized drained wetlands and corresponding midslope under different precipitation treatments.

Drain-age Cate-gory†	Inputs: Initial Total N In soil (mg pot^{-1})	Outputs‡: Plant uptake of N (mg pot^{-1})			TDN in leachate (mg pot^{-1})			Total N remaining in soil (mg pot^{-1})			Unknown: Unaccounted N (mg pot^{-1})§		
		Below¶	Normal	Above	Below	Normal	Above	Below	Normal	Above	Below	Normal	Above
UD	3694.2#	225.9 cB	254.1 bA	200.7 bC	4.16 B	10.37 bB	45.49 A	3693.7b	3438.1b	3231.7	229.5 a	8.3 a	-216.4
RD	5088.2	293.0 abA	281.3 bB	293.2 aA	0.00 B	9.15 bB	58.39 A	4501.2a	4128.1b	3851.2	-294.0 ab	-669.7 ab	-885.3
MD	4543.5	339.7 aA	345.2 aA	303.4 aB	0.00 B	2.09 bB	76.75 A	3628.4b	3778.5ab	3627.1	-575.4 b	-417.8 ab	-536.2
LD	5348.3	299.5 ab	330.9 a	292.0 a	0.00	2.18 b	47.89	4793.0a	4205.8a	4305.0	-255.8 ab	-809.5 b	-703.4
MS	4373.0	270.6 bcA	273.3 bA	228.8 bB	0.00 C	21.07 aB	73.66 A	3695.2b	3824.7ab	3522.3	-407.2 ab	-253.9 ab	-548.2
P values for drainage effect													
		0.0010	0.0001	<0.0001	0.4609	<0.0001	0.5347	0.0015	0.0349	0.2447	0.0451	0.0215	0.6563
P values for moisture effect													
UD			0.0008			0.0451			0.3895			0.4444	
RD			0.0393			0.0003			0.2070			0.2526	
MD			0.0433			0.0212			0.8999			0.9004	
LD			0.2554			0.0027			0.2875			0.3675	
MS			0.0078			0.0005			0.6794			0.6795	

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡ Means with same upper-case letter in same row (drainage category) and with same lower-case letter in same column (output or unknown) are not significantly different according to Tukey Kramer test (P>0.05).
§ Unaccounted N determined as outputs-inputs, positive values represent unaccounted gains in N while negative values represent unaccounted losses.
¶ Below, normal and above represent the three different precipitation treatments applied.
# For inputs n=1, for outputs and unknown n=3.

Table 4.3 Phosphorus nutrient budget of fertilized drained wetlands and corresponding midslope under different precipitation treatments.

	Inputs	Outputs‡									Unknown		
Drain-age Cate-gory†	Initial Total P in soil (mg pot^{-1})	Plant uptake of P (mg pot^{-1})			Loss of PO_4^{-3}-P in leachate (mg pot^{-1})			Total P remaining in soil (mg pot^{-1})			Unaccounted P (mg pot^{-1})§		
		Below¶	Normal	Above	Below	Normal	Above	Below	Normal	Above	Below	Normal	Above
UD	692.0#	25.8 bc	27.0 c	27.2 c	0.02 aB	0.06 aB	0.21 abA	753.3 c	792.5 b	694.8 a	87.1	127.5	30.1
RD	1254.0	33.1 bB	34.8 bB	39.1 abA	0.00 bB	0.06 aB	0.33 aA	1241.6 ab	1143.6 ab	1212.3 a	20.7	-75.5	-2.3
MD	1299.7	41.9 a	43.8 a	44.0 a	0.00 bB	0.01 aB	0.26 aA	1308.0 a	1216.1 a	1171.1 a	50.1	-39.9	-84.4
LD	1176.1	30.8 b	37.9 b	37.0 b	0.00 bB	0.01 aB	0.17 abA	1237.1 ab	1087.8 ab	1045.4 a	91.8	-50.4	-93.6
MS	1017.3	21.3 c	22.4 d	21.1 d	0.00 bB	0.01 aB	0.05 bA	1002.8 bc	901.2 ab	822.3 a	6.9	-93.6	-173.9
P values for drainage effect													
		0.0002	<0.0001	<0.0001	<0.0001	0.0125	0.0101	0.0006	0.0311	0.0356	0.7599	0.3937	0.6914
P values for moisture effect													
UD			0.6903			0.0016			0.4376			0.4271	
RD			0.0119			0.0002			0.7284			0.7322	
MD			0.4701			0.0042			0.2531			0.2647	
LD			0.0842			0.0053			0.2577			0.2870	
MS			0.2190			0.0016			0.4495			0.4520	

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡ Means with same upper-case letter in same row (drainage category) and with same lower-case letter in same column (output or unknown) are not significantly different according to Tukey Kramer test (P>0.05).
§Unaccounted P determined as outputs-inputs, positive values represent unaccounted gains in P while negative values represent unaccounted losses.
¶Below, normal and above represent the three different precipitation treatments applied.
#For inputs n=1, for outputs and unknown n=3.

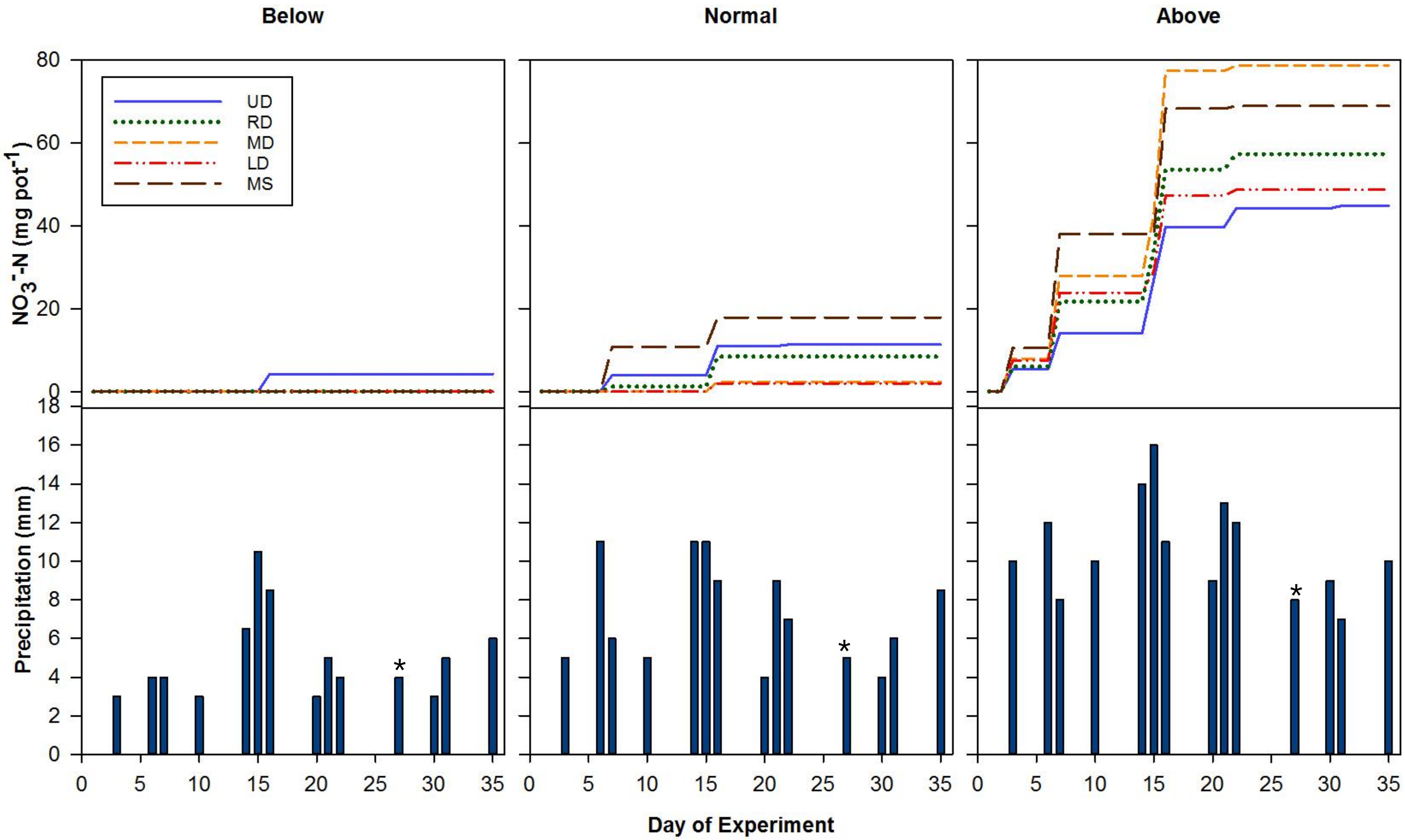

Figure 4.3 Mean cumulative NO_3^--N losses of leachate from different durations of drained soil and a midslope under three precipitation treatments over the course of the pot experiment. UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained and MS=midslope. The asterisks indicate adjustments to the initial precipitation schedule, which began on day 27 (see section 4.4.3).

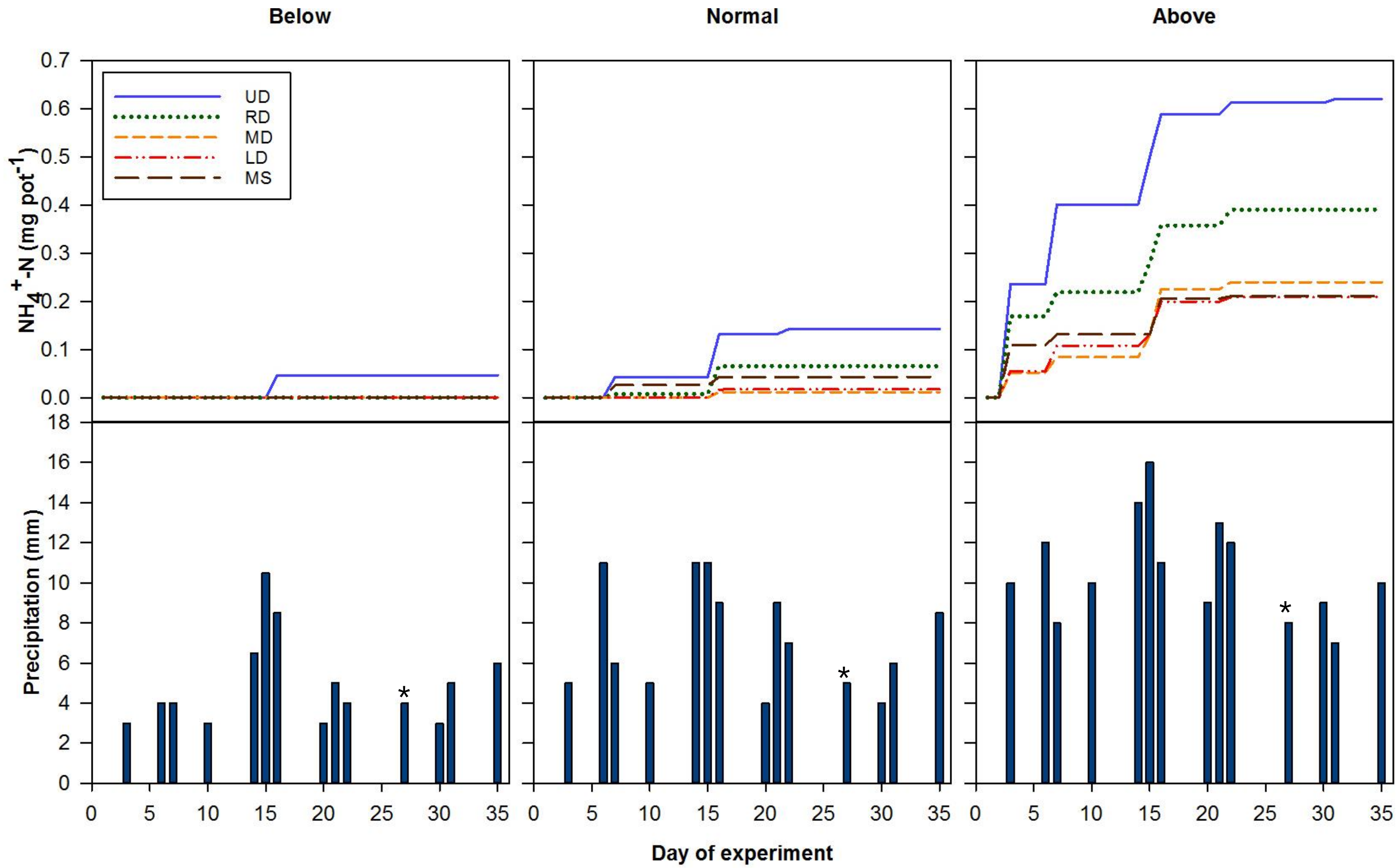

Figure 4.4 Mean cumulative NH_4^+-N losses of leachate from different durations of drained soil and a midslope under three precipitation treatments over the course of the pot experiment. UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained and MS=midslope. The asterisks indicate adjustments to the initial precipitation schedule, which began on day 27 (see section 4.4.3).

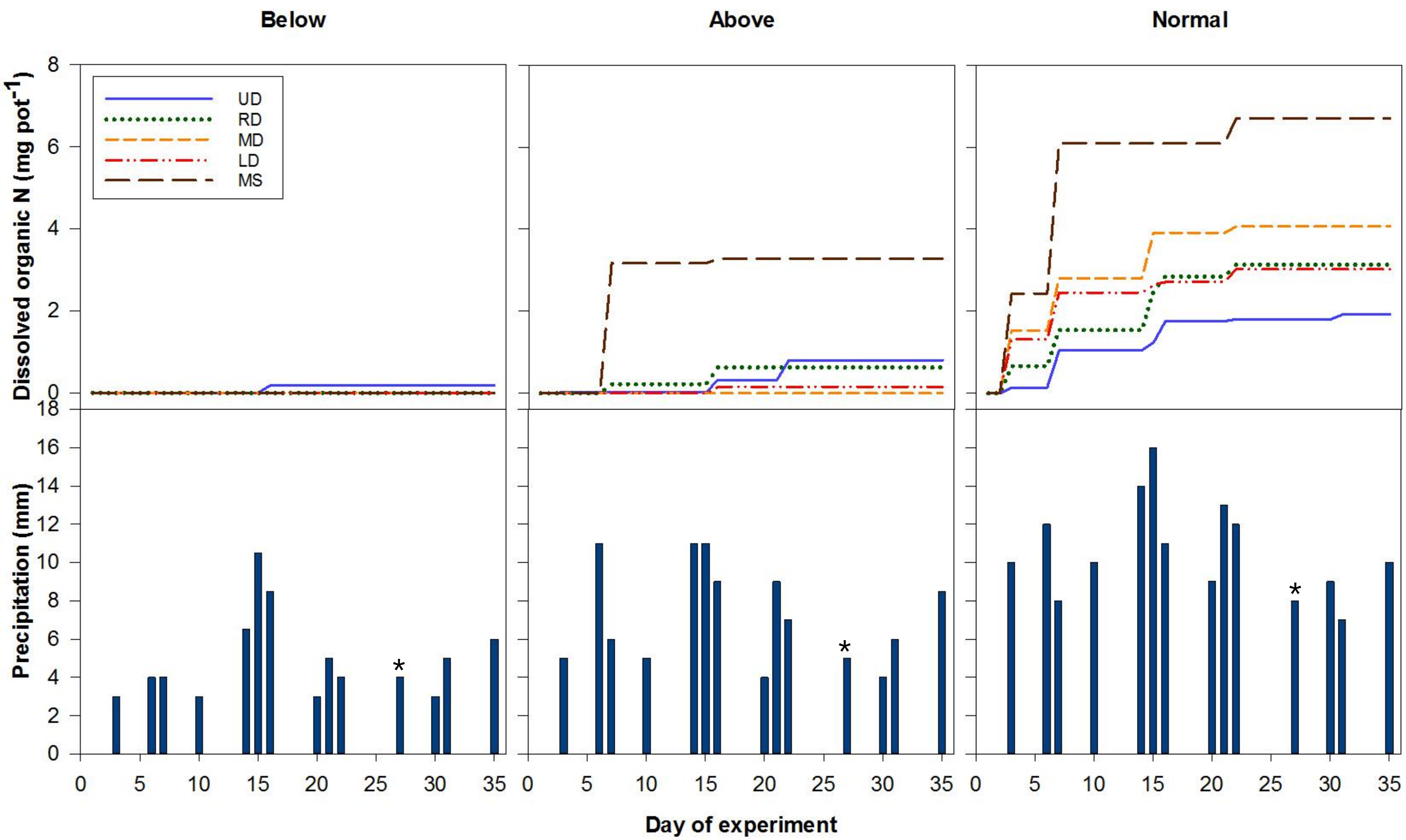

Figure 4.5 Mean cumulative dissolved organic N losses of leachate from different durations of drained soil and a midslope under three precipitation treatments over the course of the pot experiment. UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained and MS=midslope. The asterisks indicate adjustments to the initial precipitation schedule, which began on day 27 (see section 4.4.3).

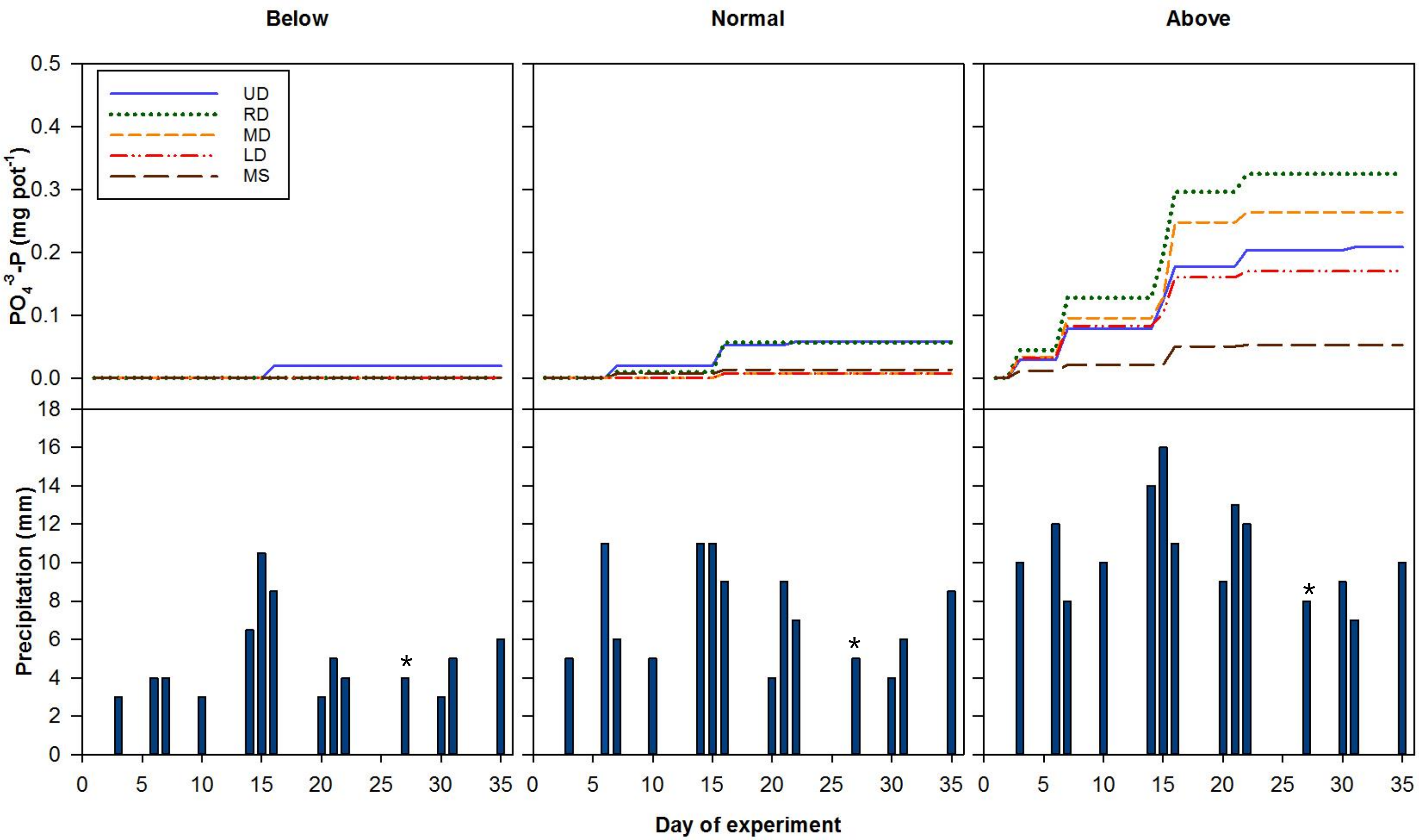

Figure 4.6 Mean cumulative PO_4^{-3}-P losses of leachate from different durations of drained soil and a midslope under three precipitation treatments over the course of the pot experiment. UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained and MS=midslope. The asterisks indicate adjustments to the initial precipitation schedule, which began on day 27 (see section 4.4.3).

Table 4.4 Effects of drainage and different precipitation treatments on soil N and P in a greenhouse experiment.

Effect	Treatment		Nitrogen				Phosphorus	
	Drainage category†	Precipitation treatment	Total N remaining in soil (mg pot^{-1})	NH_4^+ remaining in soil (mg pot^{-1})	Mineralized N (mg d^{-1})‡	NO_3^- remaining in soil (mg pot^{-1})	Total P remaining in soil (mg pot^{-1})	PO_4^{-3} remaining in soil (mg pot^{-1})
Drainage x moisture	UD	Below	3693.7§	5.34	0.27^{d}	10.12^{bc}	753.3‡	13.1
		Normal	3438.1	4.49	0.44^{d}	7.39^{c}	792.5	13.1
		Above	3231.7	3.47	0.40^{d}	5.76^{c}	694.8	10.2
	RD	Below	4501.2	6.16	0.48^{d}	12.49^{bc}	1241.6	44.7
		Normal	4128.1	4.65	0.94^{c}	6.43^{c}	1143.6	41.0
		Above	3851.2	5.02	0.91^{c}	4.48^{c}	1212.3	40.6
	MD	Below	3628.4	5.64	1.09^{bc}	11.79^{bc}	1308.0	40.2
		Normal	3778.5	5.75	1.16^{bc}	7.98^{c}	1216.1	44.4
		Above	3628.4	4.34	1.36^{ab}	5.05^{c}	1171.1	41.2
	LD	Below	4793.0	6.10	1.10^{bc}	17.69^{bc}	1237.1	26.9
		Normal	4205.8	5.51	1.38^{ab}	9.69^{bc}	1087.8	22.8
		Above	4305.0	4.87	1.56^{a}	4.32^{c}	1045.4	23.4
	MS	Below	3695.2	5.07	0.53^{d}	40.87^{a}	1002.8	5.4
		Normal	3824.7	4.57	0.51^{d}	23.47^{b}	901.2	4.7
		Above	3522.3	3.97	0.43^{d}	6.53^{c}	822.3	4.2
Drainage	UD		3454.5^{c}	4.43^{b}	0.37^{c}	7.75^{b}	746.9^{b}	12.2^{c}
	RD		4160.2^{ab}	5.28^{ab}	0.78^{b}	7.80^{b}	1199.2^{a}	42.1^{a}
	MD		3678.0^{bc}	5.24^{ab}	1.20^{a}	8.27^{b}	1231.7^{a}	41.9^{a}
	LD		4434.6^{a}	5.49^{a}	1.35^{a}	10.57^{b}	1123.4^{a}	24.4^{b}
	MS		3680.7^{bc}	4.54^{ab}	0.49^{c}	23.62^{a}	908.8^{b}	4.8^{d}
Moisture		Below	4062.3	5.66^{a}	0.70^{b}	18.59^{a}	1108.6	26.1
		Normal	3875.0	4.99^{ab}	0.89^{a}	10.99^{b}	1028.2	25.2
		Above	3707.5	4.33^{b}	0.93^{a}	5.23^{c}	989.2	23.9
P values								
Drainage x moisture	P value		0.7771	0.6031	0.0061	0.0006	0.9178	0.3930
	SEM		252.85	0.5776	0.0714	2.7259	116.41	1.9260
Drainage	P value		0.0001	0.0150	<0.0001	<0.0001	<0.0001	<0.0001
	SEM		163.53	0.4597	0.0412	1.5938	97.0590	1.3754
Moisture	P value		0.0764	0.0002	<0.0001	<0.0001	0.0665	0.1328
	SEM		138.93	0.4323	0.0319	1.2499	92.7052	1.2362

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Mineralized N estimated using unfertilized treatment
§Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.05).

4.6 **Discussion**

4.6.1 Nutrient balance of drained soils under different precipitation treatments

Fate of nutrients varied across drainage categories and precipitation treatments, indicating that soils drained for different durations of time can have differing nutrient losses, nutrient availability, and crop yields. Drained soils had greater N and P uptake, total P in soils and greater plant mass, which increased in RD and MD soils but then decreased in LD soils. Of the drained soils, the MD had greater total N losses over the course of the experiment suggesting that MD has the lowest ability to retain N.

Unaccounted losses of N and P were greater for above-normal treatment, implying the type of losses were affected by moisture. Although not measured in this study, denitrification likely contributed to unaccounted N losses. Denitrification is a process that reduces NO_3^- to N_2 and N_2O gases under anaerobic conditions. Soil conditions after moisture additions, particularly around day 6 and 15 of the experiment, were very wet. Particulate P, which was not measured in this study, may have been lost to leachate and could have contributed to unaccounted P losses that increased with greater moisture. Other studies have found increases of particulate P in leachate under higher precipitation and drainage amounts (Andersson et al., 2015). Unaccounted P gains for UD soil and all soils under below precipitation treatment represent a small percent of initial P. This apparent gain could be due to cumulative error associated with various lab procedures. The UD soil may have had unaccounted gains as a result of this particular soil having many large fragments of organic material and roots preventing the soil from being as homogenized as others. As a result, the sub-sample collected for determination of initial soil P may not have been truly representative, resulting in an underestimation of initial soil P.

Vegetation appears to be a large factor controlling fate of nutrients in drained soils. Wheat uptake accounted for the greatest removal of N and P from soil. Soil moisture is a primary determinant of root growth and nutrient availability (Brouder and Volenec, 2008), and according to Leibig’s law of the minimum, soil moisture is the most limiting factor determining yield potential (Havlin et al., 2014a). Since nutrients are taken up in soil solution by plant roots, plants with larger masses of roots have a greater advantage to accessing nutrients. A moisture deficit can restrict plant uptake and create a nutrient deficiency in plants even if soil tests show adequate levels of nutrients. A visual inspection during pot deconstruction found that normal and above-normal precipitation treatments had larger and more extensive root growth compared to below-normal. Although greater moisture did not improve plant N uptake, it did improve P uptake and increase plant mass, especially in drained soils. Greater availability and uptake of P may have resulted due to a) repetitive wetting and drying that occurred each time the pots were watered and b) enhanced P diffusion to roots as a result of increased moisture (Venterink et al., 2002; Turner and Gilliam, 1976; Havlin et al., 2014d). Unlike P that is strongly sorbed or precipitated in soils, NO_3^- is highly mobile in water (Haygarth et al., 2013). The increase in moisture may have decreased N availability to plants due to leachate losses of NO_3^- and transformations of NO_3^- to N gases due to denitrification. High concentrations of NO_3^- were found in leachate, especially for above-normal treatments.

A lack of vegetation can result in greater nutrients remaining in the soil due to decreased plant uptake, which in turn can be lost to drainage water (Andersson et al., 2015). Greater crop growth creates higher water demands from plants due to increased evapotranspiration. As water is removed from soil to plant, the soil's capacity to hold more water increases preventing water additions from leaving the soil and transporting nutrients out of the system. This is commonly observed in the prairies as overland flow is not usually generated during summer due to both a high infiltration capacity of dry soils and evapotranspiration demands from plants (Van der Kamp and Hayashi, 2009). If the vegetation were not present, more water would remain in the soil due to less evapotranspiration and there would be less capacity for soil to hold future additions of water. Since plant mass was greater for MD and LD soils in this greenhouse experiment, these soils likely had greater evapotranspiration demands. This may have decreased leachate losses and lowered cumulative nutrient losses in below and normal precipitation treatments.

4.6.2 Response of N and P pools in drained soils under different precipitation treatments

Forms of N and P responded differently across drainage categories and to precipitation treatment. Nitrate made up the greatest nutrient leachate losses, which increased substantially in the above-normal treatment, likely due to high N fertilizer application and its great mobility. There were no significant differences between drained soils and UD; however, MD lost twice as much NO_3^- as UD. The MD also had greater NO_3^- losses than RD even though initial TN and NO_3^- were greater in the RD soil. Mineralization of SOM is believed to contribute large amounts of NO_3^- to tile drainage water with some studies concluding mineralization can be as much a contributor as fertilizer additions, particularly during the non-growing season (Randall and Goss, 2008; Randall and Mulla, 2001). The estimated mineralization of soils used in this study increased with drainage duration. From the field component of this study, net mineralized N was determined as 0.30, 0.32, 0.47, 0.35, and 0.35 mg kg^{-1} d^{-1} and potential nitrification as 56.4, 58.9, 51.1, 34.6, and 26.2 mg kg^{-1} d^{-1} for UD, RD, MD, LD, and MS respectively (see chapter 3). These values show MD with the highest net mineralized N and a high potential nitrification rate, which throughout the course of this experiment may have increased available NO_3^- in the soil to both plant uptake and nutrient losses. This suggests that both fertilizer application and mineralization can contribute to NO_3^- losses in these soils.

The MS also had high NO_3^- losses for above-normal and normal precipitation, but had lower mineralized N than MD and the lowest potential nitrification of all drainage categories suggesting mineralization was not as large of a contributor to MS NO_3^- losses. Greater mineralization typically occurs in soils with higher OM content (Randall and Mulla, 2001) and these drained or undrained wetland soils have greater SOM than the MS (see chapter 3). Interestingly, MS had greater remaining NO_3^- than wetland soils and high remaining soil NO_3^- for below and normal precipitation treatments. Phosphorus availability may account for high remaining MS soil NO_3^- because crop N response declines when P is limiting. Available soil PO_4^{-3} was low in the MS at the beginning (UD: 9.74, RD: 47.78, MD: 33.84, LD: 23.57, MS: 4.39 mg kg^{-1}) (see chapter 3) and end of the experiment. The MS had lower P uptake and P content than all other soils, and plant

P uptake and content of MS (21.62 mg pot^{-1} and 0.12%) was approximately half of MD (43.23 mg pot^{-1} and 0.21%) ($p<0.0001$ for both) (Appendix Table B.1). It has been shown that when adequate levels of N and P are added to P deficient soils, recovery of applied N increases and residual soil NO_3^- decreases (Havlin et al., 2014c). Even though enough N appeared to be available for plants, N uptake may have been restricted due to a P deficiency. Indeed, N uptake was significantly lower in MS (257.55 mg pot^{-1}) than MD (329.44 mg pot^{-1}) ($p<0.0001$). Low N uptake by plants could explain the greater soil NO_3^- remaining in below and normal precipitation treatments. Less NO_3^- remaining in the soil may exist in the above-normal treatment due to removal by water and potential denitrification.

Dissolved organic N, a form of N often overlooked as a concern in drainage water, is formed through depolymerisation of crop residues and SOM by microbes (Haygarth et al., 2013). There were no significant differences among wetland soils, but MD had double the losses in the above-normal treatment compared to UD. Throughout the duration of the experiment, MD needed to be weeded more frequently than other wetland soils and may have had greater DON losses due to addition of fresh plant material. Agricultural studies have also found that DON increases with increasing water additions, through precipitation or irrigation, wetting and drying events, increasing sand content, and greater N inputs (van Kessel et al., 2009). The MS also had greater DON losses than wetland soils, but did not have an issue with weeds. If N uptake had been reduced due to a P deficiency, then plant uptake of DON may have also been reduced leaving more DON in the soil that could be loss to water. However, soil wetting and drying, and sand content may have affected DON concentrations in the MS soil. Soil drying and rewetting can affect DON losses due to an accumulation of DON during dry periods when mineralization and nitrification slow down. Once rewetting occurs this DON can be flushed out resulting in a spike of DON concentration in leachate (van Kessel et al., 2009). The MS had a lower field capacity than drained soils, and a higher sand content that may have allowed this soil to drain and dry more quickly than wetland soils. Additionally, MS had lower net mineralized N and low potential nitrification, which may have led to accumulation of DON.

Surface soil tests can be a good indicator of potential N and P losses in drainage water (Andersson et al., 2015). For all precipitation treatments, leachate losses of NH_4^+ and remaining soil PO_4^{-3} corresponded to initial levels of NH_4^+ and PO_4^{-3}. The UD soil had the greatest initial NH_4^+ concentration and losses of NH_4^+ in leachate. The high NH_4^+ concentration likely exists in UD due to previous anaerobic conditions preventing conversion of NH_4^+ to NO_3^- through nitrification. Remaining soil NH_4^+ did not relate to initial levels and was significantly greater in LD than UD; available NH_4^+ initially was determined as 10.4, 3.2, 2.2, 1.9, and 2.2 mg kg^{-1} for UD, RD, MD, LD, and MS respectively (see chapter 3). In this study, UD was essentially turned into a drained soil, which would allow for greater nitrification to occur under more aerobic conditions. The greater NH_4^+ in LD could be a result of LD's high mineralization rate, but lower potential nitrification rate (see chapter 3).

In addition to initial nutrient availability, soils capacity to sorb (retain) or desorb (release) P are important for estimating losses to drainage water (Sharpley et al., 2008). Available P was determined as 9.7, 47.8, 33.8, 23.6, and 4.4 mg kg^{-1}, P sorption as 573.30, 574.49, 539.13, 613.87, and 596.60 mg PO_4^{-3}-P kg^{-1}, and P desorption as 41.41, 61.14, 71.27, 37.30, and 32.08 mg PO_4^{-3}-P kg^{-1} for UD, RD, MD, LD, and MS respectively (see chapter 3). The RD and MD had greatest P availability, desorption, and correspondingly greater P leachate losses. The MS had lowest available soil P, higher sorption capacity, and lowest losses to water. The MS, as well as LD, had higher P sorption allowing these soils to retain more P. However, it is also important to note that total P leachate losses were low and may have even been overestimated due to the pot experiment depth of 15 cm, which contained no subsurface soil. Subsurface soil has potential to reduce P losses due to iron, aluminum and calcium that can bind with P in drainage water (Andersson et al., 2015). On the other hand, any overestimation may have been counteracted by greater P plant uptake, since P recovery in greenhouse studies is usually greater than field studies, due to limited soil volume in small pots (Withers et al., 2005).

Overall, greater water additions resulted in less N and P remaining in the soil, due to greater N and P losses to leachate, but under below and normal precipitation treatments, soil water holding capacity appears to influence nutrient losses. The UD soil had the lowest field capacity, which was an average 9.75% lower than other drainage categories. With equivalent water additions, this soil reached saturation before the others and had less ability to retain moisture resulting in greater drainage losses. The UD had greater cumulative losses of all N and P forms compared to drained soils for below and normal precipitation treatments. The MD and LD soils had greatest field capacities and had lowest cumulative losses of all nutrients in below and normal precipitation treatments. Additionally, UD's ability to reach saturation quicker likely resulted in decreased nitrification, preventing conversion of NH_4^+, contributing to greater NH_4^+ losses. The UD may have also experienced greater wetting and drying events than other soils, which increased P availability due to water dissolving Ca- PO_4^{-3} and increased mineralization of organic matter (Venterink et al., 2002; Reddy et al., 2005). Newly available PO_4^{-3} could then be flushed out with the next wetting event. This process may explain higher P losses associated with UD even though UD had some of the lowest initial available P.

4.6.3 Quantity and timing of nutrient leaching under different precipitation treatments

As would be expected, greater nutrient losses of N and P occurred as quantity of water increased. A series of tile drainage studies in Minnesota documented greater cumulative NO_3^- losses in years of greater precipitation (Randall and Goss, 2008) and particulate P losses have been found to increase with higher precipitation and drainage amounts (Andersson et al., 2015). Nutrient losses started earlier in treatments that received greater water. Nutrient losses for the below-normal treatment started the latest, on day 15, because it received less water and had greater capacity to hold future additions of water. On day 15, higher water inputs surpassed the soils' field capacity and plant requirements, resulting in nutrient losses. For normal and above, greater amounts of water passed through the soil, due to larger water additions, which led to higher cumulative concentrations of nutrients lost. Precipitation can strongly influence drainage losses as a few days of intense rainfall can result in most of the annual nutrients loss in that year. A heavy rain event in the spring or early growing season is of great concern because soil can be at or near field moist conditions and evapotranspiration is low. This results in greater production of drainage water at a time when soil contains high concentrations of NO_3^- because crops have yet to utilize nutrients in the soil (Randall and Mulla, 2001).

The greatest losses of nutrients occurred within the first 3 weeks of the experiment. After day 15, daily amounts of water decreased and plant water demand was greater. Soils were dry enough that adjustments needed to be made to precipitation treatments in order to prevent wheat from dying. Since soils were not reaching levels of saturation as frequently as before, leachate losses and associated nutrient losses decreased.

4.7 **Conclusions**

Soils drained for different durations of time can have different nutrient availability, nutrient losses and crop yields. Drained soils had greater N and P uptake, remaining soil P, and plant mass that increased in RD and MD soils and decreased in LD soil. Soils from sites with different drainage durations appeared to contribute unequally to nutrient losses. The soils' ability to store water and vegetation were two large factors influencing fate of nutrients. The lower field capacity of UD allowed soil to reach saturation prior to other soils, resulting in a greater production of leachate during below-normal and normal precipitation treatments causing greater cumulative losses of nutrients. Plant uptake accounted for the greatest removal of nutrients from soil and could prevent excess residual soil nutrients from being loss to drainage water. Other factors such as initial soil nutrient levels and mineralization also influenced leachate losses. Soils that had greater NH_4^+ and PO_4^{-3} availability tended to have greater NH_4^+ and PO_4^{-3} losses and mineralization was also believed to responsible for higher NO_3^- losses from MD under above-normal conditions.

These outcomes based on drainage duration can also vary under different precipitation scenarios. Greater moisture improved P uptake and increased plant mass but did not increase N uptake. Higher moisture resulted in increases of NO_3^- losses to leachate and also increased losses of other N and P forms. Interestingly, some soils were greater contributors to nutrient losses under one precipitation treatment but less under a wetter or drier treatment. The MD soil may be of greatest concern during wet years for NO_3^- losses, but more recently drained soils (UD and RD) may be larger contributors to NO_3^- loss in drier years. The UD soil was the larger contributor to NO_3^-, DON, and PO_4^{-3} losses under below-normal conditions but was not the greatest contributor during above-normal conditions. Finally, quantity and timing of nutrient leaching varied under different precipitation treatments with greater nutrient losses occurring earlier in the growing season and beginning sooner during years receiving greater moisture when plant demand for both nutrients and water was low and water additions greatest.

This study provides valuable information to help develop beneficial management practices to maximize nutrient use efficiency. This research also identifies that some soils may be more of a concern than others and highlights that resources and mitigation efforts could focus on more recently drained soils. Results here may also be beneficial for future modelling of nutrient exports in drained Prairie landscapes.

5 SYNTHESIS AND CONCLUSIONS

Agricultural drainage is a management tool used globally to increase agricultural productivity and help meet increasing global food demands (Ayars and Evans, 2015; Verhoef and Egea, 2013). Drainage has also been identified as a major nonpoint source of N and P loading to waterbodies (Skaggs et al., 1994; Tan and Zhang, 2011; Montagne et al., 2009; Randall and Goss, 2008; Kleinman et al., 2015b; van Kessel et al., 2009). As a result, most drainage research worldwide has focused on water quality, with most study sites being located in warmer humid areas and having a tile drained system. Research on drainage impacts to soil properties over time is lacking (Nangia et al., 2013; Bedard-Haughn, 2009; Verhoef and Egea, 2013). Furthermore, research on the effects of surface drainage on soils in Saskatchewan, an area not well recognized as needing or using agricultural drainage, is even more limited (Brunet and Westbrook, 2012; Bedard-Haughn, 2009). The research presented here addressed these gaps in eastern Saskatchewan by measuring physical and chemical soil properties in soils that had been drained for different durations of time. This study also tried to determine how nutrient forms and fate may vary under different precipitation treatments.

5.1 Summary of findings

This study found that agricultural drainage changes physical and chemical properties over time, with most changes restricted to the uppermost 0 to 15 cm (Chapter 3). Drainage was found to improve soil fertility with greatest benefits observed in more recently drained soils. Drainage improved nutrient availability through increases in available PO_4^{-3} and greater nitrification. Drained soils had lower P sorption capacity, and RD and MD soils had higher P desorption, indicating drained soils have less capacity to hold on to P and more recently drained soils have greater capacity to release P. This implies that P would be more labile and available for plant uptake in these soils, but may also be more susceptible to losses in drainage water. Additionally, the greenhouse experiment (Chapter 4) showed that drained soils had greater N and P uptake and greater above ground biomass. However, with time these perceived benefits appear to decline. Drainage also appeared to have undesirable effects on soil properties, which were more pronounced in LD soils. Bulk density increased, and quantity and quality of C decreased with drainage duration. At lower depths (30-60 cm), OC was greater in LD soils, but this change is likely not resulting from drainage. Additionally at lower depth, NO_3^- availability of drained soils became more similar to MS soils, which had greater NO_3^- than UD, indicating drainage may cause changes at lower depth with time. In addition to available NO_3^- at lower depth, other properties, including bulk density, total N, NH_4^+, P sorption and desorption, PO_4^{-3}, and OC, became similar to levels measured in MS soils with drainage duration (Chapter 3).

Some drainage effects were found to vary under different precipitation treatments (Chapter 4). Greater moisture improved P uptake and increased above ground biomass, but did not increase N uptake. Greater moisture resulted in greater cumulative nutrient losses and earlier nutrient loss. This is unsurprising as many others have documented that greater nutrient losses occur during years that receive greater precipitation (Randall and Goss, 2008; Andersson et al., 2015). Although no differences were detected between soils of different drained durations, NO_3^- loss increased drastically from normal to above-normal precipitation treatments, especially for the MD soil. Water holding capacity appeared to control nutrient losses under normal and below-normal treatments, resulting in soils that had been low contributors for above-normal precipitation to be large contributors when conditions were drier. The MD and LD, which had the highest field capacities, had some of the largest nutrient losses with above-normal precipitation but had lowest cumulative nutrient losses under below and normal precipitation. The UD, which had the lowest field capacity and some of the lowest losses of nutrients with above normal precipitation, had greater cumulative losses of N and P under below and normal precipitation.

5.2 **Drainage implications and recommendations**

Although drainage overall improves growing conditions and nutrient availability, these improvements appear to decline in LD soils (i.e., those drained for greater than 34 years), becoming more similar to cultivated midslope positions. This is not necessarily a negative outcome since midslopes are very productive cropland, but extending the benefits associated with higher nutrient and SOM of wetland soils would be desirable. If quantity and quality of C continue to decrease, mineralization, nitrification, and nutrient availability may also decrease. It is difficult to separate these measured changes in soil properties from other land use and management changes, such as fertilizer application, crop production, and tillage operations, which occur following drainage, but agricultural drainage most certainly initiates these changes allowing for cultivation to occur in the first place. Since other management practices are likely influencing changes in soil properties, long term quality of these drained soils also depends on these other management practices.

Tillage is a practice that likely has a large influence on these drained soils. This study found that the proportion of microaggregates decreased with drainage duration and that this decrease may have resulted due to disruption of macroaggregates by tillage, preventing the formation of new microaggregates (Chapter 3). This could be a concern because microaggregate C is important for long term C storage. Reduced tillage may help reverse this process and also slow down further C decomposition. Tillage is commonly used in these drained soils in efforts to further dry soil, however, reduced tillage may increase structure and improve infiltration, further improving drainage and hopefully removing the need to till. Tillage is also responsible for translocation of soil from upslope positions to drained wetland soils and offers an explanation for why soils drained for longer durations become more similar to MS soils. Tillage translocation is also thought to be a likely explanation for the apparent increase in SOC at depth in the LD and MS soils. Although this has the potential to store SOM at lower depths, the productivity of upslope soils may be reduced further providing a reason to reduce tillage.

The more recently drained soils, with greatest drainage benefits, were also soils that had greater nutrient losses (Chapter 4). Other studies have found surface soil tests can be a good indicator of N and P losses to drainage water (Andersson et al., 2015). This may be true for NH_4^+ and PO_4^{-3} in these soils since soils with greater availability of NH_4^+ and PO_4^{-3} had greater losses of these nutrients to leachate. Mineralization was also identified as a factor that could contribute to nutrient losses in drained soils. Some studies have identified that mineralization can be as large of a contributor as fertilizer additions to nutrient losses in drainage water (Randall and Goss, 2008; Randall and

Mulla, 2001). Soil test levels and fertilizer additions can be a good indicator of the soils potential to contribute to nutrient losses, but mineralization rates may be another important factor to consider. It is also important to note, soils that do not receive fertilizer applications may still contribute substantially to NH_4^+ and NO_3^- losses due to high mineralization rates.

Vegetation was one of the largest factors controlling the fate of nutrients in these soils and was responsible for the greatest removal of N and P (Chapter 4). Leaving a field bare may not be ideal since a lack of plant uptake would result in greater residual nutrients in the soil, which in turn can be lost to drainage water (Andersson et al., 2015). Greatest nutrient losses occurred early in the experiment when plant demand was low and water additions greatest. In these prairie landscapes the greatest stream flow occurs in the spring and thus is a concern for great nutrient losses.

Although the nutrient losses from the greenhouse experiment cannot be directly transferred to the field, this research is a starting point and highlights that drainage duration and soil properties can unequally affect water quality, and nutrient losses will vary under different precipitation scenarios. Future modelling of nutrient exports in drained prairie watersheds could potentially incorporate different export coefficients to drained wetlands based on drainage duration that would vary under different precipitation scenarios. This could improve estimates since the current approach is to apply the same nutrient export coefficient to each wetland (Brunet and Westbrook, 2012).

There are many best management practices (BMP's) that have been developed to help minimize nutrient N and P losses in agricultural systems. With high potential for nutrient losses in drained ecosystems, it is even more imperative that these agricultural practices are used. Applying the 4 R's of management: right place, right time, right source and right rate could substantially help reduce losses to drainage water (Haygarth et al., 2013; Smith et al., 2015; Follett, 2008). Since soil properties and nutrient losses vary among wetlands drained for different durations of time and midslope positions, site specific applications of N and P that match nutrient needs of the crop, through use of precision agriculture, may be a beneficial management tool to reduce inputs and associated costs while reducing losses to environment (Ayars and Evans, 2015).

5.3 Future research directions

This study did not address differences between drained recharge and discharge wetlands. Almost all wetlands in this study were recharge wetlands and it would be beneficial to determine if a difference exists. Would discharge wetlands be undesirable to drain? Additionally, this study aimed to select wetlands with minimal to no evidence of infill for a more accurate comparison. The drainage process involves digging ditches and many farmers use the soil from these ditches to infill drained wetlands. This has resulted in most drained wetlands having some form of infill. It would be interesting to determine if the productivity and fertility of wetlands with varying degrees of infill changes over time.

This study made an attempt to compare potential nutrient export of drained soils in a greenhouse and therefore, there were many limitations. Future research measuring *in situ* losses of nutrients throughout the growing season and across multiple sites would be useful. Other scientists also stress that there is need for field studies investigating nutrient fate and transport within soils (Kleinman et al., 2015a, 2015b; King et al., 2015). Finally, there is need to develop and test site-appropriate mitigation measures.

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APPENDIX A: EFFECTS OF DRAINAGE DURATION ON MINERAL WETLAND SOILS IN A PRAIRIE POTHOLE AGROECOSYSTEM

Table A.1 Basic profile descriptions using the Canadian System of Soil Classification for each sampling location in study.

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
UD-R1-Z1-205	Ahca	0-20	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Bg	20-45	CL	10YR 3/3	common, distinct		
	Cg	45-100	SCL	2.5Y 5/2	common, distinct		
	IICg	100+	S	10YR 4/6	common, distinct		
UD-R1-Z1-79	Ah	0-25	SiCL	10YR 2/1			Humic Luvic Gleysol
	Ae	25-30	Si	10YR 4/1			
	Btg	30-75	CL	2.5Y 3/2	common, distinct		
	Cgk	75+	CL	2.5Y 4/3	common, distinct	strong	
UD-R3-Z1-123	Ah	0-10	SiCL	10YR 2/1			Orthic Humic Gleysol
	Bg	10-50	CL	2.5Y 4/2	common, distinct		
	Cgk	50+	SCL	2.5Y 5/3	common, distinct	strong	
UD-R4-Z1-300	Ah	0-20	SiCL	10YR 2/1			Humic Luvic Gleysol
	Ae	20-30	CL	2.5Y 3/1	common, distinct		
	Btg	30-70	CL	2.5Y 4/2	common, distinct		
	Cgk	70+	CL	2.5Y 5/3	common, distinct	strong	
UD-R1-2-84	Ah	0-15	SiL	10YR 2/1			Humic Luvic Gleysol
	Aeg	15-35	SiC	10YR 4/1	common, faint		
	Btg	35-50	SiC	2.5Y 3/2	many, prominent		
	Ck	50-75	SiC	2.5Y 4/2	many, prominent		
	Cgk	75+	SiC	2.5Y 6/2	many, prominent	strong	
UD-R2-Z2-83	Ah	0-20	SiCL	10YR 2/1			Orthic Humic Gleysol
	Bg	20-45	CL	2.5Y 3/2	common, prominent		
	Cgk	45-85	SL	2.5Y 5/3	common, prominent	moderate	
	IICgk	85+	CL	2.5Y 6/2	common, prominent	strong	
UD-R2-2-88	Ahk	0-20	SiCL	10YR 2/1		faint	Humic Luvic Gleysol
	Aeg	20-25		10YR 4/1	common, distinct		
	Btg	25+	CL	2.5Y 4/1	common, distinct		

(continued on next page)

Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
UD-R4-Z2-137	Ah	0-15	SiCL	10YR 2/1			Humic Luvic Gleysol
	Aeg	15-22	SiCL	2.5Y 5/2	common, distinct		
	Btg	22-80	CL	2.5Y 4/2	common, distinct		
	Cg	80-95	CL	2.5Y 4/3	common, distinct		
	Cgk	95+	CL	2.5Y 4/3	common, distinct	strong	
UD-R1-Z4-112	Ah	0-15	SiCL	10YR 2/1			Humic Luvic Gleysol
	Aeg	15-20	SL	2.5Y 4/1	reduced colour		
	Btg	20-80	CL	2.5Y 5/2	common, prominent		
	Cgk	80+	CL	2.5Y 6/2	common, prominent	strong	
UD-R2-Z4-118	Apk	0-15	SiCL	10YR 2/1		very faint	Humic Luvic Gleysol
	Aeg	15-30	SiCL	2.5Y 4/1	reduced colour		
	Btg	30-65	CL	2.5Y 4/2	common, distinct		
	Cg	65-80	CL	2.5Y 5/3	common, distinct		
	Cgk	80+	CL	2.5Y 5/3	common, distinct	moderate	
RD-R1-1-24	Apk	0-10	SiCL	10YR 2/1		moderate	Humic Luvic Gleysol
	Ah	10-20	SiCL	10YR 2/1			
	Ae	20-25	Si	2.5Y 3/1			
	Btg	25-40	CL	2.5Y 3/2	common, distinct		
	Cg	40+	CL	2.5Y 5/2	many, distinct		
RD-R2-1-31	Ap	0-20	SiCL	10YR 2/1			Orthic Humic Gleysol
	Bg	20-95	CL	2.5Y 4/2	many, distinct		
	Cgk	95+	CL	2.5Y 4/2	many, distinct	moderate	
RD-R3-1-26	Apk	0-5	SiCL	10YR 2/1		moderate	Humic Luvic Gleysol
	Ah	5-25	SiCL	10YR 2/1			
	Ae	25-30	Si	2.5Y 3/2	few		
	Btg	30-90	CL	2.5Y 3/2	few, distinct		
	Cgk	90+	SiC	2.5Y 5/2	common, prominent	strong	

(continued on next page)

Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
RD-R4-1-23	Apk	0-5	SICL	10YR 2/1		moderate	Humic Luvic Gleysol
	Ah	5-35	SiCL	10YR 2/1			
	Ae	35-40	SiL	2.5Y 5/2	common, distinct		
	Btg	40+	CL	2.5Y 5/1	many, distinct		
RD-R1-2-9	Ap	0-20	SiCL	10YR 2/1			Humic Luvic Gleysol
	Ae	20-35	SiCL	10YR 3/2			
	Btg	35-90	SiC	10YR 4/2	many, prominent		
	Cg	90-115	SiC	2.5Y 5/2	few, faint		
	IICg	115-125	SiCL	2.5Y 5/2	few, faint		
	IIICg	125+	SiL	2.5Y 5/2	few, faint		
RD-R2-2-11	Ap	0-20	SiL	10YR 2/1			Humic Luvic Gleysol
	Ae	20-35	SiCL	2.5Y 5/2			
	Bgt	35+	SC	2.5Y 4/2	common, prominent		
RD-R3-2-42	Ap	0-12	SiCL	10YR 2/1			Orthic Humic Gleysol
	Bg	12-50	SiC	5Y 5/2	reduced colour		
	Cg	50-80	SiC	5Y 5/2	reduced colour		
	Cgk	80+	SiC	5Y 5/2	reduced colour	moderate	
RD-R4-2-10	Ap	0-20	SiCL	10YR 2/1			Orthic Humic Gleysol
	Bg	20-50	C	2.5Y 4/1	common, distinct		
	Cg	50+	CL	2.5Y 3/2	common, distinct		
RD-R1-3-55	Ap	0-10	SiCL	10YR 2/1			Orthic Humic Gleysol
	Bg	10-60	CL	2.5Y 4/2	common, distinct		
	Cgk	60+	SiCL	2.5Y 6/3	common, distinct	strong	
RD-R2-3-18	Apk	0-20	SiCL	10YR 2/1		moderate	Humic Luvic Gleysol
	Ah	20-40	SiCL	10YR 2/1			
	Aeg	40-45	CL	2.5Y 5/1	few, faint		
	Bgt	45-100	CL	2.5Y 5/3	common, distinct		
	Cgk	100+	CL	2.5Y 5/4	common, distinct	strong	

(continued on next page)

Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
RD-R3-3-56	Apk	0-25	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Ahk	25-40	SiCL	10YR 2/1		faint	
	Bgk	40-65	CL	2.5Y 3/1	few, distinct	faint	
	Cgk	65-90	SCL	2.5Y 5/2	common, distinct	moderate	
	Cgk	90+	SL	5Y 6/2	common, distinct	strong	
MD-R1-4-75	Ap	0-30	SiL	10YR 2/1			Orthic Humic Gleysol
	Bg	30-90	CL	2.5Y 3/2	common, distinct		
	Cgk	90+	CL	2.5Y 4/2	common, distinct	strong	
MD-R2-4-22	Ap	0-40	SiCL	10YR 2/1			Orthic Humic Gleysol
	Bg	40-65	CL	2.5Y 3/1	reduced colour		
	Cg	65+	CL	2.5Y 4/3	many, distinct		
MD-R3-4-76	Apk	0-10	SiCL	10YR 2/1		strong	Orthic Humic Gleysol
	Ah	10-35	SiCL	10YR 2/1			
	Bg	35-65	CL	2.5Y 4/2	few, faint		
	Cg	65+	CL	2.5Y4/2	many, prominent		
MD-R4-4-125	Apk	0-30	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Bg	30-40	CL	2.5Y 3/2	few, faint		
	Cg	40-90	SiC	2.5Y 5/3	common, distinct		
	IICg	90+	S	2.5Y 5/4	common, distinct		
MD-R1-5-200	Ap	0-30	SiL	10YR 2/1			Orthic Humic Gleysol
	Bg	30-60	SiC	10YR 4/1	few, distinct		
	Cg	60-80	SiC	5Y 5/2	many, prominent		
	Cgk	80+	SiC	5Y 5/2	many, prominent	strong	
MD-R2-5-36W	Apk	0-35	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Bgk	35-60	SiCL	10YR 3/1	reduced colour	strong	
	Cgk	60+	SiCL	2.5Y 3/2	common, faint	strong	
MD-R3-5-134	Ap	0-35	SiCL	10YR 2/1			Rego Humic Gleysol
	Bg	35-40	CL	2.5Y 5/1	many, prominent		
	Cg	40+	CL	2.5Y 4/2	many, prominent		

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Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
MD-R1-6-47	Ap	0-35	SiCL	10YR 2/1			Humic Luvic Gleysol
	Aegj	35-40	SiCL	10YR 4/1			
	Btg	40-55	CL	2.5Y 3/2	common, distinct		
	Cgk1	55-90	CL	2.5Y 4/2	common, distinct	very faint	
	Cgk2	90+	CL	2.5Y 5/2	common, distinct	moderate	
MD-R2-6-45	Ap	0-25	SiCL	10YR 2/1			Humic Luvic Gleysol
	Ae	25-40	SiL	2.5Y 5/2	reduced colour		
	Btg	40-90	CL	2.5Y 5/3	common, distinct		
	Cgk	90+	CL	2.5Y 5/3	common, distinct	very faint	
MD-R3-6-46	Ap	0-15	SiCL	10YR 2/1			Humic Luvic Gleysol
	Ae	15-20	SiL	2.5Y 3/3	reduced colour		
	Btg	20-80	CL	2.5Y 5/2	common, prominent		
	Cg	80+	SL	2.5Y 5/2	common, prominent		
LD-R2-7-12	Ap	0-20	SiCL	10YR 2/1			Humic Luvic Gleysol
	Aeg	20-50	SiC	10YR 2/1	common, distinct		
	Btg	50-100		2.5Y 4/1	common, distinct		
	Cgk	100+		2.5Y 5/1	common, distinct	moderate	
LD-R3-7-43	Apk	0-25	SiCL	10YR 2/1		faint	Orthic Humic Gleysol
	Bgk	25-40	SiC	2.5Y 3/2	few, faint	faint	
	Cgk	40-70	SiC	2.5Y 4/2	few, faint	faint	
	Cgk	70+	SiC	2.5Y 5/2	few, prominent	strong	
LD-R4-7-13	Ap	0-35	SiCL	10YR 2/1			Orthic Humic Gleysol
	Bg	35+	SiC	2.5Y 5/2	few, faint		
LD-R1-7-17	Apk	0-30	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Bg	30-80	SiC	2.5Y 4/1	common, prominent		
	Cg	80+	SiC	2.5Y 3/1	common, prominent		
LD-R1-8-70	Apk	0-30	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Bg	30-95	CL	2.5Y 4/2	common, distinct		
	Cgk	95+	CL	5Y 5/2	few, distinct	moderate	

(continued on next page)

Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
LD-R2-8-120	Apk	0-40	SiCL	10YR 2/1		strong	Orthic Humic Gleysol
	Bgk	40-60	CL	2.5Y 3/3	few, faint	very faint	
	Cgk	60+	CL	2.5Y 4/3	common, prominent	very faint	
LD-R3-8-69	Apk	0-10	SiCL	10YR 2/1		faint	Orthic Gleysol
	Bg	10-50	CL	2.5Y 4/2	common, distinct		
	Cgk1	50-90	CL	2.5Y 5/2	common, distinct	moderate	
	Cgk2	90+	CL	2.5Y 5/2	common, distinct	strong	
LD-R4-8-119	Apk	0-20	SiCL	10YR 2/1		strong	Orthic Humic Gleysol
	Ah	20-30	SiCL	10YR 2/1			
	Bg	30-60	CL	2.5Y 3/2	reduced colour		
	Cg	60-90	CL	2.5Y 4/2	few, faint		
	Cgk	90+	CL	2.5Y 4/2	few, faint	very faint	
LD-R2-9-59	Apk	0-30	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Bg	30-95	CL	2.5Y 4/3	common, distinct		
	Cgk	95+	CL	2.5Y 6/2	common, distinct	strong	
LD-R3-9-57	Apk	0-30	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Ah	30-40	SiCL	10YR 2/1			
	Bg	40+	C	2.5Y 5/4	common, distinct		
LD-R4-9-66	Apk	0-20	SiCL	10YR 2/1		moderate	Orthic Humic Gleysol
	Ah	20-30	SiCL	10YR 2/1			
	Bg	30-60	C	2.5Y 3/2	common, distinct		
	Cg	60-100	C	2.5Y 4/3	common, distinct		
	Cgk	100+	C	2.5Y 4/3	common, distinct	strong	
MS-R1-1-24	Ap	0-35	SiCL	10YR 2/1			Calcareous Black Chernozem
	Bm	35-55	CL	10YR 3/4			
	Bmk	55-70	CL	10YR 3/4		strong	
	Ck	70+	SiL	2.5Y 5/4		strong	
MS-R2-1-31	Ap	0-10	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	10-35	CL	10YR 4/3			
	Ck	35+	CL	2.5Y 5/3		strong	

(continued on next page)

Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
MS-R3-1-26	Ap	0-10	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	10-20	CL	10YR 3/2			
	Ck	20-55	CL	2.5Y 5/3		strong	
	IICk	55-75	SCL	2.5Y 5/3		strong	
	IIICk	75+	CL	2.5Y 5/3		strong	
MS-R4-1-23	Ap	0-20	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	20-50	CL	10YR 3/3			
	Ck	50+	CL	2.5Y 5/3		strong	
MS-R1-2-9	Ap	0-20	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	20-35	SiCL	10YR 2/2			
	C	35-90	SiL	10YR 3/4			
	IICk	90-120	LS	10YR 5/4		moderate	
	IIICk	120+	SiL	2.5Y 5/3		strong	
MS-R2-2-11	Ap	0-30	SiCL	10YR 2/1			Calcareous Black Chernozem
	Bmk	30-45	CL	10YR 4/3		moderate	
	Ck	45+	SiC	2.5Y 5/3		strong	
MS-R3-2-42	Apk	0-40	SiCL	10YR 2/1		moderate	Calcareous Black Chernozem
	Bmk	40-75	SiC	10YR 3/2		strong	
	Ck	75-90	SiC	2.5Y 4/3		strong	
	IICk	90-95	SC	2.5Y 4/3		strong	
	IIICk	95+	SiC	2.5Y 4/3		strong	
MS-R4-2-10	Ap	0-25	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	25-40	CL	10YR 4/3			
	Ck	40+	CL	2.5Y 6/4		strong	
MS-R1-3-55	Ap	0-10	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	10-20	CL	10YR 3/6			
	Ck	20+	CL	2.5Y 6/3		strong	
MS-R2-3-18	Ap	0-20	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	20-35	CL	10YR 3/3			
	Ck	35+	CL	2.5Y 6/2		strong	

(continued on next page)

Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
MS-R3-3-56	Ap	0-15	SiCL	10YR 2/1			Orthic Black
	Bm	15-30	CL	10YR 3/4			Chernozem
	Ck	30+	CL	2.5Y 5/3		strong	
MS-R1-4-75	Ap	0-15	SiL	10YR 2/1			Orthic Black
	Bm	15-20	SiCL	10YR 3/3			Chernozem
	Ck	20+	CL	2.5Y 5/3		strong	
MS-R2-4-22	Ap	0-15	SiL	10YR 2/1			Orthic Black
	Bm	15-25	SiCL	10YR 3/4			Chernozem
	Ck	25+	CL	2.5Y 4/3		strong	
MS-R3-4-76	Ap	0-40	SiCL	10YR 2/1			Orthic Black
	Bm	40-60	CL	10YR 3/3			Chernozem
	Ck1	60-80	CL	2.5Y 5/3		moderate	
	Ck2	80+	CL	2.4Y 5/3		strong	
MS-R4-4-125	Ap	0-30	SiCL	10YR 2/1			Orthic Black
	Bm	30-50	CL	10YR 3/4			Chernozem
	Ck	50+	CL	2.5Y 5/3		strong	
MS-R1-5-200	Ap	0-20	SiL	10YR 2/1			Orthic Black
	Bm	20-45	SiCL	10YR 4/3			Chernozem
	Ck	45+	SiCL	5Y 5/3		strong	
MS-R2-5-36W	Ap	0-30	SiCL	10YR 2/1			Calcareous Black
	Bmk	30-50	SiCL	10YR 3/2		moderate	Chernozem
	Ck1	50-70	SiC	2.5Y 5/2		strong	
	Ck2	70+	SiC	2.5Y 6/2		strong	
MS-R3-5-134	Ap	0-40	SiCL	10YR 2/1			Calcareous Black
	Bmk	40-50	SiC	10YR 3/3		moderate	Chernozem
	BCk	50-70	SiC	10YR 4/3		strong	
	Ck	70+	SiC	2.5Y 6/3		strong	
MS-R1-6-47	Ap	0-20	SiCL	10YR 2/1			Orthic Black
	Bm	20-50	CL	10YR 4/4			Chernozem
	Ck	50+	SiCL	2.5Y 5/3		strong	

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Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
MS-R2-6-45	Ap	0-20	SiCL	10YR 2/1			Orthic Black
	Bm	20-40	CL	10YR 4/6			Chernozem
	Ck1	40-50	CL	2.5Y 5/4		moderate	
	Ck2	50+	CL	2.5Y 6/4		strong	
MS-R3-6-46	Ap	0-10	SiCL	10YR 2/1			Orthic Black
	Bm	10-30	CL	10YR 4/4			Chernozem
	Ck	30+	CL	2.5Y 5/4		strong	
MS-R2-7-12	Ap	0-20	SiCL	10YR 2/1			Orthic Black
	Bm	20-45	SiC	10YR 3/1			Chernozem
	BC	45-60	SiC	10YR 4/3			
	Ck	60+	SiCL	2.5Y 5/3		strong	
MS-R3-7-43	Ap	0-40	SiCL	10YR 2/1			Orthic Black
	Bm	40-55	CL	10YR 5/4			Chernozem
	Ck	55+	SiC	2.5Y 5/3		strong	
MS-R4-7-13	Apk	0-15	SiCL	10YR 2/1		very faint	Calcareous Black
	Bmk	15-20	CL	10YR 4/2		moderate	Chernozem
	Ck	20+	CL	10YR 6/3		strong	
MS-R1-7-17	Apk	0-25	SiCL	10YR 2/1		faint	Calcareous Black
	Bmk	25-30	CL	10YR 4/3		moderate	Chernozem
	Ck	30+	CL	10YR 5/3		Strong	
MS-R1-8-70	Ap	0-30	SiCL	10YR 2/1			Orthic Black
	Bm	30-40	CL	10YR 3/3			Chernozem
	BCk	40-50	CL	10YR 4/3		moderate	
	Ck	50+	CL	2.5Y 5/4		strong	
MS-R2-8-120	Ap	0-35	SiCL	10YR 2/1			Orthic Black
	Bm	35-50	CL	10YR 3/4			Chernozem
	Ck	50+	CL	2.5Y 5/4		strong	
MS-R3-8-69	Ap	0-20	SiCL	10YR 2/1			Calcareous Black
	Bmk	20-45	CL	10YR 4/3		strong	Chernozem
	Ck	45+	CL	2.5Y 5/3		very strong	

(continued on next page)

Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
MS-R4-8-119	Ap	0-15	SiCL	10YR 2/1			Orthic Black
	Bm	15-30	CL	10YR 3/4			Chernozem
	Ck	30+	CL	2.5Y 5/3		strong	
MS-R2-9-59	Ap	0-30	SiCL	10YR 2/1			Orthic Black
	Bm	30-60	CL	10YR 4/4			Chernozem
	Ck	60+	CL	2.5Y 5/4		strong	
MS-R3-9-57	Ap	0-10	SiCL	10YR 2/1			Orthic Black
	Bm	10-20	CL	10YR 3/4			Chernozem
	Ck	20-55	CL	2.5Y 5/4		strong	
	IICk	55+	SCL	2.5Y 5/4		strong	
MS-R4-9-66	Ap	0-25	SiCL	10YR 2/1			Calcareous Black
	Bmk	25-40	CL	10YR 3/4		faint	Chernozem
	Ck1	40-80	CL	2.5Y 5/3		moderate	
	Ck2	80+	CL	2.5Y 5/3		strong	
MS-R1-Z1-205	Ap	0-20	SiCL	10YR 2/1			Orthic Black
	Bm	20-40	CL	10YR 3/4			Chernozem
	BCk	40-65	SiL	10YR 4/4		strong	
	Ck	65+	SL	2.5Y 5/4		strong	
MS-R1-Z1-79	Ap	0-20	SiCL	10YR 2/1			Orthic Black
	Bm	20-30	CL	10YR 3/4			Chernozem
	Ck	30+	CL	2.5Y 5/3		strong	
MS-R3-Z1-123	Ap	0-30	SiCL	10YR 2/1			Orthic Black
	Bm	30-70	CL	10YR 3/3			Chernozem
	Ck	70-95	SiC	2.5Y 4/2		moderate	
	IICk	95+	SL	2.5Y 4/3		moderate	
MS-R4-Z1-300	Ap	0-30	SiCL	10YR 2/1			Orthic Black
	Bm	30-60	CL	10YR 4/4			Chernozem
	Ck	60+	SiCL	2.5Y 5/3		strong	

(continued on next page)

Table A.1 - continued

Sample Identification†	Horizon	Depth (cm)	Hand Texture	Colour (moist)	Mottles	Effervescence	Classification
MS-R1-Z2-84	Ap	0-40	SiCL	10YR 2/1			Calcareous Black Chernozem
	Bmk	40-50	SiC	10YR 4/3		moderate	
	Ck	50-90	SiC	10YR 6/3		strong	
	Bbuk	90-120	SaCL	10YR 4/2		Strong	
	Ck	120+	SiC	10YR 6/3		Strong	
MS-R2-Z2-83	Ap	0-20	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	20-35	CL	10YR 3/3			
	C	35-70	SiC	10YR 4/4			
	Ck	70+	SiC	2.5Y 5/3		strong	
MS-R2-Z2-88	Ap	0-40	SiCL	10YR 2/1			Calcareous Black Chernozem
	Bmk	40-60	CL	10YR 3/2		faint	
	Ck	60-85	CL	2.5Y 4/3		strong	
	IICk	85+	SCL	2.5Y 4/3		strong	
MS-R4-Z2-137	Ap	0-20	SiCL	10YR 2/1			Orthic Black Chernozem
	Bm	20-60	CL	10YR 4/3			
	Ck	60+	CL	2.5Y 5/3		strong	
MS-R1-Z4-112	Ap	0-15	SiCL	10YR 2/1			Orthic Black Chernozem
	Bmu	15-28	SCL	10YR 3/6		crotevena	
	Ck	28+	CL	2.5Y 6/3		strong	
MS-R2-Z4-118	Apk	0-35	SiCL	10YR 2/1		faint	Calcareous Black Chernozem
	Bmk	35-45	CL	10YR 3/3		faint	
	Ck1	45-90	CL	2.5Y 5/3		Moderate	
	Ck2	90+	CL	2.5Y 5/3		strong	

†Sample identification stands for drainage category-replicate (R)-site/zone-wetland number. Drainage categories: UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, and MS=midslope. Each wetland or MS sampled was considered a replicate within each site or zone (Fig. 3.2). A sample from a zone has the letter Z present before the number; no letter Z indicates a site number. Only UD wetlands and corresponding MS were selected by zone. Sites 1, 2 and 3 correspond to RD wetlands, sites 4, 5, and 6 to MD wetlands, and sites 7, 8, and 9 to LD wetlands. Each wetland, drained or undrained, was assigned a unique number that has a paired MS with the same number.

Table A.2 UTM coordinates of wetlands and midslopes sampled in drainage study. All sampling locations were located within UTM Zone 13N.

Sample Identification†	Coordinates (m)		
	X	Y	Z
RD-R1-2-9	720876	5660089	508
MS-R1-2-9	720865	5660086	513
MD-R1-5-200	722461	5662367	511
MS-R1-5-200	722464	5662342	511
MD-R2-5-36W	722277	5662381	511
MS-R2-S-36W	722269	5662402	513
MD-R3-5-134	722102	5662657	504
MS-R3-5-134	722059	5662668	508
LD-R1-7-17	721310	5661544	513
MS-R1-7-17	721340	5661529	512
LD-R2-7-12	721845	5661414	511
MS-R2-7-12	721865	5661412	513
LD-R3-7-43	721835	5661050	516
MS-R3-7-43	721837	5661093	513
LD-R4-7-13	721454	5661463	512
MS-R4-7-13	721478	5661457	513
RD-R2-2-11	720488	5660374	508
MS-R2-2-11	720481	5660580	507
MS-R1-Z2-84	721153	5663254	513
UD-R1-Z2-84	721152	5663238	513
UD-R3-Z2-88	720463	5662748	515
MS-R3-Z2-88	720470	5662764	515
RD-R3-2-42	720632	5660387	506
MS-R3-2-42	720648	5660428	508
MS-R4-2-10	720698	5660120	508
RD-R4-2-10	720642	5660133	508
UD-R2-Z2-83	719449	5662196	512
MS-R2-Z2-83	719450	5662187	512
MS-R1-Z1-205	718544	5662025	515
UD-R1-Z1-205	718562	5662001	516
MS-R1-4-75	718193	5663239	515
MD-R1-4-75	718263	5663253	513
MD-R2-4-22	718071	5663520	510
MS-R2-4-22	718072	5663498	512
MD-R3-4-76	718485	5663672	514
MS-R3-4-76	718502	5663673	514

(continued on next page)

Sample	Coordinates (m)		
Identification†	X	Y	Z
MD-R4-4-125	718337	5663686	516
MS-R4-4-125	718365	5663697	515
MS-R1-1-24	718815	5663930	514
RD-R1-1-24	718787	5663928	511
MS-R2-Z1-79	717893	5663258	513
UD-R2-Z1-79	717882	5663282	513
RD-R2-1-31	718716	5663706	513
MS-R2-1-31	718722	5663698	514
MS-R3-1-26	719111	5663680	514
RD-R3-1-26	719166	5663638	513
MS-R3-Z1-123	718754	5664480	515
UD-R3-Z1-123	718689	5664485	513
RD-R4-1-23	718680	5663846	517
MS-R4-1-23	718697	5663830	515
MS-R4-1-300	718213	5663078	518
UD-R4-1-300	718221	5663087	519
LD-R1-8-70	723791	5659250	511
MS-R1-8-70	723774	5659125	510
UD-R4-2-137	720031	5663937	514
MS-R4-2-137	720058	5663923	515
LD-R3-8-69	724164	5659050	508
MS-R3-8-69	724226	5659051	511
LD-R4-8-119	724141	5659171	509
MS-R4-8-119	724110	5659260	512
LD-R2-8-120	724182	5659541	508
MS-R2-8-120	724232	5659551	509
MS-R1-6-47	724792	5660389	511
MD-R1-6-47	724771	5660426	512
MS-R2-6-45	725228	5660425	508
MD-R2-6-45	725219	5660442	509
MS-R3-6-46	725299	5660416	510
MD-R3-6-46	725321	5660406	508
LD-R2-9-59	726000	5654095	505
MS-R2-9-59	725864	5654121	507
LD-R3-9-57	726236	5654196	503
LD-R3-9-57	726280	5654196	505

(continued on next page)

Sample Identification†	Coordinates (m)		
	X	Y	Z
MS-R4-9-66	726317	5654469	501
LD-R4-9-66	726221	5654349	505
RD-R1-3-55	725379	5655821	505
MS-R1-3-55	725308	5655882	504
RD-R2-3-18	724874	5656099	506
MS-R2-3-18	724882	5656083	505
RD-R3-3-56	724823	5655729	506
MS-R3-3-56	724912	5655822	500
UD-R1-Z4-112	724899	5653618	503
MS-R1-Z4-112	725043	5653597	503
UD-R2-Z4-118	725195	5653249	505
MS-R2-Z4-118	725120	5653201	505

†Sample identification stands for drainage category-replicate (R)-site/zone-wetland number. Drainage categories: UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, and MS=midslope. Each wetland or MS sampled was considered a replicate within each site or zone (Fig. 3.2). A sample from a zone has the letter Z present before the number; no letter Z indicates a site number. Only UD wetlands and corresponding MS were selected by zone. Sites 1, 2 and 3 correspond to RD wetlands, sites 4, 5, and 6 to MD wetlands, and sites 7, 8, and 9 to LD wetlands. Each wetland, drained or undrained, was assigned a unique number that has a paired MS with the same number.

Figure A.1 An example of an unsuitable drained wetland that has evidence of infill. Here it appears that there is a mixed horizon from 0-50 cm overlying the original A horizon.

Table A.3 Macronutrients in drained wetlands and corresponding midslopes.

Depth (cm)	Drainage category†	n	Available NH_4^+-N (mg kg^{-1})	Available NO_3^--N (mg kg^{-1})	Available PO_4^{-3}-P (mg kg^{-1})	Available K (mg kg^{-1})
0-15	UD	10	9.6^{a} (9.9)‡	8.2 (6.4)	12.3^{bc} (9.2)	361.9^{a}(134.8)
	RD	11	3.3^{b} (1.1)	10.7(7.8)	20.3^{ab}(12.8)	380.4^{a} (88.2)
	MD	10	2.3^{b} (0.3)	11.9(5.9)	22.7^{a} (11.5)	392.2^{a}(131.1)
	LD	11	3.2^{b} (1.1)	9.7 (5.9)	13.8^{ab} (8.5)	324.3^{a} (71.8)
	MS	42	3.8^{b} (3.1)	9.0 (5.2)	8.2^{c} (6.8)	193.3^{b} (53.7)
15-30	UD	10	3.4^{a} (2.2)	1.8 (1.4)	4.7^{bc} (5.7)	243.1^{ab} (77.9)
	RD	11	1.8^{ab}(0.8)	2.2 (2.5)	8.9^{a} (7.9)	280.6^{a} (34.1)
	MD	10	1.7^{ab}(0.9)	3.9 (3.9)	12.0^{a} (14.3)	259.1^{ab}(130.3)
	LD	11	1.4^{b} (0.9)	2.8 (2.0)	6.0^{ab} (3.3)	194.0^{b} (31.7)
	MS	42	2.1^{b} (2.6)	2.7 (5.6)	3.4^{c} (0.9)	123.2^{c} (34.4)
30-60	UD	10	1.9^{a} (0.8)	0.5^{b} (0.2)	2.4^{b} (1.3)	217.7^{a} (91.3)
	RD	11	1.1^{a} (0.5)	0.5^{b} (0.3)	4.3^{a} (1.8)	261.6^{a} (48.7)
	MD	10	1.5^{a} (0.9)	0.7^{ab}(0.5)	4.7^{a} (3.2)	249.4^{a} (137.5)
	LD	11	1.3^{a} (0.5)	0.8^{ab}(0.8)	4.9^{a} (4.4)	223.2^{a} (49.7)
	MS	42	1.2^{b} (0.7)	0.9^{a} (0.8)	4.8^{a} (2.3)	111.3^{b} (40.9)
P values						
0-15			0.0006	0.2636	<0.0001	<0.0001
15-30			0.0437	0.3350	<0.0001	<0.0001
30-60			0.0527	0.0172	0.0065	<0.0001

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=mid-slope.

‡Mean (SD) are reported for each drainage category.

§Means with same letter in same column and depth are not significantly different according to Tukey Kramer test (P>0.10).

APPENDIX B: FATE AND FORM OF N AND P IN DRAINED PRAIRIE SOILS UNDER DIFFERENT PRECIPITATION SCENARIOS: A GREENHOUSE EXPERIMENT

Table B.1 Effects of drainage and precipitation treatments on plant N and P in a fertilized greenhouse experiment.

Effect	Treatment				Nitrogen	Phosphorus	
	Drainage category†	Precipit-ation treatment	Plant Mass (g pot^{-1})	N uptake (mg pot^{-1})	N plant content (%)	P uptake (mg pot^{-1})	P plant content (%)
Drainage x moisture	UD	Below	14.86‡	225.85	1.53	25.82	0.18
		Normal	16.44	254.06	1.56	27.03	0.17
		Above	16.68	200.66	1.28	27.21	0.17
	RD	Below	15.18	293.01	1.93	33.06	0.22
		Normal	17.33	281.30	1.63	34.83	0.20
		Above	17.74	293.23	1.66	39.06	0.22
	MD	Below	18.29	339.74	1.87	41.91	0.23
		Normal	21.73	345.20	1.60	43.75	0.20
		Above	21.86	303.39	1.39	44.02	0.20
	LD	Below	16.02	299.46	1.87	30.80	0.19
		Normal	19.27	330.87	1.72	37.86	0.20
		Above	20.49	291.96	1.44	36.96	0.18
	MS	Below	16.00	270.59	1.69	21.33	0.13
		Normal	17.93	273.28	1.56	22.43	0.13
		Above	19.08	228.79	1.20	21.09	0.11
Drainage	UD		15.99[b]	226.85[d]	1.46[b]	26.69[c]	0.17[b]
	RD		16.75[b]	289.18[b]	1.74[a]	35.65[b]	0.21[a]
	MD		20.63[a]	329.44[a]	1.62[ab]	43.23[a]	0.21[a]
	LD		18.59[ab]	307.43[ab]	1.68[ab]	35.21[b]	0.19[ab]
	MS		17.67[ab]	257.55[c]	1.48[b]	21.62[d]	0.12[c]
Moisture		Below	16.07[b]	285.73[a]	1.78[a]	30.58[b]	0.19
		Normal	18.54[a]	296.94[a]	1.61[b]	33.18[a]	0.18
		Above	19.17[a]	263.61[b]	1.39[c]	33.67[a]	0.18
P values							
Drainage x moisture	P value		0.9905	0.0535	0.6223	0.0962	0.6243
	SEM		1.3152	11.7296	0.1054	1.4684	0.0107
Drainage	P value		0.0017	<0.0001	0.0083	<0.0001	<0.0001
	SEM		0.7594	8.4866	0.0630	1.0166	0.0064
Moisture	P value		0.0019	<0.0001	<0.0001	0.0016	0.1322
	SEM		0.5882	7.6753	0.0504	0.8994	0.0052

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.

‡Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.05).

Table B.2 Effects of drainage and precipitation treatments on plant N and P in an unfertilized greenhouse experiment.

Effect	Treatment			Nitrogen		Phosphorus	
	Drainage category†	Precipitation treatment	Plant Mass (g pot^{-1})	N uptake (mg pot^{-1})	N plant content (%)	P uptake (mg pot^{-1})	P plant content (%)
Drainage x moisture	UD	Below	3.46^{efg} ‡	27.74^{b}	0.82	9.66^{fg}	0.29
		Normal	4.17^{defg}	33.21^{b}	0.82	11.04^{ef}	0.28
		Above	3.25^{fg}	29.88^{b}	0.92	10.56^{ef}	0.33
	RD	Below	6.27^{abcd}	55.89^{a}	0.90	20.35^{abc}	0.33
		Normal	7.97^{ab}	69.02^{a}	0.86	22.19^{ab}	0.28
		Above	8.49^{a}	67.49^{a}	0.79	23.08^{a}	0.27
	MD	Below	6.56^{abcd}	59.46^{a}	0.91	18.43^{abcd}	0.28
		Normal	5.24^{cdef}	56.20^{a}	1.10	14.75^{de}	0.28
		Above	5.84^{bcde}	63.85^{a}	1.11	16.55^{cd}	0.29
	LD	Below	7.10^{abc}	58.13^{a}	0.82	17.95^{bcd}	0.25
		Normal	7.82^{ab}	67.39^{a}	0.86	20.70^{abc}	0.27
		Above	7.57^{abc}	70.00^{a}	0.95	20.34^{abc}	0.27
	MS	Below	3.38^{efg}	35.36^{b}	1.05	7.23^{fgh}	0.21
		Normal	2.77^{fg}	30.00^{b}	1.16	5.23^{gh}	0.19
		Above	2.54^{g}	26.06^{b}	1.05	4.42^{h}	0.17
Drainage	UD		3.63^{c}	30.28^{b}	0.85^{c}	10.42^{c}	0.30^{a}
	RD		7.58^{a}	64.13^{a}	0.85^{c}	21.87^{a}	0.29^{a}
	MD		5.88^{b}	59.84^{a}	1.04^{ab}	16.58^{b}	0.28^{a}
	LD		7.50^{a}	65.17^{a}	0.88^{bc}	19.66^{a}	0.26^{a}
	MS		2.90^{c}	30.47^{b}	1.09^{a}	5.63^{d}	0.19^{b}
Moisture		Below	5.35	47.30^{a}	0.90	14.72	0.27
		Normal	5.60	51.16^{a}	0.96	14.78	0.26
		Above	5.54	51.46^{a}	0.97	14.99	0.27
			P values				
Drainage x moisture	P value		0.0353	0.0044	0.5448	0.0181	0.3433
	SEM		0.5072	2.7160	0.08425	1.0391	0.01935
Drainage	P value		<0.001	<0.0001	0.0008	<0.0001	<0.0001
	SEM		0.3252	1.5681	0.05592	0.7048	0.01117
Moisture	P value		0.7089	0.0391	0.3196	0.8937	0.5992
	SEM		0.2747	1.2146	0.04830	0.6165	0.00865

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.

‡Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.05).

Table B.3 Effects of drainage and precipitation treatments on soil N and P in an unfertilized greenhouse experiment.

Effect	Treatment		Nitrogen				Phosphorus	
	Drainage category†	Precipitation treatment	Total N remaining in soil (mg pot^{-1})	NH_4^+ remaining in soil (mg pot^{-1})	Mineralized N (mg d^{-1})‡	NO_3^- remaining in soil (mg pot^{-1})	Total P remaining in soil (mg pot^{-1})	PO_4^{-3} remaining in soil (mg pot^{-1})
Drainage x moisture	UD	Below	3664.1§	2.47	0.27^{d}	2.34^{de}	800.7 ‡	11.05
		Normal	3520.8	1.84	0.44^{d}	4.12^{cde}	685.4	11.54
		Above	3382.8	2.34	0.40^{d}	4.31^{cde}	849.3	10.73
	RD	Below	4380.2	3.23	0.48^{d}	0.87^{e}	1169.9	36.68
		Normal	4493.8	4.58	0.94^{c}	3.27^{cde}	1174.8	39.30
		Above	4501.4	3.35	0.91^{c}	5.08^{bcd}	1202.2	39.69
	MD	Below	3701.1	2.89	1.09^{bc}	4.50^{bcd}	1237.9	41.55
		Normal	3792.7	3.61	1.16^{bc}	9.15^{a}	1203.0	48.91
		Above	3694.0	3.05	1.36^{ab}	7.81^{ab}	1194.2	50.32
	LD	Below	4469.0	3.56	1.10^{bc}	0.94^{e}	1082.3	22.71
		Normal	4551.4	4.47	1.38^{ab}	2.42^{cde}	1128.0	22.87
		Above	4827.9	3.64	1.56^{a}	5.81^{abcd}	1045.3	21.33
	MS	Below	4099.1	2.27	0.53^{d}	3.95^{cde}	889.2	3.99
		Normal	3653.7	3.42	0.51^{d}	5.18^{bcd}	938.0	4.50
		Above	3945.9	1.88	0.43^{d}	5.83^{abc}	824.8	4.48
Drainage	UD		3522.6^{b}	2.21^{b}	0.37^{c}	3.59^{bc}	778.5^{b}	11.11^{d}
	RD		4458.5^{a}	3.72^{a}	0.78^{b}	3.07^{c}	1182.3^{a}	38.56^{b}
	MD		3729.3^{b}	3.19^{ab}	1.20^{a}	7.15^{a}	1211.7^{a}	46.93^{a}
	LD		4616.0^{a}	3.89^{a}	1.35^{a}	3.06^{c}	1085.2^{a}	22.30^{c}
	MS		3899.6^{b}	2.52^{b}	0.49^{c}	4.99^{b}	884.0^{b}	4.32^{e}
Moisture		Below	4062.7	2.89^{b}	0.70^{b}	2.52^{b}	1036.0	23.20
		Normal	4002.4	3.58^{a}	0.89^{a}	4.83^{a}	1025.8	25.42
		Above	4070.4	2.85^{b}	0.93^{a}	5.77^{a}	1023.2	25.31
				P values				
Drainage xmoisture	P value		0.7992	0.4143	0.0061	0.0293	0.7553	0.5076
	SEM		238.57	0.5481	0.0714	0.6770	80.9154	2.2383
Drainage	P value		<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001
	SEM		158.69	0.4103	0.0412	0.4072	56.0243	1.3405
Moisture	P value		0.8651	0.0235	<0.0001	<0.0001	0.9562	0.2133
	SEM		137.24	0.3768	0.0319	0.3276	49.5682	1.0743

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Mineralized N estimated using unfertilized treatment
§Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.05).

Table B.4 Effects of drainage and precipitation treatments on cumulative leachate nitrogen in a greenhouse experiment.

Effect	Treatment		Fertilized				Unfertilized			
	Drainage category†	Precipitation treatment	TDN in leachate (mg pot^{-1})	DON in leachate (mg pot^{-1})	NH_4^+ in leachate (mg pot^{-1})	NO_3^- in leachate (mg pot^{-1})	TDN in leachate (mg pot^{-1})	DON in leachate (mg pot^{-1})	NH_4^+ in leachate (mg pot^{-1})	NO_3^- in leachate (mg pot^{-1})
Drainage x moisture	UD	Below	4.16‡	0.18	0.05^{cd}	4.18	1.06	0.48^{e}	0.05^{ef}	0.53
		Normal	10.37	0.81	0.14^{cd}	11.30	2.17	1.07^{de}	0.14^{de}	0.98
		Above	45.50	1.92	0.62^{a}	44.89	4.19	2.33^{bc}	0.26^{b}	1.60
	RD	Below	0.00	0.00	0.00^{d}	0.00	0.89	0.30^{e}	0.02^{f}	0.58
		Normal	9.15	0.63	0.07^{cd}	8.45	3.53	0.55^{e}	0.05^{ef}	3.02
		Above	58.39	3.14	0.39^{b}	57.36	5.43	2.73^{abc}	0.21^{bcd}	2.50
	MD	Below	0.00	0.00	0.00^{d}	0.00	0.77	0.32^{e}	0.03^{f}	0.43
		Normal	2.09	0.00	0.01^{d}	2.41	1.95	0.82^{de}	0.07^{ef}	1.07
		Above	76.75	4.07	0.24^{bc}	78.75	6.93	3.23^{ab}	0.25^{bc}	3.45
	LD	Below	0.00	0.00	0.00^{d}	0.00	0.86	0.26^{e}	0.03^{f}	0.58
		Normal	2.18	0.16	0.02^{d}	2.01	0.97	0.31^{e}	0.03^{f}	0.63
		Above	47.89	3.03	0.21^{bcd}	48.75	5.46	2.54^{abc}	0.19^{bcd}	2.73
	MS	Below	0.00	0.00	0.00^{d}	0.00	1.35	0.48^{e}	0.05^{ef}	0.83
		Normal	21.07	3.28	0.04^{cd}	17.88	4.88	1.70^{cd}	0.15^{cde}	3.03
		Above	76.75	6.70	0.21^{bcd}	68.99	8.05	3.60^{a}	0.36^{a}	4.09
Drainage	UD		20.01	0.97^{b}	0.27^{a}	20.12	2.47^{b}	1.29^{b}	0.15^{ab}	1.04
	RD		22.51	1.26^{b}	0.15^{b}	21.94	3.28^{ab}	1.18^{b}	0.09^{c}	2.03
	MD		26.28	1.36^{b}	0.08^{b}	27.05	3.22^{ab}	1.46^{ab}	0.11^{bc}	1.65
	LD		16.69	1.06^{b}	0.08^{b}	16.92	2.43^{b}	1.03^{b}	0.08^{c}	1.31
	MS		31.58	3.33^{a}	0.09^{b}	28.96	4.76^{a}	1.93^{a}	0.19^{a}	2.65
Moisture		Below	0.83^{b}	0.04^{b}	0.01^{b}	0.84^{b}	0.99^{c}	0.37^{c}	0.03^{c}	0.59^{b}
		Normal	8.97^{b}	0.98^{b}	0.06^{b}	8.41^{b}	2.70^{b}	0.89^{b}	0.09^{b}	1.75^{ab}
		Above	60.44^{a}	3.77^{a}	0.33^{a}	59.75^{a}	6.01^{a}	2.89^{a}	0.25^{a}	2.87^{a}
						P values				
Drainage xmoisture	P value		0.4355	0.1315	0.0033	0.3584	0.2970	0.0319	0.0252	0.5364
	SEM		9.1094	0.7881	0.04293	8.6366	0.8741	0.2687	0.02817	0.7900
Drainage	P value		0.3323	0.0049	<0.0001	0.4286	0.0187	0.0002	<0.0001	0.1337
	SEM		5.2593	0.4550	0.02527	4.9863	0.5047	0.2081	0.02318	0.4561
Moisture	P value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0004
	SEM		4.0738	0.3525	0.01994	3.8624	0.3909	0.1938	0.02204	0.3533

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.05) with exception of drainage effect on DON in leachate that was determined according to Tukey Kramer test (P>0.1).

Table B.5 Effects of drainage and different precipitation treatments on cumulative leachate phosphorus in a greenhouse experiment.

Effect	Treatment		Fertilized	Unfertilized
	Drainage category†	Precipitation treatment	PO_4^{-3} in leachate (mg pot^{-1})	PO_4^{-3} in leachate (mg pot^{-1})
Drainage x moisture	UD	Below	0.02[d]‡	0.04[e]
		Normal	0.06[cd]	0.09[de]
		Above	0.21[ab]	0.19[cd]
	RD	Below	0.00[d]	0.03[e]
		Normal	0.06[cd]	0.08[de]
		Above	0.33[a]	0.39[b]
	MD	Below	0.00[d]	0.05[de]
		Normal	0.01[d]	0.15[cde]
		Above	0.26[ab]	0.60[a]
	LD	Below	0.00[d]	0.03[e]
		Normal	0.01[d]	0.03[e]
		Above	0.17[bc]	0.26[bc]
	MS	Below	0.00[d]	0.03[e]
		Normal	0.01[d]	0.07[de]
		Above	0.05[cd]	0.16[cde]
Drainage	UD		0.10[ab]	0.11[bc]
	RD		0.13[a]	0.17[b]
	MD		0.09[ab]	0.27[a]
	LD		0.06[bc]	0.10[bc]
	MS		0.02[c]	0.09[c]
Moisture		Below	0.004[b]	0.04[c]
		Normal	0.03[b]	0.09[b]
		Above	0.20[a]	0.32[a]
		P values		
Drainage x Moisture	P value		0.0002	<0.0001
	SEM		0.0240	0.0293
Drainage	P value		0.0001	<0.0001
	SEM		0.0141	0.0173
Moisture	P value		<0.0001	<0.0001
	SEM		0.0111	0.0136

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.

‡Means with same letter in same column are not significantly different according to Tukey Kramer test (P>0.05).

Table B.6 Nitrogen nutrient budget of fertilized drained wetlands and corresponding midslope under different precipitation treatments.

	Inputs	Outputs									Unknown		
Drain-age Cate-gory†	Initial Total soil N (mg pot^{-1})	Plant uptake of N (mg pot^{-1})			TDN in leachate (mg pot^{-1})			Total N remaining in soil (mg pot^{-1})			Unaccounted N (mg pot^{-1})‡		
		Below§	Normal	Above	Below	Normal	Above	Below	Normal	Above	Below	Normal	Above
UD	3625.6¶	225.9Bc	254.1Ab	200.7Cb	4.16B	10.37Bb	45.49A	3613.6b	3363.5b	3161.6	218.0a	-2.4a	-217.8
		(22.7)#††	(14.2)	(16.6)	(2.76)	(4.50)	(28.4)	(22.8)	(279.5)	(581.3)	(44.4)	(281.9)	(614.4)
RD	4975.8	293.0Aab	281.3Bb	293.2Aa	0B	9.15Bb	58.39A	4390.2a	4026.3ab	3756.3	-292.6ab	-659.1ab	-867.87
		(15.2)	(10.2)	(7.2)	(0)	(5.17)	(9.95)	(343.8)	(481.4)	(299.4)	(357.3)	(473.2)	(292.5)
MD	4447.0	339.7Aa	345.2Aa	303.4Ba	0B	2.09Bb	76.75A	3541.1b	3687.6ab	3539.9	-566.2b	-412.1ab	-526.9
		(29.2)	(22.7)	(19.6)	(0)	(3.62)	(46.72)	(65.0)	(575.7)	(643.6)	(40.0)	(557.8)	(579.0)
LD	5214.9	299.5ab	330.9a	292.0a	0	2.18b	47.89	4660.3a	4089.3a	4185.8	-255.1ab	-792.5b	-689.2
		(38.8)	(20.5)	(19.8)	(0)	(3.78)	(18.5)	(332.0)	(158.8)	(639.2)	(358.3)	(174.2)	(651.5)
MS	4276.2	270.6Abc	273.3Ab	228.8Bb	0C	21.07Ba	73.66A	3602.1b	3728.4ab	3433.6	-403.5ab	-253.5ab	-540.1
		(21.9)	(15.3)	(6.2)	(0)	(6.55)	(13.72)	(370.6)	(526.2)	(415.0)	(357.9)	(519.0)	(412.2)
P values for drainage effect													
		0.0010	0.0001	<0.0001	0.4609	<0.0001	0.5347	0.0016	0.0395	0.2598	0.0449	0.0217	0.6595
P values for moisture effect													
UD			0.0008			0.0451			0.3895			0.4444	
RD			0.0393			0.0003			0.2070			0.2526	
MD			0.0433			0.0212			0.8999			0.9004	
LD			0.2554			0.0027			0.2875			0.3675	
MS			0.0078			0.0005			0.6794			0.6795	

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Unaccounted N determined as outputs-inputs, positive values represent unaccounted gains in N while negative values represent unaccounted losses.
§Below, normal and above represent the three different precipitation treatments applied.
¶For inputs n=1, for outputs and unknown n=3.
#Mean (SD).
††Means with same upper-case letter in same row (drainage category) and with same lower-case letter in same column (output or unknown) are not significantly different according to Tukey Kramer test (P>0.05).

Table B.7 Phosphorus nutrient budget of fertilized drained wetlands and corresponding midslope under different precipitation treatments.

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.

Drainage Category†	Inputs: Initial total soil P (mg pot^{-1})	Outputs: Plant uptake of P (mg pot^{-1})			Outputs: Loss of PO_4^{-3}-P in leachate (mg pot^{-1})			Outputs: Total P remaining in soil (mg pot^{-1})			Unknown: Unaccounted P (mg pot^{-1})‡		
		Below§	Normal	Above	Below	Normal	Above	Below	Normal	Above	Below	Normal	Above
UD	692.0¶	25.8 bc (2.3)#††	27.0 c (1.7)	27.2 c (3.1)	0.02 aB (0.00)	0.06 aB (0.02)	0.21 abA (0.06)	753.3 c (95.1)	792.5 b (95.4)	694.8 a (68.9)	87.1 (92.8)	127.5 (93.8)	0.1 (67.2)
RD	1254.0	33.1 bB (1.5)	34.8 bB (3.1)	39.1 abA (1.3)	0.00 bB (0.00)	0.06 aB (0.03)	0.33 aA (0.04)	1241.6 ab (193.8)	1143.6 ab (161.6)	1212.3 a (279.5)	20.7 (193.7)	-75.5 (161.3)	-2.3 (278.3)
MD	1299.7	41.9 a (3.8)	43.8 a (3.0)	44.0 a (1.9)	0.00 bB (0.00)	0.01 aB (0.01)	0.26 aA (0.11)	1308.0 a (231.9)	1216.1 a (256.6)	1171.1 a (239.9)	50.1 (228.8)	-39.9 (254.0)	-84.4 (238.8)
LD	1176.1	30.8 b (5.1)	37.9 b (1.5)	37.0 b (2.6)	0.00 bB (0.00)	0.01 aB (0.01)	0.17 abA (0.08)	1237.1 ab (138.8)	1087.8 ab (288.2)	1045.4 a (295.7)	91.8 (141.5)	-50.4 (287.0)	-93.6 (297.8)
MS	1017.3	21.3 c (0.4)	22.4 d (1.4)	21.1 d (1.5)	0.00 bB (0.00)	0.01 aB (0.01)	0.05 bA (0.01)	1002.8 bc (136.0)	901.2 ab (233.2)	822.3 a (73.4)	6.9 (135.6)	-93.6 (233.4)	-173.9 (73.1)
P values for drainage effect													
		0.0002	<0.0001	<0.0001	<0.0001	0.0125	0.0101	0.0006	0.0311	0.0356	0.7599	0.3937	0.6914
P values for moisture effect													
UD			0.6903			0.0016			0.4376			0.4271	
RD			0.0119			0.0002			0.7284			0.7322	
MD			0.4701			0.0042			0.2531			0.2647	
LD			0.0842			0.0053			0.2577			0.2870	
MS			0.2190			0.0016			0.4495			0.4520	

‡Unaccounted P determined as outputs-inputs, positive values represent unaccounted gains in P while negative values represent unaccounted losses.

§Below, normal and above represent the three different precipitation treatments applied.

¶For inputs n=1, for outputs and unknown n=3.

#Mean (SD).

††Means with same upper-case letter in same row (drainage category) and with same lower-case letter in same column (output or unknown) are not significantly different according to Tukey Kramer test (P>0.05).

Table B.8 Nitrogen nutrient budget of unfertilized drained wetlands and corresponding midslope under different precipitation treatments.

Drain-age Cate-gory†	Inputs: Initial Total soil N (mg pot^{-1})	Outputs: Plant uptake of N (mg pot^{-1})			TDN in leachate (mg pot^{-1})			Total N remaining in soil (mg pot^{-1})			Unknown: Unaccounted N (mg pot^{-1})‡		
		Below§	Normal	Above	Below	Normal	Above	Below	Normal	Above	Below	Normal	Above
UD	3164.1¶	27.7 b (1.0)#††	33.2 b (7.3)	29.9 b (2.8)	1.06 C (0.24)	2.17 B (0.83)	4.19 bA (0.50)	3664.1 (202.9)	3520.8 c (272.4)	3382.8 b (325.5)	528.8 (202.3)	392.1 (270.4)	252.9 (325.4)
RD	4558.0	55.9 aB (0.6)	69.0 aA (2.8)	67.5 aA (7.5)	0.89 (0.11)	3.53 (3.94)	5.43 ab (0.77)	4308.2 (652.4)	4493.8 ab (457.4)	4501.4 ab (650.1)	-121.1 (652.1)	8.3 (454.0)	16.3 (647.6)
MD	4013.4	59.5 a (3.7)	56.2 a (5.5)	63.9 a (5.3)	0.77 B (0.28)	1.95 B (1.52)	6.93 abA (1.25)	3701.1 (158.9)	3792.7 abc (436.6)	3694.0 ab (784.2)	-252.0 (156.9)	-162.5 (441.42)	-248.6 (778.0)
LD	4818.2	58.1 a (4.9)	67.4 a (4.0)	70.0 a (5.8)	0.86 B (0.14)	0.97 B (0.14)	5.46 abA (0.84)	4469.0 (264.9)	4551.0 a (125.5)	4827.9 a (464.1)	-290.2 (268.2)	-198.8 (121.4)	85.2 (469.1)
MS	3842.8	35.4 b (3.7)	30.0 b (5.7)	26.1 b (3.8)	1.35 B (0.66)	4.88 AB (2.67)	8.05 aA (2.25)	4099.1 (298.8)	3653.6 bc (159.3)	3945.9 ab (189.0)	293.0 (302.1)	-154.3 (163.1)	137.2 (190.3)
P values for drainage effect													
		<0.0001	<0.0001	<0.0001	0.3006	0.3159	0.0273	0.0615	0.0091	0.0395	0.0724	0.2145	0.7839
P values for moisture effect													
UD			0.3917			0.0011			0.2189			0.2298	
RD			0.0242			0.1341			0.9333			0.9153	
MD			0.2351			0.0012			0.9558			0.9618	
LD			0.0577			<0.0001			0.1255			0.1208	
MS			0.1051			0.0145			0.1210			0.1243	

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Unaccounted N determined as outputs-inputs, positive values represent unaccounted gains in N while negative values represent unaccounted losses.
§Below, normal and above represent the three different precipitation treatments applied.
¶For inputs n=1, for outputs and unknown n=3.
#Mean (SD).
††Means with same upper-case letter in same row (drainage category) and with same lower-case letter in same column (output or unknown) are not significantly different according to Tukey Kramer test (P>0.05).

Table B.9 Phosphorus nutrient budget of unfertilized drained wetlands and corresponding midslope under different precipitation treatments.

Drainage Category†	Inputs: Initial total soil P (mg pot^{-1})	Outputs: Plant uptake of P (mg pot^{-1})			Loss of PO_4^{-3}-P in leachate (mg pot^{-1})			Total P remaining in soil (mg pot^{-1})			Unknown: Unaccounted P (mg pot^{-1})‡		
		Below§	Normal	Above	Below	Normal	Above	Below	Normal	Above	Below	Normal	Above
UD	656.7¶	9.7 b (0.6)#††	11.0 cd (0.6)	10.6d (1.0)	0.04 abC (0.01)	0.09 B (0.04)	0.19 bcA (0.03)	800.7 b (59.6)	685.4 b (65.1)	849.3 bc (133.7)	153.7 (59.8)	39.8 (65.0)	203.4 (134.6)
RD	1218.7	20.4 a (0.8)	22.2 a (2.3)	23.1 a (0.6)	0.03 abB (0.01)	0.08 B (0.04)	0.39 bA (0.06)	1169.9 ab (147.6)	1174.8 a (187.1)	1202.2 a (202.8)	-28.4 (148.2)	-21.6 (189.5)	7.0 (202.5)
MD	1264.4	18.4 a (0.9)	14.8 bc (4.1)	16.6 c (1.5)	0.05 aB (0.01)	0.15 B (0.10)	0.60 aA (0.14)	1237.9 a (238.4)	1203.0 a (151.4)	1194.2 ab (127.7)	-8.0 (238.0)	-46.6 (153.1)	-53.1 (127.7)
LD	1140.8	18.0 a (2.2)	20.7 ab (2.5)	20.3 b (1.9)	0.03 bB (0.00)	0.03 B (0.00)	0.26 bcA (0.04)	1082.3 ab (185.7)	1128.0 a (123.7)	1045.3 abc (68.1)	-40.5 (185.8)	8.0 (121.5)	-74.9 (68.5)
MS	981.9	7.2 bA (0.6)	5.2 dAB (2.0)	4.4 eB (1.3)	0.03 bB (0.01)	0.07 B (0.02)	0.16 cA (0.04)	889.2 ab (69.7)	938.0 ab (114.3)	824.8 c (51.8)	-85.5 (69.1)	-38.6 (114.5)	-152.5 (51.5)
P values for drainage effect													
		<0.0001	0.0001	<0.0001	0.0134	0.1466	0.0003	0.0274	0.0009	0.0102	0.3863	0.7983	0.0586
P values for moisture effect													
UD			0.1571			0.0010			0.1395			0.1441	
RD			0.1445			0.0001			0.9691			0.9644	
MD			0.2205			0.0030			0.9444			0.9379	
LD			0.3257			<0.0001			0.6921			0.6880	
MS			0.0148			0.0033			0.3149			0.3093	

†UD=undrained, RD=recently drained, MD=medium drained, LD=longest drained, MS=midslope.
‡Unaccounted P determined as outputs-inputs, positive values represent unaccounted gains in P while negative values represent unaccounted losses.
§Below, normal and above represent the three different precipitation treatments applied.
¶For inputs n=1, for outputs and unknown n=3.
#Mean (SD).
††Means with same upper-case letter in same row (drainage category) and with same lower-case letter in same column (output or unknown) are not significantly different according to Tukey Kramer test (P>0.05).