HYDRIC SOIL INDICATORS, MAGNETIC SUSCEPTIBILITY AND GREENHOUSE GAS EMISSIONS AMONG DIFFERING LAND-USES OF PRAIRIE POTHOLE REGION WETLAND SOILS

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ABSTRACT

Land-use change is prevalent across the Prairie Pothole Region (PPR) because of widespread agricultural expansion over the last century. Different land-use histories will affect the distributions of native vegetation and soil biogeochemistry of PPR wetlands. Furthermore, because native vegetation is partially required for wetland classification, supplementary methods are needed for proper wetland delineation. Accurate estimates of GHG emissions are required for correct climate change models; therefore proper investigation of contrasting land-use histories on GHG emissions is essential. This study focused on determining the effect that different land-use histories had on the expression of soil hydric features and magnetic susceptibility as well as examining interacting effects among contrasting land-use histories and biogeochemical controls of GHG emissions of PPR wetlands.

To determine the differing effects of land-use histories on hydric soil indicators and magnetic susceptibility, fifteen ephemeral wetlands under differing land-uses (annually cultivated, restored grassland, seeded pasture and native grassland) were sampled to a depth of 1 m with samples collected every 10 cm. An upland pit was correspondingly sampled for each wetland. Soils were then analyzed for organic C, inorganic C, dithionite extractable Fe, particle size distributions, wet stable aggregate distributions and magnetic susceptibility at four different temperature treatments (room temperature, 100 °C, 300 °C and 500 °C). While some variables had observable difference among the land-uses (i.e. organic C, dithionite extractable Fe and magnetic susceptibility), the most pronounced differences were between the different pit positions (i.e. wetland pits vs. upland pits). The data was holistically analyzed through non-metric multidimensional scaling (NMDS) and position based differences were easily identified through this approach; however, only slight differences were present with respect to contrasting land-use histories.

The controls of GHG emissions and their interactions were evaluated through two laboratory incubations (i.e. CH_4 incubation and N_2O incubation), with a factorial design using land-use history treatments as well as biogeochemical controls specific to each GHG (i.e. CH_4: SO4- additions; N2O: water filled pore space [WFPS] treatments and NO_3^- additions). Both incubations had the presence of interacting factors among the differing land-use histories. During the CH_4 incubation, each land-use history responded oppositely to sulfate additions. During the N_2O incubations, both WFPS treatments and NO_3^- additions had additive effects on the emissions of N_2O. Moreover, the presence of the interactions satisfied the objective of the incubation study.

Overall it was determined that while land-use history significantly altered the response of GHG controls with respect to GHG emissions, it did not have strong effects in influencing hydric soil indicators and magnetic susceptibility values.

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LIST OF ABBREVIATIONS

ANOVA – Analysis of variance

CEC – Cation exchange capacity

CV – Coefficient of variation

DF – Dithionite extractable iron

FD – Frequency dependent charge

IC – Inorganic carbon

LME – Linear mixed effects model

MS – Magnetic susceptibility

NGS – Native grassland site

NMDS – Non-metric multidimensional scaling

OC – Organic carbon

OM – Organic matter

PPR – Prairie Pothole Region

S0 – Sulfate treatment: 0% sulfidic pond water

S10 – Sulfate treatment: 10% sulfidic pond water

S50 – Sulfate treatment: 50% sulfidic pond water

S100 – Sulfate treatment: 100% sulfidic pond water

SDNWA – St. Denis National Wildlife Area

SOC – Soil organic carbon

SOC_{eq} – Soil organic carbon equivalency (0 – 30 cm)

Tukey's HSD – Tukey's honestly significant difference

W60 – Water filled pore space treatment: 60%

W80 – Water filled pored space treatment: 80%

W120 – Water filled pore space treatment: 120%

WFPS – Water filled pore space

1. INTRODUCTION

Humans have always altered their surroundings for the purpose of improving their quality of life; however, these changes have always had an environmental cost. Historically, the most common anthropogenic land-use change was for agrarian purposes and since the beginnings of agriculture, c. 10 000 BCE, humans have made constant changes to their surrounding environments for the production of food, fiber and fuel. The first of these systems, herding of pastoral animals, was blamed as the primary degrader of arable land through the overgrazing of sloped areas that exacerbated soil erosion. Later, crop production was attributed with land degradation because sodic irrigation water brought about widespread salinization of Middle Eastern soils (Diamond, 1994, 2006).

Within the Canadian Prairies, widespread land-use change began with European settlement in the later 19^{th} century. The Lord Selkirk settlers of 1812 are often attributed as being the first farming community of the present day Canadian Prairies, though some fur trading forts experimented with vegetable production years prior. Prairie agricultural expansion continued steadily for the next several decades but the true western agrarian booms began after the completion of the Canadian Pacific Railway in 1881. The European settlement of the Canadian Prairie Pothole Region (PPR) was largely encouraged after the construction of the new railroad and population quickly rose in these areas. Therefore, agriculture on the Canadian PPR goes back over a century in most areas (Thomas, 2011).

The PPR itself is characterized by its hummocky, rolling topography that gives rise to many depression areas. These depression areas are prone to collecting moisture after the spring snowmelt; furthermore, this moisture influences the development of wetland flora, fauna and soils. In addition to providing a habitat for many invertebrates and vegetation (Euliss et al., 2001), these wetlands provide nesting grounds for much of North America's migratory waterfowl (Klett et al., 1988). These small wetland areas, because of their temporary ponding nature, can often be cultivated at later parts in the season and are thus susceptible to agricultural land-uses through both cultivation and runoff nutrients.

Land-use changes on the Canadian Prairies, usually through agriculture, have been found to disturb native vegetation, soils and wildlife. Since the start of agriculture on the Prairies, it is estimated that nearly half of the soils' native organic matter (OM) has been lost through continued cultivation and cropping of the region (Janzen et al., 1998). In addition, agriculture accelerates the spread of invasive plant species and destroys natural habitats of the indigenous wildlife (DiTomaso, 2000; DUC, 2003). The effect that land-use histories have on the different areas of the Prairies is important to study because they allow for proper quantification of the Prairie landscapes that may ultimately lead to better protection and management.

The natural features of PPR wetlands serve another important task, namely in classification criteria. The main method of wetland delineation on the PPR relies on native plant species to identify concentric zones of wetlands, which are used to classify the wetlands into one of seven classes (Stewart and Kantrud, 1971). Prolonged cultivation of smaller size wetlands (Class I and II) may have altered seedbeds relative to their native grassland states. One such supplementary tool for classification may be through pedological analysis of hydric features. Depth and duration of standing water may additionally be used to delineate wetlands of cropped areas where natural vegetation may not present though additional criteria would be beneficial to wetland classification. The disruptions to the native seedbed from continued cultivation requires that another supplementary method be made available for proper classification; such supplementary tools for classification may be found through analysis of pedological features.

When soils undergo frequent and prolonged saturation, they will develop specific hydric features and altered magnetic susceptibilities (MS). Waterlogged soils will develop visual and chemical traits based on the accumulation of organic matter (OM), reduction and translocation of Fe and Mn and the reduction of S compounds. Magnetic susceptibility values are affected by the oxidation state of Fe and Mn within a soil; oxidized levels of Fe and Mn will cause higher MS values whereas reduced forms of the metallic atoms will results in lower magnetic susceptibility values (de Jong et al., 2000). The US Environmental Protection Agency has commonly used hydric soils, and to a lesser extent magnetic susceptibility, as a means of delineating wetland soils from non-wetland soils for conservation purposes (Grimley and Vepraskas, 2000; Vepraskas and Faulkner, 2000). Therefore, these hydric soil and MS features may have potential as supplementary classification criteria in the absence of the native plant species. Land-use changes, however, do not only affect the classification methods of PPR wetlands.

Another major influence of land-use changes is their effect on the nutrient regimes of the soils; these different soil nutrient statuses can affect their surrounding environment through greenhouse gas (GHG) emissions. Agriculture, through its manipulation of soil physical features (i.e. bulk density, temperature, moisture content, etc.), causes recalcitrant forms of nutrients to become more exposed to weathering and degradation and thus more available to soil flora and fauna. Additionally, agriculture commonly involves the addition of exogenous nutrients, particularly those containing available forms of N. The changing of the nutrient dynamics within soils can cause increased emission of climate-changing GHGs (Smith et al., 2003; Havlin et al., 2004).

The effect of land-use change as it relates to GHG production has been the topic of several past studies (Chan and Parkin, 2001; Bedard-Haughn et al., 2006a; Schaufler et al., 2010). What have been less studied are the interacting factors that may exist between contrasting land-use histories and the biogeochemical controls of GHG production. Several biogeochemical GHG controls exist that will regulate the production of the emitted gases. For CH_4 production, the presence of thermodynamically favored reducing agents relative to CO_2, will affect the levels of CH_4 produced; of these reducing agents, SO_4^- is the most widely associated. In terms of N_2O, water filled pore space (WFPS) levels and available NO_3^- are strong controllers of emitted gases. The knowledge of potential interacting factors would help to close the gap on unknown global GHG emission accounts (Le Mer and Rogers, 2001).

The effect of land-use therefore raises multiple questions in relation to PPR wetlands. One question raised is how hydric soil features of PPR wetlands may be affected by contrasting land-use histories. Another question raised is whether contrasting land-use histories have interacting effects with biogeochemical controls of GHG production with respect to their emitted gases.

The overall goals of this study were to examine the effects that differing land-use histories had on hydric pedological features of soils and their biogeochemical controls of GHG production.

1.1 Objectives

Objective 1: Determine if hydric features and magnetic susceptibility of Prairie Pothole Region wetland soils differ with contrasting land-use histories (annual cultivation, native grassland, restored grassland and seeded pasture grassland).

Objective 2a: Investigate the presence of interacting effects between differing land-uses and SO_4^- additions with respect to CH_4 emissions of Prairie Pothole Region wetland soils.

Objective 2b: Investigate the presence of interacting effects among differing land-uses, water filled pore space treatment and NO_3^- additions with respect to N_2O emissions of Prairie Pothole Region wetland soils.

2. LITERATURE REVIEW

2.1 Pedology of Wetland Soils

2.1.1 Prairie Pothole Region wetlands

The Prairie Pothole region (PPR) is located in North America and occupies approximately 900 000 km^2 (Fig. 2.1). The region is characterized by its hummocky, rolling topography with kettle type depressions frequenting the landscape. These depression areas are colloquially referred to as potholes or sloughs and often have undeveloped surface drainage channels; therefore, these potholes are prone to collecting water after events of moisture redistribution (i.e. spring snowmelt; large precipitation events) and influence the development of wetland flora, fauna and soils (Richardson et al., 1994).

The Prairie Pothole Region classification is broad and contains several zones of classification. The region can also be defined and classified in terms of its soil (e.g. Brown Soil Zone, Black Soil Zone, etc.) or vegetation (e.g. Prairie Parkland, Moist Mixed Grassland, Mixed Grassland, etc.) (Soils Classification Working Group, 1998; Gauthier and Wilken, 2003).

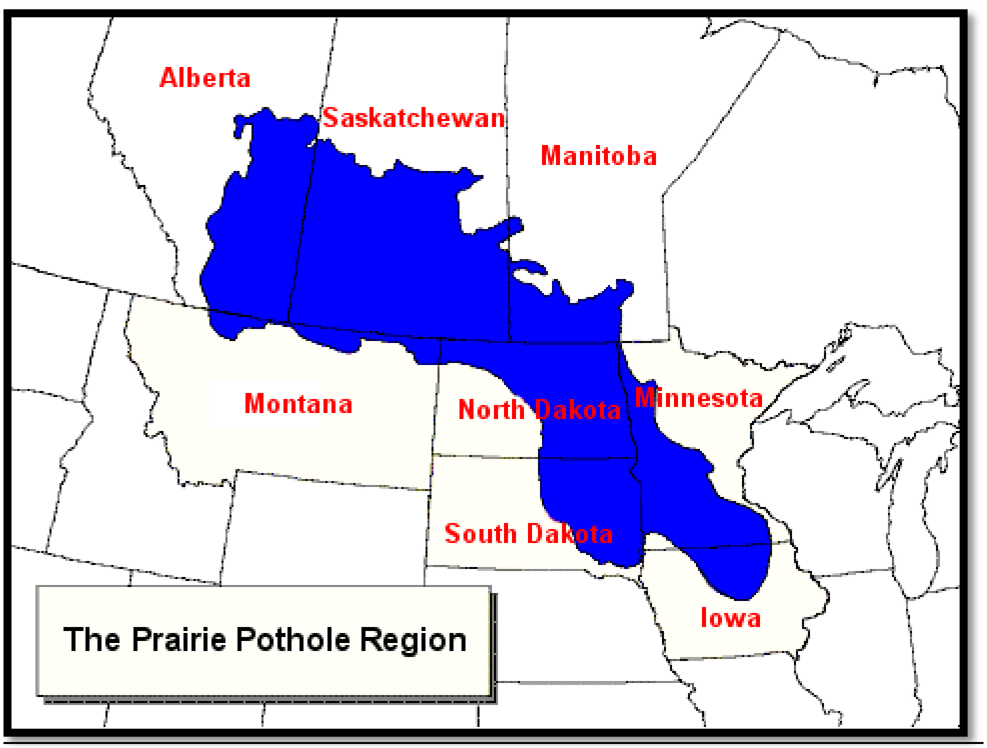

Fig. 2. 1. Map of the Prairie Pothole Region (PPR). The dark area denotes the approximate boundaries of the PPR with political boundaries included. The region covers approximately 900 000 km^2, spanning three Canadian provinces and four American states. Credit: U.S. Fish and Wildlife Service.

Climatically, the average lows in January are -21.6°C and the average highs in July are 25.0°C (Environment Canada, 2012). Annual precipitation in the PPR ranges from approximately 350 mm to 800 mm with the higher annual precipitation rates in the East (Richardson et al., 1992; Akinremi et al., 1999). The potential evapotranspiration rates decrease on a northern orthogonal gradient. Most years, the region will experience a moisture deficit whereby the potential evapotranspiration is less than annually received precipitation (Akinremi et al., 1999). The moisture deficit of the region can be observed through the limited durations of ponding water within the wetlands. The small wetland depressions will usually only have standing water for a portion of the year, often ranging from three weeks to five months after the spring snowmelt (Euliss et al., 2004), which is referred to as the 'hydroperiod' (van der Kamp and Hayashi, 2009). These limited hydroperiods separate PPR wetlands from others with longer periods of standing water. The wetlands cover approximately 11% of the landscape and vary in size from < 0.5 ha to 4 ha (Richardson et al., 1994).

Drought periods on the PPR usually occur every one or two decades, and last for two to three years. Droughts help preserve the region's wetlands because they prevent tree encroachment of the wetlands through lack of moisture (Mitsch and Gosselink, 2007). The drought periods, in conjunction with the yearly dry down periods, are responsible for maintaining the saline ponds of some areas. These drought years will also strongly influence the length of the wetland's hydroperiod, whereby a wetland's hydroperiod can be highly different between drought and deluge years.

Waterfowl and other birds are the main animal species associated with the PPR. While the PPR makes up approximately 10% of North America`s duck breeding ground, it is responsible for the production of over 50% of the Anatinae (dabbling duck) population (Klett et al., 1988). Other waterfowl such as geese also rely on the nesting grounds supplied by the PPR. Many environmental organizations support wetland restoration efforts within the PPR because of their importance to waterfowl populations (DUC, 2003). In addition to waterfowl, many species of Prairie-specific amphibians are threatened through habitat loss and fragmentation of PPR ponds (Lehtinen et al., 1999).

2.1.2 Hydrology of the Prairie Pothole Region

Surface flow and groundwater flow are two of the major components of hydrology, however, the latter is more important in the PPR because surface flow is only ephemerally present (Hayashi et al., 1998). Wetlands within the region are sparsely connected because of a combination of high evapotranspiration and low precipitation rates that limit the amount of surface runoff. The wetlands themselves are often internally drained and no connection exists to main prairie streams (Hayashi et al., 2003). The exception to this is the case of the fill-and-spill runoff system (Spence and Woo, 2003) which usually occurs during snowmelt and heavy spring precipitation events (Fang et al., 2007). Fill-and-spill events occur when formerly unconnected surface water channels are connected through excess moisture, typically occurring during snowmelt (Shaw et al., 2012). Fill-and-spill runoff events operate in the fashion that upland wetlands will retain their water until they are filled, which in turn will cause them to spill out their water to lower wetlands, essentially creating a cascading effect. This cascade will continue until the water reaches an outlet, such as a major stream or a larger wetland basin (Fang et al., 2007); however, only a fraction (approx. 39%) of the cascading water will reach an outlet during these events (Shaw et al., 2012). The cascading effect is one of the ways that lower elevation wetlands may have elevated solute concentrations (i.e., from all other wetlands draining into them followed by high evapotranspiration rates later in the season).

Miller et al. (1985) made note of three distinct wetland types within the PPR; recharge, discharge and flowthrough wetlands. The recharge wetlands are located in the elevated, upland areas and will have a net downward movement of water through the soil. It is only during the deluge periods where the recharge wetlands receive groundwater contributions. With continual moisture being washed downward, the soils are low in dissolvable salts and the ponding water is likely non-saline (Heagle et al., 2013).

The discharge wetlands, located on the lowland areas, conversely receive strong contributions from groundwater (Miller et al., 1985). These discharge wetlands retain their standing water longer relative to the recharge wetlands because they receive continual additions from groundwater. The discharge wetlands are more prone to receiving groundwater additions than their recharge counterparts because their lower elevated landscape position favors such an occurrence; albeit, recharge and discharge are ephemeral classifications and will change depending on the dynamics of the season. The net neutral or upward moisture movement causes discharge soils to accumulate dissolvable salts as the solute rich groundwater is allowed to evaporate within these depressional areas (Heagle et al., 2013). The ponding water therefore can often be slight to moderately saline within these discharge wetlands (Richardson et al., 1994).

Flowthrough wetlands occur as intermediary between their recharge and discharge counterparts (Miller et al., 1985). These wetlands have groundwater laterally moving through them. They will have some level of dissolvable salt accumulations though it will not usually be as pronounced as what is observed within the discharge wetlands. Flowthrough wetlands are often criticized as not being recognized as its own category because they do not occur in high enough quantities relative to recharge and discharge wetlands.

The hydrology of a region will be influence by several factors including climate, topography, vegetation, parent material and anthropogenic activity (Richardson et al., 1994). While it is argued that climate and topography alone determine the genesis of a wetland (Zoltai, 1988), many other factors such as land-use history and prolonged cultivation may alter the hydrological regimes (Richardson et al., 1994; van der Kamp et al., 2003).

2.1.3 Land-use changes of the Prairie Pothole Region

The main land-use on the PPR is agriculture which began at the turn of 19^{th} century. Agricultural expansion on the PPR has led to the drainage and cultivation of PPR wetlands with total wetland losses estimated at 70 – 80% (Patterson, 1999). Of the remaining wetlands, the majority are impacted through adjacent agrarian land-uses (Neraasen and Nelson, 1999). Cultivation affects many chemical, biological, physical and pedological aspects of the PPR soils.

The physical alteration of soil is most evident through the processes of cultivation. While the specific tillage practice will influence the level of alteration, agricultural use in general will cause soil compaction, reduced water permeability and macroaggregate destruction. The bulk density of a soil will increase with machinery traffic and intensive cropping, particularly of saturated and OM-rich soils (Hamza and Anderson, 2005). The compaction of the soil will influence its water infiltrability and reduce its saturated conductivity (Hillel, 1982), which potentially causes longer water ponding periods (van der Kamp et al., 2003). Agricultural tillage will also cause breakdown of fragile aggregates, favoring poor conditions for soil micro-biodiversity (Six et al., 2004).

The nutrient status of the soil will undergo several changes with agrarian land-uses. Often added fertilizer will increase nutrient regime of one type while depleting the soil of anther nutrient. For example, P often becomes oversaturated within agricultural soils (Havlin et al., 2004) whereas the natural N and C soil stocks are often reduced after prolonged cultivation (Aslam et al., 1999). Phosphorus is a relatively immobile nutrient within soil so any over application of this nutrient will be retained within the soil. Nitrogen, in its inorganic form (NO_3^-), is a mobile nutrient and this causes excess N contents to be partially lost to local environment if they are not taken up by the local plant and microbial community. Carbon is maintained in the soil through the presence of OM and tillage operations will often cause faster degradation rates of OM thus lowering C amounts (Six et al., 2000).

Prolonged cultivation will cause changes to the soil microbial communities. The physical disruption of macroaggregates will favor different microbial communities and lead to reduced microbial biomass because native biosites are no longer present (Gupta and Germida, 1988; Aslam et al., 1999). Community shifts, as detailed by 16S rRNA analyses, have been found between native and cultivated land-uses that were unaffected by plant species (Smalla et al., 2001).

Within the PPR, cultivation and seeded vegetation will affect the hydrological dynamics of a soil. A study looking at a restored grassland site, with respect to an annually cultivated counterpart, revealed that the native grassland had a shorter ponding duration because of its increased evapotranspiration rates and soil infiltration (van der Kamp et al., 2003). Other studies have shown that standing water height is much more variable within an annually cultivated depression, relative to a comparable non-cultivated grassland depression (Euliss and Mushet, 1996).

A major issue of cultivation, as it relates to PPR wetlands, is the changing of the native seedbed. The wetland delineations process relies on the presence of native species and changes to them will influence their identified wetland classification.

2.1.4 Wetland classification of the Prairie Pothole Region

The main method of wetland delineation on the PPR is the Stewart and Kantrud (1971) system which makes use of concentric bodies of vegetation and associated hydroperiod. Ponding length and the presence of standing water will influence the development of specific vegetation. The development of obligate hydrophilic vegetation is associated with longer durations of standing water whereas facilitative hydrophilic vegetation would occur with shorter standing water periods. The Stewart and Kantrud (1971) defines several types of concentric vegetation groups occurring within PPR wetlands. The different concentric rings of vegetation are used as proxies in order to determine the specific class of the wetland.

Class I wetlands are referred to as 'ephemeral ponds' and they contain only a single concentric group of vegetation, 'low-prairie zone' vegetation (i.e. *Poa pratensis* L. [common meadow-grass], *Panicum virgatum* L. [switchgrass], and *Artemisia ludoviciana* Nutt. [silver wormwood]). Class II wetlands, referred to as 'temporary ponds' contain two types of concentric vegetation; 'wet meadow zone' (*Boltonia asteroids* Sims [white doll's daisy] and *Artemisia biennis* Willd. [biennial wormwood]) and 'low-prairie zone', from depression center to less ponded areas respectively (Stewart and Kantrud, 1971; Fig 2.2).

Under prolonged periods of cultivation, the seedbed within a soil will become altered to reflect the ongoing alterations. These alterations include the distribution of invasive foreign species, changes of the soil conditions to favor differing vegetation and fragmentation of native areas (Patten, 1998; Marzluff and Ewing, 2001). The Stewart and Kantrud (1971) method of classification requires the occurrence of native vegetation for wetland delineation and in its absence, PPR wetlands cannot be properly classified within the system. Other criteria are therefore required to supplement the possible lack of native vegetation.

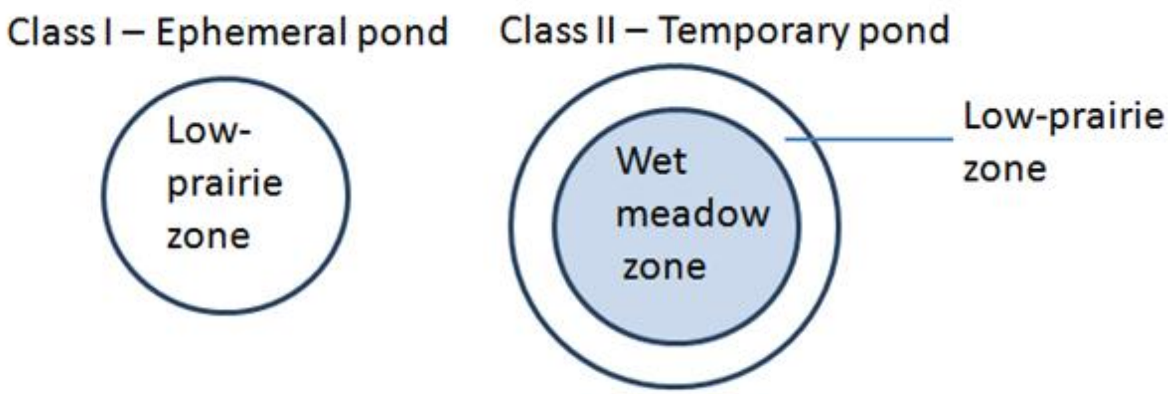

Fig. 2. 2. Representation of concentric wetland groupings according to Stewart and Kantrud (1971). Concentric bodies of vegetation are the main indicator of identification whereby the number of different vegetation groups within a wetland will be the main means of classification. The Class I – Ephemeral pond has only a single concentric group of vegetation whereas the Class II – Temporary pond has two. Figure adapted from Stewart and Kantrud (1971).

2.1.5 Wetland soils

Wetland soils are a visually distinct group of soils that have developed during prolonged saturation and are currently used by the USDA to delineate wetland areas within the United States (Vepraskas et al., 2006). While the dominant Canadian soil order within the PPR is the Chernozem, frequent and periodic saturation within the depression areas will favor the development of the wetland soil order, Gleysols (Soil Classification Working Group, 1998; Pennock et al., 2011). Gleysols themselves are indicated by their presence of "dull colored subsoils and/or brighter colored prominent mottles" (Bedard-Haughn, 2011). These form through oxidation-reduction reactions that occur with high fluctuating water tables. Briefly, when oxygen is not present in soils, such as waterlogged soils, other terminal electron acceptors are required to yield energy for biological processes. These other terminal electron acceptors include oxidized metallic ions (i.e. Fe^{3+}, Mn^{3+} and Mn^{4+}) and oxidized S compounds (i.e. SO_4^-) (Vepraskas and Faulkner, 2000). The reduced forms of the metallic ion compounds bring about the dull color matrixes indicative of Gleysols (Bedard-Haughn, 2011). Furthermore, the reduced Fe and

Mn are more mobile within the soil profile than their oxidized counterparts, which encourage both leaching and accumulation of these compounds within the soil profile. When a soil is later exposed to sufficient levels of oxygen, likely through a dropping of the water table, localized accumulations of Fe and Mn become oxidized and form prominent colored mottles. Reduced forms of S cause easily detectable malodorous conditions (Vepraskas and Faulkner, 2000).

The accumulation of organic matter (OM) is also an indicator of hydric soils (Vepraskas and Faulkner, 2000). Waterlogged conditions slow OM decomposition, through lack of sufficient electron acceptors (Vepraskas and Faulkner, 2000) and reduced enzyme activity (Fenner and Freeman, 2011). Under low redox conditions, the OM decomposition rates are drastically reduced while the accumulation rates of OM are only slightly reduced; these OM rate changes ultimately favor large accumulations of OM.

Organic matter accumulations have many documented effects on soils, including pedogenic properties. The A horizon thickness and darkness increases with increasing amounts of OM (Mueller and Pierce, 2003). Essentially, the A horizon (depth and color) can be a used a proxy for the amount of OM accumulation within a particular soil. In addition to visual changes to the soils, OM positively influences many soil chemical and physical properties. The continual decomposition of OM releases several nutrients required for plant and microbial growth. On average, each 1% of OM will release 20 – 30 kg ha^{-1} of N upon its decomposition along with considerable amounts of P and S (Havlin et al., 2004). Organic matter within the soil also influences the cation exchange capacity (CEC) of the soil, which directly correlates to its ability to retain soil nutrients (Brady and Weil, 2001).

Physical properties of the soil, such as aggregation and structure, are also heavily influenced by the OM content of the soil. The level of soil aggregation is a complex interaction among microorganisms, roots, soil fauna, inorganic binding agents and environmental variables, though in general, high levels of OM will promote the development of soil aggregates (Six et al., 2004). Adequate levels of macro- and microaggregates influence the porosity and bulk densities of soils, ultimately leading to conditions more favorable for plant and microbial communities. The porosity of a soil is directly related to its aeration, whereby the soil can maintain a constant supply of O_2 to continually fuel the catabolic requirements of flora and microfauna (Stirzaker et al., 1996). Soil porosity will also influence the soil's infiltration. The bulk density is improved by adequate soil aggregation as it is less compacted and allows for easier expansion of roots (Stirzaker et al., 1996).

Organic matter will influence the water holding capacity of the soil. Hudson (1994) reports that OM within the soil will increase the available water holding capacity of a soil, regardless of the soil's texture; this phenomena is due to the high volume to weight ratio relative to the other constituents of a soil.

Many of the same dynamics of hydric soil development will influence other non-visual traits of the soil. For instance, magnetic susceptibility (MS) will be affected by the prolonged and repeated saturation, as common within wetland areas.

2.1.6 Soil magnetic susceptibility

Magnetic susceptibility is based on the principles of magnetism. Briefly, magnetism is created when charged atoms are oriented in a similar direction, thus creating positive and negative poles. Magnetic susceptibility is the potential for a substance to develop a magnetic charge and it is determined by inducing a magnetic field to orient charged atoms within a material and its magnetic field is then measured (de Jong, 2002). Within a soil, the amount of MS is influenced by the presence of either reduced or oxidized forms of Fe and Mn (Blundell et al. 2009). When these metallic ions are in their reduced forms (Fe^{2+} and Mn^{2+}), they contribute less to the MS than when they are in their oxidized forms (Fe^{3+} and Mn^{4+}). Metallic ions freely change from their reduced and oxidized forms based on the environments they occupy. Aforementioned, waterlogged soils tend to have prominent reducing conditions that will encourage the speciation of reduced Fe and Mn forms (de Jong, 2002). Conversely, well aerated soils will encourage the speciation of oxidized metallic atoms (Blundell et al., 2009). Magnetic susceptibility values are indicative of the soil's history because histories of reduced soil conditions will cause lower MS values than those that are consistently aerated and well drained.

Magnetic susceptibility has been used as a tool to quickly distinguish between differing drainage classes and wetland boundaries (Lu et al. 2012). Delineation of hydric soils can be also be aided by magnetic susceptibly measurements (Vepraskas and Grimley, 2000). Within Canada, studies have successfully used MS to delineate Gleysolic from Chernozemic soil orders (de Jong, 2002; de Jong et al., 2005).

Wetlands frequently occur on the PPR and they are best delineated using their native vegetation. With extensive cultivation of the region, the native seed beds have been altered though other factors exist that may discriminate the levels of saturation of the soils. Both hydric indicators and soil MS have been previously used to successfully discriminate wetland from non-wetland soils though their abilities to assess intra-wetland soils remain untested.

2.1.7 Statistics

One of the major challenges of designing an ecological study is selecting the appropriate method of statistical analysis. Ecological studies will often include multiple interacting variables with many confounding effects. When determining the influence that fixed effects (i.e. land-use history) may have on a response variable with additional random effects included (i.e. soil transects), then mixed models are required for proper analysis (Pinheiro and Bates, 2000).

In other cases, ecological studies may have multiple explanatory variables where typical cause-and-effect models are not capable of interpreting. Multivariate statistical analyses (i.e. ordinations) would be used in these cases, as they allow the similarities and dissimilarities to be assessed, on a scale specific to those sampling units.

The analysis of hydric soil indicators and MS include examining the influences that multiple non-hierarchical variables have on the different types of wetlands and their corresponding upland areas. The examination of a single hydric indicator or MS value requires the use of LME models because the sampled variables contain many spatially linked groupings (i.e. 10 depth samples per pit; 2 pits per wetland). A fully holistic approach to examining all the hydric indicators and MS values as they were influenced by the wetland type would furthermore require a multivariate statistics approach, such as ordinations.

2.1.7.1 Linear mixed effects models

Analysis of variance (ANOVA) is the most commonly used statistical technique within ecological studies that relies on the generation of linear or non-linear models (Bennington and Thayne, 1994). A common statistical axiom is to use the simplest technique available, provided no assumptions are violated; in the use of ANOVA, fitting data as a linear model would be the simplest technique. Ecological data, however, contains both fixed and random effects, which makes general linear models incapable of proper analysis. Random effects (i.e. time sequences, depth increment or blocking) can be included in models for ANOVA; however, this requires use of linear mixed effects (LME) models.

Mixed effect models include both fixed and random effects. For example, blocking is a spatially dependent random effect because it is not included within the primary research question; however, it must be recognized for proper statistical interpretation. Mixed models can also be used to account for temporal dependencies within the sampling scheme, such as time sequence sampling regimes (Pinheiro and Bates, 2000).

Within soil science, spatial dependencies will commonly occur when multiple samples are extracted from a single soil pit (i.e. incremental depth sampling) or when multiple pits are excavated from a single transect (i.e. catena based sampling). The risk of spatial relationships becomes a statistical concern when both spatially related and non-spatially related soils would be compared collectively in an indiscriminate manner. Linear mixed effects models, in place of linear models, can easily be used to account for these spatial dependencies when conducting ANOVAs.

2.1.7.2 Ordination techniques

Ecological studies often have large multivariate datasets with no explicit explanatory variable and many other interacting variables. To analyze these datasets with basic cause-and-effects statistics (i.e. ANOVA), a single explanatory variable has to be chosen for each individual test conducted. This process of simplifying multivariate data to be analyzed by cause-and-effects statistics only allow small pieces of the data to be analyzed and full dataset patterns may be missed. Multivariate statistical tests allow for the use of multiple unranked variables with no explanatory variable. They are usually based on showing similarities among the sampled units relative to observed dissimilarities among the variables (Clarke, 1993).

Ordinations are a common visual statistical technique for analyzing multivariate datasets; within ordinations, similar objects or experimental sample units are spatially grouped together, whereas dissimilar objects are far apart. Several methods of ordination exist including principal component analysis, correspondence analysis and non-metric multidimensional scaling (NMDS). Each holds their own advantages and disadvantages, and the nature of the dataset will usually determine what ordination is selected.

Non-metric multidimensional scaling (NMDS) has the advantage of having few assumptions; particularly, normality of data is not required. It is also very robust as many features of the analysis can be manipulated to accommodate for different datasets including the amount of axes, dissimilarity indexes and linking objects back to their environment (McCune and Grace, 2002).

Mycock (2011) used NMDS ordinations to compare the characteristics of smelter affected soils along with including their environmental vectors for further analysis. The study used a diverse set of soil and landscape variables to compare the differences smelter-affected soil pits and its use of the NMDS were essential in maintaining that no statistical assumptions were violated. While no major new data patterns were observed through the NMDS ordinations of the study, it was necessary as it allowed for a holistic analysis of the entire dataset (Mycock, 2011).

Clarke (1993) had success in using NMDS ordinations to observe changing community structures with different types of environmental stresses. In these studies, nematode populations from both polluted and non-polluted areas were sampled; furthermore, NMDS ordinations allowed easily interpretable clusters to be identified of the polluted and non-polluted communities of nematodes.

2.2 Greenhouse Gas Emissions

2.2.1 Global greenhouse gas emissions and wetlands

Proper accounts of greenhouse gas (GHG) inventories are required to accurately predict the global threat of climate change. Wetlands occupy 8% of the Earth's surface and are therefore important in the study of global GHG emissions (Mitsch and Gosselink, 2007). In terms of climate change, the greatest contributors to global warming potentials are CO_2, CH_4 and N_2O with global warming potentials of 1, 25 and 298 in CO_2 equivalent values respectively (IPPC Working Group, 2007). Therefore, the rates of CH_4 and N_2O emission and consumption are important to developing proper global GHG prediction models.

Wetlands are permanently or periodically saturated with water and have relatively large stocks of organic matter (OM), which in combination are ideal conditions for GHG production. Methane is most commonly associated with wetlands and globally these areas account for 85% of CH_4 emissions from undisturbed natural sources (EPA, 2010). Within Canada, most CH_4 emissions are associated with the northern peatlands because of their large C stocks (Godin et al., 2012), though PPR wetlands are significant emitters due to their large cumulative coverage area (Badiou et al., 2011).

Globally, N_2O emissions in natural wetlands will not occur in significant amounts because these systems are relatively low in N (Holloway et al., 2011); however, certain conditions will greatly increase N_2O emissions from these areas. The addition of N through nearby or adjacent lands (i.e. fertilizer runoff) will cause high N_2O emission spikes.

2.2.2 Methane production and controls

Methanogenesis, or CH_4 production, occurs during anaerobic decomposition of organic matter (OM). Decomposition, both aerobic and anaerobic, requires terminal electron acceptors in order for energy to be released (Reddy and DeLaune, 2008). Oxygen is the preferred electron acceptor when available because it yields the most energy; when O_2 is present in adequate amounts simple carbohydrates will ultimately be decomposed into H_2O and CO_2 molecules (Eq. [1]). Conversely, OM decomposition will produce CH_4 and CO_2 when no other preferred electron acceptors are present (Eq. [2]; Le Mer and Roger, 2001).

$$C_6O_6H_{12} + 6O_2 \rightarrow 6H_2O + 6CO_2 \quad [1]$$

$$C_6O_6H_{12} \rightarrow 3CH_4 + 3CO_2 \quad [2]$$

The two major pathways of methanogenesis are CO_2 reduction and acetotrophy (Le Mer and Roger, 2001). In anaerobic systems, less thermodynamically preferred electron acceptors are used in place of O_2, including: NO_3^-, Fe^{3+}, Mn^{4+}, SO_4^- and CO_2 respectively from decreasing thermodynamic preference (Achtinich et al., 1995). When CO_2 is used as a terminal electron acceptor, it is reduced to CH_4 (Karhadkar et al., 1987).

Acetotrophy is the other main pathway of methanogenesis, which involves the decomposition of acetate (Eq. [3]). Acetate compounds are commonly produced during OM decomposition and are often present in anaerobic systems (Segers, 1998). The fermentation of acetate compounds is carried out by species of the Archaea domain and will produce CH_4 and CO_2 (Klüber and Conrad, 1998; Ferry, 1992).

$$CH_3COO^- + H^+ \rightarrow CH_4 + CO_2 \quad [3]$$

The reverse process of methanogenesis is methanotrophy, where CH_4 molecules are oxidized by methanotrophic bacteria. Two forms of methanotrophy exist, high affinity and low affinity methanotrophy. High affinity methanotrophy is CH_4 oxidation at low CH_4 concentrations (< 12 ppm CH_4) and low affinity methanotrophy is CH_4 oxidation at high CH_4 concentrations (> 40 ppm CH_4). High affinity methanotrophy occurs at CH_4 concentrations similar to that found in the ambient environment: however, this form only accounts for approximately 10% of CH_4 oxidation. Low affinity CH_4 oxidation is the predominant form of methanotrophy within wetland soils because of the high level of methanogenesis occurring concurrently (Le Mer and Roger, 2001).

Methanotrophic bacteria receive both their energy and C from the oxidation of CH_4. The main limiting factors for the methanotrophs activity are O_2 and CH_4 sources (Segers, 1998). Partially saturated soils, where both O_2 and CH_4 may be present, can be CH_4 sinks because of high rates of localized methanotrophy (Le Mer and Rogers, 2001).

The CH_4 emissions from a soil are based on the rates of methanogenesis, methanotrophy and additionally, the fugacity of CH_4. Methane must be transported to the atmosphere to induce its GHG effects; this can occur through several pathways including ebullition, plant mediated flow, and diffusion (Segers, 1998). Ebullition involves the bubbling of CH_4 up to the surface. Preferential plant flow involves CH_4 entering plant roots to escape out the leaf and stem tissue. Diffusion relies on the principles of Fick's laws: CH_4 moves through the soil along a decreasing concentration gradient (Le Mer and Rogers, 2001).

The inhibition of methanogenesis by more favored electron acceptors like SO_4^- and NO_3^- is well documented (Kardhadkar et al., 1987; Achtinich et al., 1995; Kluber and Conrad, 1998; Abram and Nedwell, 1978; Laanbroek, 2010). Sulfate-reducing bacteria, in the presence of adequate supplies of SO_4^-, will compete with methanogens for substrate. Laboratory and in situ experiments have shown suppressed emissions with the addition of SO_4^- to systems (Ro et al., 2011; Pennock et al., 2010; Eriksson et al., 2010). This competition for substrate can often lead to diminished CH_4 emissions; this was observed by Dise and Verry (2001) in soil affected by acid rain.

Land-use changes such as altering vegetation and tillage can also affect rates of CH_4 emissions from soils (Morse et al., 2012). The altering of vegetation and inclusion of tillage will have multifaceted effects on the CH_4 production because they will affect the availability of OM, the water regime, soil aeration and the soil temperature (Blevins, 1983); all of which are documented controls of methanogenesis (Sainju et al., 2012; Le Mer and Rogers, 2001). A conversion from annually cultivated crops to perennial switch grass saw lower CH_4 emissions (Monti et al., 2012). van der Kamp et al. (2003) observed longer wetland ponding durations among cultivated annual crops than an untilled restored grassland.

2.2.3 Nitrous oxide production and controls

Nitrous oxide emissions rank third in terms of net global warming potential, after CO_2 and CH_4 emissions. In gross emissions, N_2O (18.8 Tg N_2O-N yr^{-1}) is considerably less than that of CO_2 (9.28 Pg CO_2 yr^{-1}) or CH_4 (566 Tg CH_4 yr^{-1}); however, N_2O is more volatile and persistent in the atmosphere than the other gases (EPA, 2010). On a 100-year scale, an N_2O molecule has a global warming potential of 298 CO_2 molecules (IPCC Working Group, 2007). Soils account for approximately two thirds of global N_2O emissions (Prather et al., 1995).

The factors governing emissions of N_2O in wetlands relate to fluctuating redox conditions and available N. The hydrology, or the depth of the water, will govern whether there is an anaerobic or aerobic environment for the microbial activity. An anaerobic system will favor the full reduction of N through denitrification; however, system disturbances, such as a change to an oxic system, may influence higher N_2O emissions by interruption of the denitrification process. Dunmola et al., (2010) state that most N_2O emissions occur during the dry-down period, after a soil goes from complete to partial saturation within the PPR. The availability of N will also influence the extent of nutrient cycling within the system and thus the presence of N fertilizer will increase the amount of N_2O emissions from soil (Dalal et al., 2003).

Denitrification is the microbial mediated reduction of NO_3^-. This process contains multiple steps and N_2O is an intermediary compound during the full process (Eq. [4]; Bouwman, 1996). Since N_2O is an intermediary of the denitrification process, the process can be a sink as well as a source depending on environmental conditions such as pH, O_2 levels and temperature (Sorai et al., 2007). Microbes require reduced conditions either in soil microsites or broadly within the soil ecosystem (Bouwman, 1996).

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \qquad [4]$$

Denitrification is spatially and temporally variable on the Prairies. Landscape variation has a strong influence on the levels of denitrification and low slope areas will have higher rates of denitrification; ultimately caused by increased water redistribution to these lower areas, compared to their upslope counterparts (Pennock et al., 1992; Corre et al., 1996). Denitrification rates are favored during the early spring relative to times later in the season because of fertilizer application timing; this corresponds to the available N present within these systems (Pennock et al., 1992). Increased amounts of N_2O emissions will also occur after spring snowmelt and soil thaw, which is attributed to the denitrification process (Dunmola et al., 2010).

Within soils, water filled pore space (WFPS) of > 80% will favor the process of denitrification. Nitrous oxide emissions via denitrification would be caused when the process is not allowed to go to completion; this is achieved through a fluctuating water tablet that encourages dynamic redox conditions (EPA, 2010). In addition, warmer soil conditions increase biological activity of microbes responsible for N_2O emissions resulting in higher emissions as temperatures increase (Clayton et al., 1997).

Nitrification, the other major pathway of N_2O emissions, is the transformation of NH_4^+ to NO_3^-; a bacterially mediated two-step aerobic process. The first step involves the oxidation of NH_4^+ to NO_2^- mediated by *Nitrosomonas spp* (Eq. [5]). The second step of the process oxidizes the NO_2^- to NO_3^- and is mainly mediated by *Nitrobacter spp* (Eq. [6]). Nitrous oxide is a by-product of the process, produced at two to three orders of magnitude less than that of the primary products (Smith et al., 2003).

$NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$ [5]

$2NO_2^- + O_2 \rightarrow 2NO_3^-$ [6]

In soil, nitrification requires an adequate supply of transient N, and larger supplies of N may allow for more N_2O production (Bouwman, 1996). The hole-in-the-pipe model is often used to describe N_2O production from nitrification, where the pipe signifies the process of nitrification and the holes represent losses to N_2O; higher rates of nitrification will ultimately lead to more N_2O losses (i.e. leaks) (Davidson and Verchot, 2000).

When soils are < 80% WFPS, nitrification usually becomes the dominant source of N_2O emissions, albeit their emissions are less than those of denitrification (Pennock et al., 2010). Drier upland soils that have positive net emission of N_2O would be expected to emit N_2O through the nitrification pathway.

Soils with WFPS of around 60% are ideal for nitrification derived N_2O. This range of WFPS optimizes the available oxygen and moisture levels for the N-converting microbes. Much like denitrification derived N_2O, favorable temperatures for microbial growth will also encourage nitrification-produced N_2O (Clayton et al., 1997).

Pennock et al. (2010) noted that high bursts of N_2O emissions occur from ephemeral PPR wetlands during the dry-down period (i.e. WFPS < 80%). This was likely the result of the changing redox status within the soil during the dry-down period. Drier wetlands (WFPS: 60 - 80%) are capable of nitrification derived N_2O with adequate supplies of N (Bedard-Haughn et al., 2006a).

Disturbance of natural wetland systems poses a great risk to increase the amount of N_2O emissions (EPA, 2010). Agrarian wetlands, such as rice paddies, contribute significantly to the global N_2O budget because of an additional supply of N from fertilizer (Davidson, 2009). Natural or restored wetlands adjacent to agricultural lands are likely to receive N from fertilizer runoff and have more potential to become N_2O emitters (Mosier et al., 1998). Within the PPR, agriculture is the primary land-use of the area and most wetlands will be adjacent to these land-uses. Therefore, the PPR wetlands will have high risk of N fertilizer runoff.

Contrasting land-use histories (i.e. cultivated vs. uncultivated) influence the production and emissions of N_2O of PPR wetlands. Bedard-Haughn et al. (2006a) observed higher rates of denitrification derived N_2O in uncultivated wetlands throughout a growing season than their cultivated counterparts. The study observed that N_2O emissions declined as the growing season progressed, while no such trend was observed for the uncultivated wetlands.

Contrasting land-use histories will affect many chemical and physical properties of the soil. Because soils are a fundamental part of every terrestrial environment, the effect of differing land-use histories can be important to many environmental processes. This study examined the effects of several contrasting land-use histories on soil environmental factors, including the expression of hydric soil features, MS and their GHG emissions with respect to biogeochemical controls of GHG production.

3. EXPRESSION OF HYDRIC SOIL FEATURES AND MAGNETIC SUSCEPTIBILTY AMONG DIFFERING LAND-USES ON THE PRAIRIE POTHOLE REGION

3.1 Introduction

The Prairie Pothole Region (PPR) spans an area of over 900 000 km^2 within North America (Gleason et al., 2011). The landscape was formed through the ablation of the Wisconsin Glaciers approximately 10 000 years ago, which led to the development of its hummocky rolling topography (Clark et al., 2009; Richardson et al., 1994). The depression areas commonly have undeveloped surface drainage channels and are prone to localized accumulations of moisture (Richardson et al., 1994). During seasonal periods of excess moisture (i.e. after spring snowmelt or large precipitation events), these depression areas become saturated for prolonged periods and influence the development of hydric soils, vegetation and invertebrates (Vepraskas and Faulkner, 2000; Silver et al., 2012). The thick grassy hydrophilic vegetation of these areas makes them prime nesting grounds for migratory waterfowl of North America (Mitsch and Gosselink, 2007).

European settlement of the PPR during the early 20th century encouraged the cultivation of much of the regions' arable lands. Over the past century, many of the smaller ponds have been brought into cultivation; these land-use changes cause alterations to native vegetation of the ponds, ultimately limiting their suitability for waterfowl nesting (Patterson, 1999). During the past several decades, wetland restoration has occurred for the purpose of restoring proper nesting grounds for migratory waterfowl (DUC, 2003), however, proper classification of these wetlands can be challenging.

Classification of wetlands is a powerful tool in their study and conservation. Cowardin et al. (1979) state that proper accounts of wetlands are required for wetland management and protection. Identification methods also allow for continued research and further understanding of their importance, as pertaining to size, function and other important traits (Mitsch and Gosselink, 2007). The current classification system of the region makes use of concentric bodies of native vegetation, in conjunction with water levels and duration, as a means of delineating the different classes of the wetlands (Stewart and Kantrud, 1971). Hydrophytic vegetation, while being highly visible, is a short-term indicator of moisture and its boundaries can change by several decimeters each year (Richardson et al., 1994). Additionally, past and present cultivation will disrupt the native seedbeds causing drastic changes to the vegetation present within PPR wetlands (Euliss et al., 2001). Therefore, non-ephemeral and land-use independent criteria for wetland identification are required.

Hydric soil features have been studied intensively for the past three decades (Fiedler and Sommer, 2004; Faulkner and Patrick, 1992). Protective legislation of wetlands requires that these regions be properly identified, and this has historically been the main purpose of using hydric soil features (Simms and Lobred, 2011). Hydric soils encompass many different indicators, however their development is based upon one of three changes to the soil: Firstly, the accumulation of OM is promoted under saturated conditions. Within saturated and reduced conditions, the decomposition rates of OM are lowered and there often will be a net gain of OM, when compared to non-saturated conditions (Sahrawat, 2003). Secondly, under these same reduced and saturated conditions, naturally occurring Fe and Mn within the soil will change to reduced redoximorphic states (i.e. $Fe^{3+} \rightarrow Fe^{2+}$). The reduced states of the metallic compounds are highly mobile and leach downward with water percolation to cause localized accumulations at lower depths. Thirdly, S-based compounds within the soil will convert to reduced redoximorphic states and cause distinct odors and yellow pigments (Simms and Lobred, 2011).

Soil magnetic susceptibility (MS), which shares development patterns with hydric indicators, can be used as a supplement for wetland delineation (Grimley and Vepraskas, 2000). Soil MS measures the ability of a soil to become magnetic and is indicative of the concentration of oxidized Fe compounds contained in the soil. Saturation causes the Fe to change to a reduced state thus lowering its MS value and making wetland soils discernible from their upland counterparts. Past studies have shown MS corresponds with other hydric based indicators (Grimley and Vepraskas, 2000; Simms and Lorbred, 2011).

Given the many land-uses of PPR wetlands, one initial question to answer is how a given land-use may affect the development or expression of these hydric features. Land-use has been shown to alter the water regime of the wetlands either through a change in pond duration or fluctuation of water table levels (Euliss and Mushet, 1996; van der Kamp et al., 2003) and thus the expression of hydric features or MS could be altered. Therefore, this study focused on examining hydric soil indicators and MS under differing land-uses.

3.2 Materials and Methods

3.2.1 Site characteristics

The sampling area included two sites: St. Denis National Wildlife Area (SDNWA) and an adjacent native grassland site (NGS). The SDNWA occupies a 1.5 section area (508 ha) and is located approximately 40 km east of Saskatoon (52.2145° N, 106.0976° W) with a legal land description of 28 – 37 – 1 W3. It has hummocky, glacial till terrain along with groups of episodically connected wetlands (Pennock et al., 2010). St. Denis National Wildlife Area is located within the Dark Brown soil zone (Table 3.1). A cultivated upland zone (annually cultivated) exists within SDNWA, along with restored grassland and seeded pasture areas. The seeded pasture was planted to a tame grassland mixture in 1982-83, which includes *Bromus inermis* L.(brome grass), *Medicago sativa* L. (alfalfa) and *Melilotus officinalis* L. (yellow sweet clover; Hogan and Conly, 2002). The restored grassland was seeded to a diverse grassland mixture in 2004 including *Agropyron elongatum* (Host) Beav. (tall wheatgrass), *Thinopyrum intermedium* (Host) Barkworth & Dewey (intermediate wheatgrass), *Bromus erectus* Huds. (meadow brome), *Elymus dauricus* Turc. ex Griseb (Dahurian wild rye), *Festuca rubra* L. (red fescue), *Onobrychis viciifolia* Scop. (common sainfoil), *Elymus canadensis* L. (Canada wild rye), *Elymus trachycaulus* Gould ex Shinners (slender wheatgrass) and *M. sativa* (Hogan and Conly, 2002; Yates et al., 2006). The cultivated area of SDNWA had commonly contained rotations of *Triticum aestivum* L. (wheat) and *Brassica napus* L. (canola).

The NGS is comprised of knob and kettle glacial moraine interspersed with wetlands. It occupies approximately one-eighth of a section (approx. 65 ha) and is situated about 5 km west of St. Denis (52.1717° N, 106.1726° W) with a legal land description of NE 10 – 37 – 2 W3. Similar to the SDNWA, the NGS is located in the Dark Brown soil zone (Table 3.1). The area is dominated by graminoid and forb vegetation including *Festuca altaica* Trin. Ex Ledeb (Northern rough fescue), *Stipa spartea var. curtiseta* Barkworth (porcupine grass), *Carex obtusata* L. (obtuse sedge), *Agropyron smithii* A. Love (western wheatgrass), *Anemone patens* L. *var wolfgangiana* (prairie crocus), *Thermopsis rhombifolia* Nutt. ex Richardson (golden bean) and *Vicia Americana* Muhl. ex Willd. (American vetch). Common vegetation species usually present in the depression areas include *Symphoricarpos occidentalis* Hook. (Western snowberry), *Elaeagnus commutata* L. (wolf-willow) and *Rumex patientia* L. (Western dock; Slobodian et al., 2002).

The mean annual temperature of the region is 2.5 °C with a mean daily maximum of 8.4 °C and mean daily minimum of -3.4 °C (Environment Canada, 2012). The region typically experiences a moisture deficit, whereby potential evapotranspiration is higher than precipitation (Nadler and Bullock, 2011).

Table 3. 1. Soil survey reports of the two sites of the field study (Soil Survey Working Group, 1978; Soil Survey Working Group, 1988).

Site	Soil Series	Dominant Soil Order	Significant Soil Orders	Landforms
SDNWA	Weyburn	Dark Brown Chernozem	Gleysolic	Hummocky glacial till
Native Grassland	Weyburn	Dark Brown Chernozem	Gleysolic	Knob and Kettle Moraine

3.2.2 Wetland selection

Temporary wetlands (Class II; Stewart and Kantrud, 1971) were selected from four different land-use histories. Three of the land-uses were located within the SDNWA site (Fig. 3.1) (annually cultivated grassland, restored grassland, and seeded pasture) and the fourth land-use (native grassland) was situated in the NGS (Fig. 3.2).

The selection of comparable wetlands first used previous reports that broadly classified the SDNWA (Hogan and Conly, 2002) whereas smaller wetlands, either of Class I or II (Stewart and Kantrud, 1971) were pooled together. Furthermore, the wetlands were then inspected for comparability based upon basin size and shape and appropriate replicates were selected within each land-use.

3.2.3 Field sampling and storage

Sampling occurred during August and September of 2011. For each wetland, two sampling locations were selected: a depression pit and an upland pit. The depression pit was determined by selecting the point at the wetland depression center where water ponding persists the longest. The upland pit was located on the shoulder slope of the wetland depression and selected based on its representativeness of the surrounding upland area.

At each sampling location, a soil pit was excavated to a depth of 1 m and classified according to the Canadian System of Soil Classification, including the mottling prominence and depth to mottling (Soil Classification Working Group, 1998). Soil horizons were assessed for texture using field hand texturing techniques and measured for color using a Munsell color chart (Watson, 2009). Representative soil samples were collected at 10 cm increments (approx. 1 kg soil per increment) to a depth of 1 m (n = 10 per pit).

Each sample was homogenized then handled in three different ways. A first set of sub-samples was stored at 4° C at field moisture content until wet aggregate stability analysis. A second set of sub-sampled soil was air-dried and sieved to 2-mm diameter for analysis of particle size distribution. A third set of sub-samples was also air-dried and mechanically ground with a ball mill to pass through a 2-mm sieve; this sub-set was used for analysis of all other soil properties, including magnetic susceptibility (MS), dithionite extractable Fe (DF), OC content and total C content.

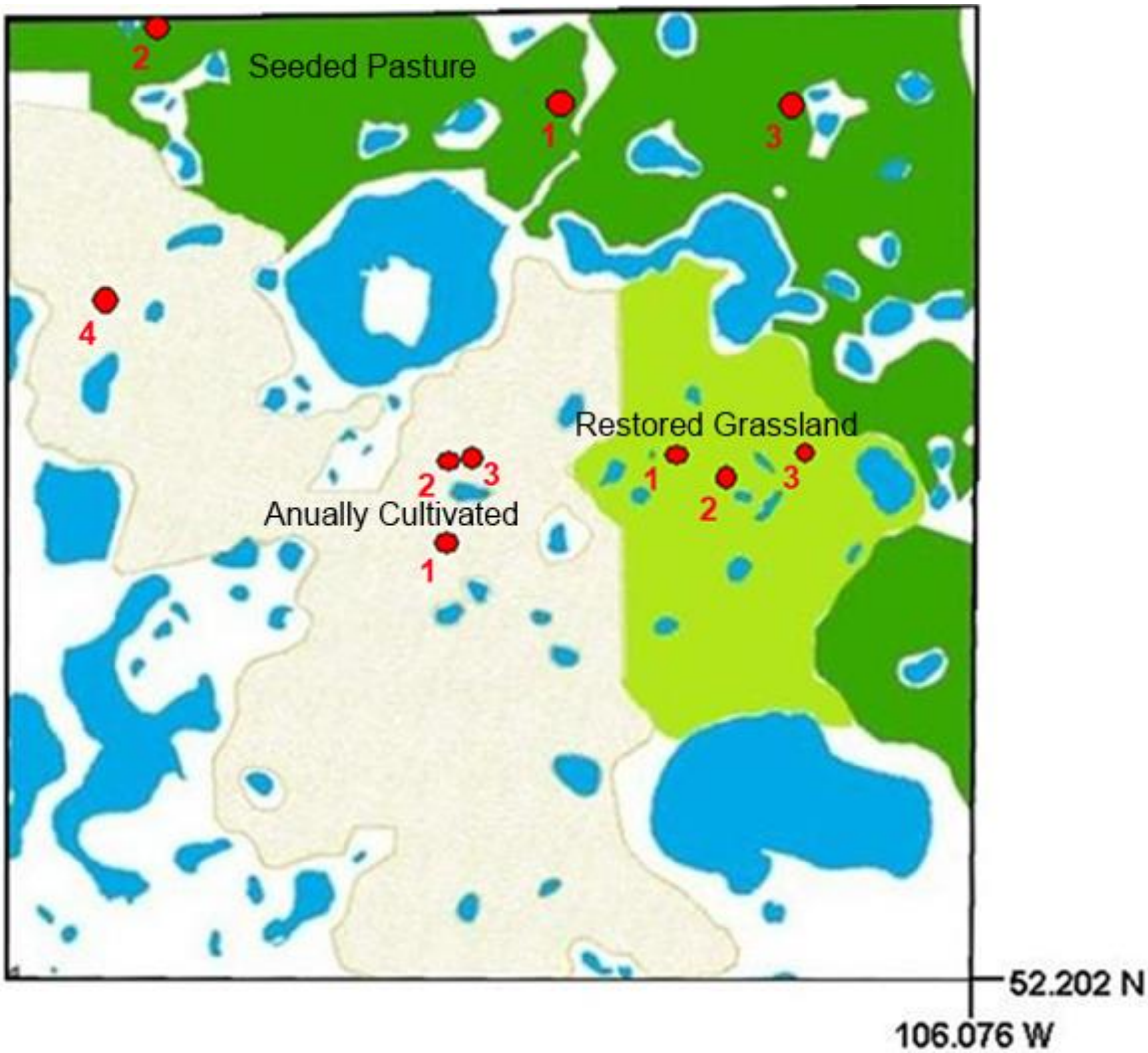

Fig. 3. 1. East section of St Denis National Wildlife Area (SDNWA) with labeled land-uses at time of study. Sampled pits are denoted by red dots. Red dots represent sampling locations (Map courtesy of Environment Canada, 2012). Corresponding numbers beside dots represent their identification number with respect to their land-use histories.

3.2.3 Laboratory analysis

Wet aggregate stability was measured using an oscillating dual-layered sieve machine (modified from Six et al., 2000). Briefly, the 0- to 10- cm samples were kept at field moisture and gently sieved to 2 mm with roots and plant material removed. The machine used three sets of two sieves: 250 µm and 53 µm; the former was stacked above the latter. The stacked sieves were submersed in deionized water. Soil (5 g) was added to the top of each sieve set and allowed a 2 min slaking period in which no oscillations or disruptions occurred to the soil. After the slaking period, the sieves were oscillated 50 times (18.75 oscillations min^{-1}; 2.58 cm s^{-1}). Floating debris (i.e. fibrous plant material) was removed with vacuum suction and subtracted from the total soil added. The remaining water and soils from the three sets of sieves were composited and then dried in the oven at 60°C overnight, weighed and placed into one of three size groups: >250 µm, 250-53 µm and <53 µm sized aggregates. This procedure was replicated three times per soil.

Fig. 3. 2. Native grassland site (NGS) of the experiment. Sampled wetland pits are denoted by red circles (Image courtesy of FlySask.ca, accessed August 2012). Corresponding numbers beside pits represent their identification number of the native grassland pits.

Organic and total C contents were measured using combustion and subsequent infrared detection with a LECO C 632 analyzer (LECO Corporation, St Joseph, MI, USA). Organic C was measured via a 120 s combustion at 814°C (Wang and Anderson, 1998). Total C was determined via a 180 s combustion at 1100°C. Inorganic C (IC) was determined by the difference between total and organic C. Sucrose and mineral soil standards were used for equipment calibration of the high and low infrared detector cells, respectively.

Soil organic C equivalency values (SOC_{eq}) were calculated to a depth of 30 cm for each land-use history using the analyzed OC and bulk density contents. Briefly, this method involves adjusting OC storage of each land-use relative to their bulk densities to ensure there that C storage is not over- or under-reported due to discrepancies in bulk density (Ellert and Bettany, 1996). The annually cultivated soil was used as the comparative baseline and the masses of the other land-use histories were adjusted accordingly to calculate SOC storage on an equivalent mass basis.

A dithionite extraction with subsequent atomic adsorption detection was used to quantify the extractable free Fe within the soil (Courchesne and Turmel, 2008). This method is the standard used for describing Fe accumulations for Gleysol delineation (Soil Classification Working Group, 1998). Briefly, 5 mL of 2 M $Na_2S_2O_4$ was added to a 10 mL soil-water solution containing 2 g of soil sample and 0.5 M of $NaC_6H_7O_7$, creating high reducing conditions with a neutral pH buffer. The extractant, containing reduced Fe in solution, was filtered to remove particulate matter. The Fe content of extractant was determined by atomic adsorption (AAS 220, Varian Incorporated, Palo Alto, CA).

Magnetic susceptibility of soils was determined using a Bartington MS-2B meter (Bartington Instruments Limited, Whitney, England) (de Jong et al., 2005). The instrument applies a magnetic field to the soil and subsequently analyzes how much of that magnetic field is still retained in the soil. Both low (0.47 kH, χ_{lf}) and high (4.7 kH, χ_{hf}) frequencies were measured for all soils after four different temperature treatments (ambient, 100°C, 300°C and 500°C). Temperature treatments involved placing soils within heat-resistant glass tubes, within a Thermolyne Industrial Benchtop Muffle Furnace (Thermo Fisher Scientific, Waltham, MA) for 16 h (overnight). While high frequency results are not reported, they were used to calculate frequency dependent charge (FD) (Eq. [7]) (Lu et al., 2012). The FD values were only used in the ordinations because of the high variability of these values with respect to soil depths.

$$FD = 100 \times [(\chi_{lf} - \chi_{hf}) / \chi_{lf}] \qquad [7]$$

3.2.4 Statistical analysis

General linear mixed effects (LME) models were constructed using the 'nlme' library (function 'lme') of R Statistics (version 2.13.1; R Core Team, 2011). Briefly, the LME models involved using continuous explanatory variables and categorical fixed effects to explain the variation and noise of a response variable. Individual pits (as per 10 depth samples) and their corresponding depression/upland reference were included as random nested variables to avoid pseudo-replication within the model.

Fitting of model residuals were used to assess the LME models predictive abilities and logarithmic transformations were applied when required to correct for residual fittings (Zuur et al., 2007). Effects were confirmed significant at $P < 0.1$.

Tukey's honestly significant difference (Tukey's HSD) test was performed using JMP (version 10.0.0; SAS Institute Inc., Cary, NC) to measure differences among SOC_{eq} and soil aggregate sizes. Briefly, comparison of SOC_{eq} used a generation of a linear mixed effect model ("MIXED procedure") with pit position included as a random effect to avoid pseudo-replication. The analysis of soil aggregate sizes involved using a linear model. Effects were confirmed significant at $P < 0.1$.

Unpaired T-tests were conducted using R Statistics. Effects were confirmed significant at $P < 0.1$.

To interpret the multivariate dataset (i.e. a dataset with multiple dependant variables of similar importance) within the study, non-metric multi-dimensional scaling (NMDS) was used. Briefly, NMDS ordinations were generated in R Statistics (R Development Team, 2011) using the 'vegan' library (Oksanen, 2011). The function 'metaMDS' was used to generate the ordination whereby Euclidean distances were measured from the transformed dataset. Ordinations were generated using a best start configuration with a maximum of 100 iterations to avoid local minima. Two axes were selected to portray the ordinations because they exhibited a low stress value (< 10%) and they are graphically easy to portray (Clarke, 1993). The 'metaMDS' function involved principal component analysis-like rotation of the axis to allow the first axis (axis 1) to portray the largest amount of variance with other axes having subsequently lesser amounts of variance portrayed (Oksanen, 2011). Stress plots were constructed to examine the goodness of fit against the dissimilarity of samples whereby $r^2 > 0.95$ were accepted. In addition to plotting the points of the ordination, the magnitude and correlation of the variables used were overlaid on the ordination to allow for interpretation of influences of specific factors using the 'envfit' function (Mycock, 2011).

3.3 Results

3.3.1 Field observations

All of the soils were classified as variants of Chernozems or Gleysols. Within the SDNWA (land-uses: annually cultivated, restored grassland and seeded pasture) depression soil pits were generally classified within the Gleysol group; the exception being pit L1 where no mottles were observed (Table 3.2). Conversely, the NGS depression pits were mainly classified as Chernozem Great Group soils with the exception being pit G2. Soils from both sites' corresponding uplands were all classified as Chernozem Great Group soils; the dominant soil classification of these uplands was Orthic Black Chernozem.

Mottling occurred at depths >50 cm within the NGS, which caused many of the wetland soils under this land-use to be classified as Chernozems (Table 3.2). All pits had comparable A horizon thicknesses, however the depth to mottling was more varied amongst all treatment groups, particularly within the grassland site (Table 3.3). Depths to mottling were significantly correlated with the water table depth and A horizon thickness (Table 3.4). Water table depth and A horizon thickness were not found to be significantly correlated. Full soil profile details of each pit are located in Appendix A.

Table 3. 2. Soil classification of depression and upland pits of each land-use as according to the Canadian System of Soil Classification (Soils Working Group, 1998). Pits were mainly identified as either Chernozemic or Gleysolic Great Groups.

		Soil Classification (Soil Classification Working Group, 1998)	
Land-use	Transect	Depression Pits	Upland Pits
Native Grassland	G1	Eluviated Black Chernozem	Orthic Black Chernozem
	G2	Orthic Gleysol	Calcareous Black Chernozem
	G3	Orthic Black Chernozem	Eluviated Black Chernozem
	G4	Orthic Black Chernozem	Orthic Black Chernozem
	G5	Orthic Black Chernozem	Orthic Black Chernozem
Annually Cultivated	C1	Humic Luvic Gleysol	Calcareous Black Chernozem
	C2	Humic Luvic Gleysol	Gleyed Calcareous Black Chernozem
	C3	Humic Luvic Gleysol	Orthic Black Chernozem
	C4	Humic Luvic Gleysol	Calcareous Black Chernozem
Restored Grassland	R1	Humic Luvic Gleysol	Orthic Black Chernozem
	R2	Humic Luvic Gleysol	Orthic Black Chernozem
	R3	Humic Luvic Gleysol	Calcareous Black Chernozem
Seeded Pasture	L1	Calcareous Black Chernozem	Calcareous Black Chernozem
	L2	Humic Luvic Gleysol	Orthic Black Chernozem
	L3	Humic Luvic Gleysol	Orthic Black Chernozem

3.3.2 Organic carbon

Organic C declined with depth regardless of land-use (Fig. 3.3). Large error bars at most depths show the high variation found within each particular land-use. The depth profile of OC also shows slight variations among land-uses.

Table 3. 3. Collection of field observations for the wetland soils of each land-use. Values are mean observations with standard error in parentheses. Water table depths were recorded at the time of pit excavation during the experiment's field work in summer and fall 2011. A-horizon thickness includes the entire depth of the A horizon, as recognized by the Canadian System of Soil Classification. Depth to mottling refers to depth from surface where mottles were observed, according to the Canadian System of Soil Classification (1998).

Site	Water table depth	A horizon thickness	Depth to mottling
	----------------------------------cm	(S.D.)	---------------------------------
Annually Cultivated	86.25 (4.79)	44.75 (14.59)	28.25 (4.57)
Restored Grassland	80.00 (26.46)	48.33 (14.05)	40.00 (15.39)
Seeded Pasture	73.33 (5.77)	44.67 (13.87)	24.00 (2.83)
Native Grassland	131.0 (37.48)	42.80 (23.15)	60.80 (33.83)

Table 3. 4. Spearman's correlation of 'depth to mottling' and other selected field variables.

Variable	R_s†	*P*
Water table depth	0.658	0.01
A horizon thickness	0.559	0.038

† Spearman's rank correlation coefficient

At the soil surface (depth: 0 – 10 cm) of the depression pits, the native grassland land-use had the highest average OC content followed by the seeded pasture, annually cultivated and restored grassland land-uses respectively; these differences were all non-significant (Tukey's HSD; $P > 0.1$).

The depression pits generally have higher OC contents then their comparable upland pits; the exception to this is observed within the restored grassland land-use where at several depths, the upland pits have higher OC amounts.

Fitting the full OC dataset (i.e. all depth increments included) into a linear mixed effects model reveals the main indicators for variation are related to depth and land-use (Table 3.5). The major indicator of variation was depth (F-statistic = 83.41; P <0.0001) whereas pit position and land-use (F-statistic = 2.970, 3.819; P = 0.0540, 0.0635 respectively) were lesser indicators of variation though they were still significant. The only significant interacting effects among the variables were between depth and land-use (F-statistic = 1.888; P = 0.0075).

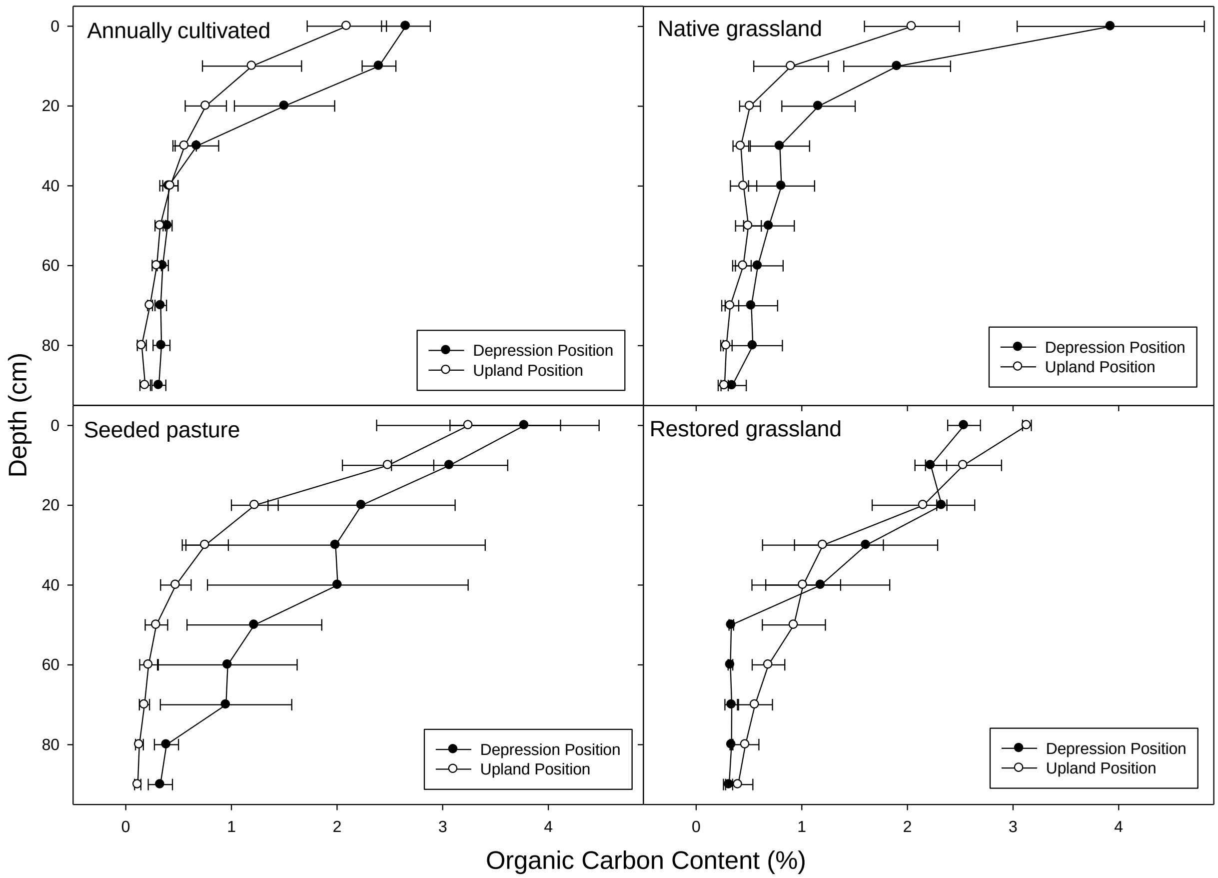

Fig. 3. 3. Depth profiles of organic C by land-use history and pit position. Each panel represents a different land-use history, with the closed circles representing the mean OC content of the depression soil pits and the open circles representing the mean OC content of upland soil pits. Land histories include annually cultivated (n=4), native grassland (n=5), seeded pasture (n=3) and restored grassland (n=3). Bars represent standard error of the mean.

Table 3. 5. Analysis of a linear mixed effects model using organic C (%) as a response variable with depth, land-use and pit position included as explanatory variables. Individual pits and associated depression/upland reference were included as nested random variables to address within-profile and soil position relationships.

Explanatory variable	df	Denominator df	F- statistic	*P*
Depth	9	194	83.41	<.00001
Land-use	3	22	2.970	0.0540
Pit Position	1	22	3.819	0.0635
Depth : Land-use	27	194	1.888	0.0075
Depth : Pit Position	3	194	0.8059	0.6113
Land-use : Pit Position	3	22	0.1682	0.9167
Depth : Land-use : Pit Position	27	194	1.381	0.1098

Soil organic C equivalency values of pits further illustrate the pit position effect on C storage (Table 3.6). Depression pits on average have higher C storage amounts than their upland counterparts, except for the native grassland land-use history. No significant differences were found among the mean SOC_{eq} values of contrasting land-use histories through a Tukey's HSD of a mixed effect model.

Table 3. 6. Soil organic C equivalency (SOC_{eq}) values of each depression and upland pits. Equivalency values were calculated per Ellert and Bettany (1996). Means of each land-use are included in bolded text with their standard error values included in parentheses.

		Soil OC	
		SOC_{eq} (0 - 30 cm) (Mg ha^{-1})	
Land-use	Transect	SOC Depression	SOC Upland
Native Grassland	N1	90.20	84.09
Native Grassland	N2	54.41	73.96
Native Grassland	N3	59.62	92.66
Native Grassland	N4	106.17	140.58
Native Grassland	N5	133.28	48.78
Native Grassland Mean (S.E.)		88.74 (14.69)	88.01 (15.06)
Annually Cultivated	C1	86.97	44.40
Annually Cultivated	C2	105.38	105.39
Annually Cultivated	C3	89.44	34.02
Annually Cultivated	C4	90.32	63.14
Annually Cultivated Mean (S.E.)		93.03 (4.12)	61.74 (15.75)
Restored Grassland	R1	85.60	77.92
Restored Grassland	R2	105.64	47.87
Restored Grassland	R3	114.26	32.19
Restored Grassland Mean (S.E.)		101.83 (8.49)	52.66 (12.42)
Seeded Pasture	L1	179.60	110.51
Seeded Pasture	L2	107.40	82.32
Seeded Pasture	L3	107.51	109.66
Seeded Pasture Mean (S.E.)		131.50 (24.05)	100.83 (9.26)

3.3.3 Inorganic carbon

The inorganic carbon (IC) depth profile illustrates the higher IC content present within the upland soils, relative to their depression soil counterparts (Fig. 3.4). A trend of IC increasing with depth also exists from observation of the IC profile.

A higher concentration of IC was measured just below the surface soil (10 - 20 cm) of the depression pits where the IC content approaches that of their upland equivalents. It was most pronounced within the grassland land-use; the trend was still present in the other land-uses though less apparent.

A linear mixed effects model (Table 3.7) revealed there was significant explanatory power within the variables of depth and pit position. The general results of IC do not differ significantly with land-use.

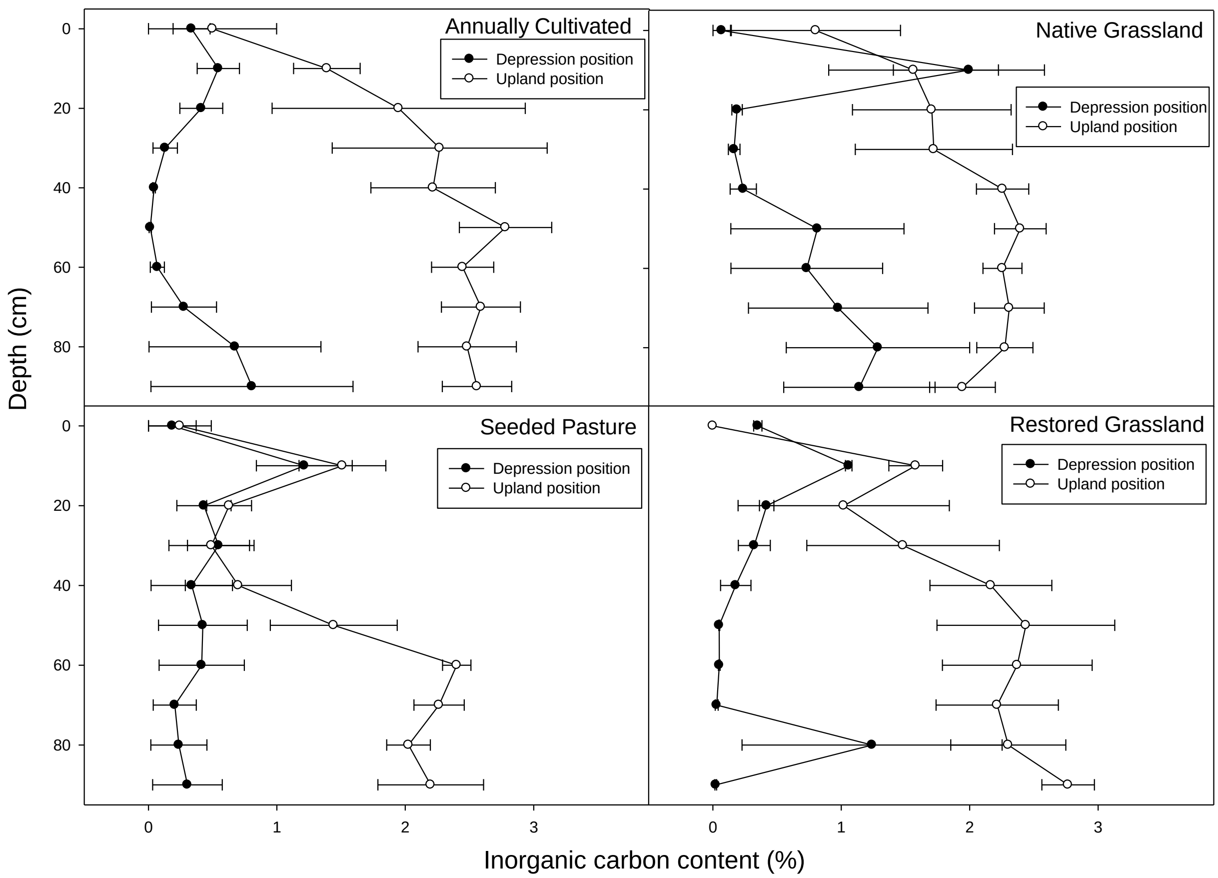

Fig. 3. 4. Comparison of inorganic C content with respect to depth in differing land-uses (annually cultivated, native grassland, seeded pasture, restored grassland) and slope positions (depression, upland positions). Each panel represents a different land-use, with the closed circles representing the depression pit soils and the open circles representing the upland pit soils. Bars represent standard error of the mean.

3.3.4 Particle size distribution

The clay content, as determined by hand texturing, had a general increasing trend with respect to depth (Fig. 3.5). The depression pits on average had higher clay contents than their upslope counterparts. The clay content estimates were derived from field hand texturing of soil horizons so depth-based incremental analysis cannot be conducted. Full hand texturing data with respect to soil horizon are located in Appendix A.

Table 3. 7. Analysis of a linear mixed effects model with inorganic C as a response variable and depth, horizon, land-use, pit position and clay content as explanatory variables. Individual pits and associated depression/upland reference were included as nested random variables to address within-profile and soil position relationships.

Explanatory variable	df	Denominator df	F- statistic	*P*
Depth	9	194	9.183	<0.0001
Land-use	3	22	1.138	0.3554
Pit Position	1	22	45.48	<0.0001
Depth : Land-use	27	194	0.5353	0.9718
Depth : Pit Position	9	194	5.129	<0.0001
Land-use : Pit Position	3	22	0.3622	0.7809
Depth : Land-use : Pit Position	27	194	1.270	0.1795

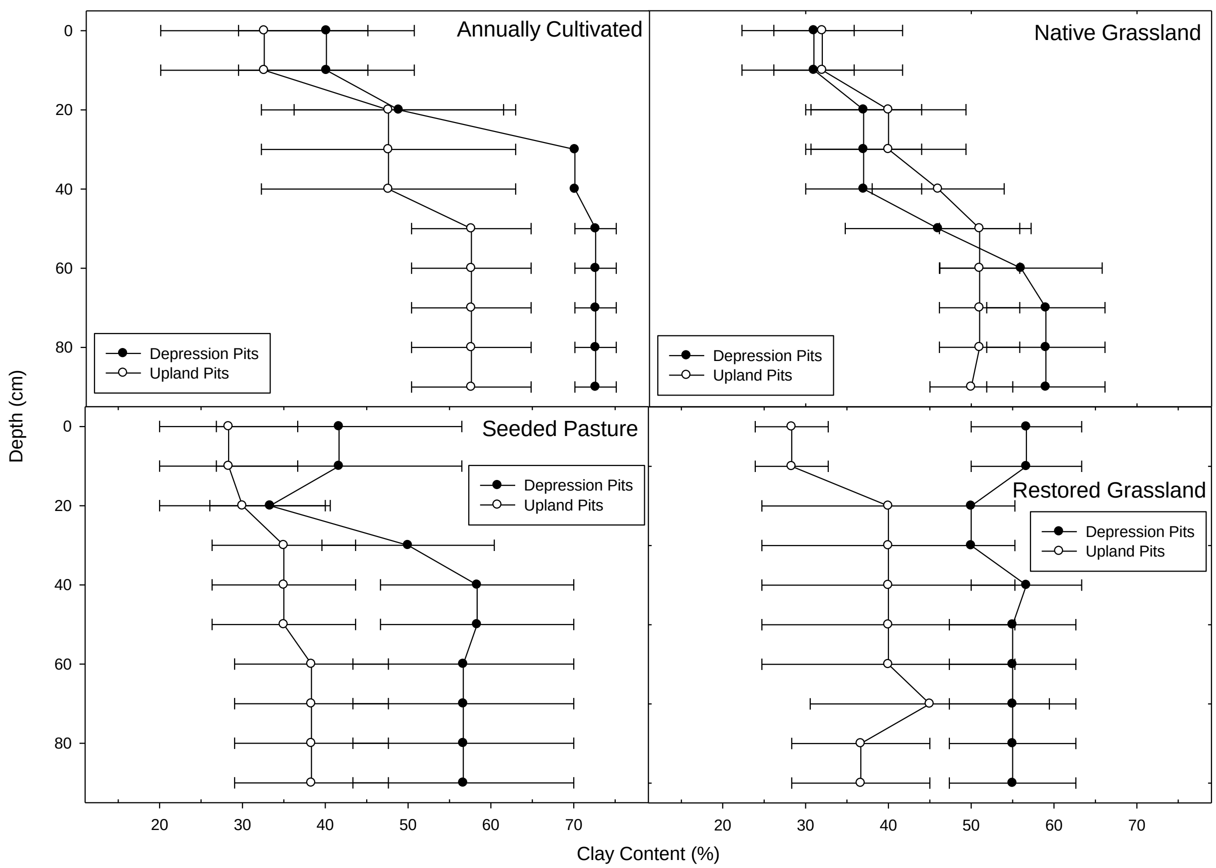

Fig. 3. 5. Comparison of soil clay content through hand texturing with respect to depth in differing land-uses (annually cultivated, native grassland, seeded pasture, restored grassland) and slope positions (depression, upland positions). Each panel represents a different land-use, with the closed circles representing the depression pit soils and the open circles representing the upland pit soils. Bars represent standard error of the mean.

3.3.5 Dithionite extractable iron

The profiles of dithionite-extractable Fe (DF) illustrate the variation with depth (Fig. 3.6). The upland soils tend to have relatively consistent DF values throughout the entire profile whereas the depression soils have accumulations in the lower depths (> 40 cm). Within the surface depth (0 – 10 cm) of the land-use profiles, the annually cultivated soils have noticeably higher DF values in their upland pits compared to their depression pits; within the other land-uses (native grassland, restored grassland and seeded pasture) the DF values of the upland and depression pits are generally consistent.

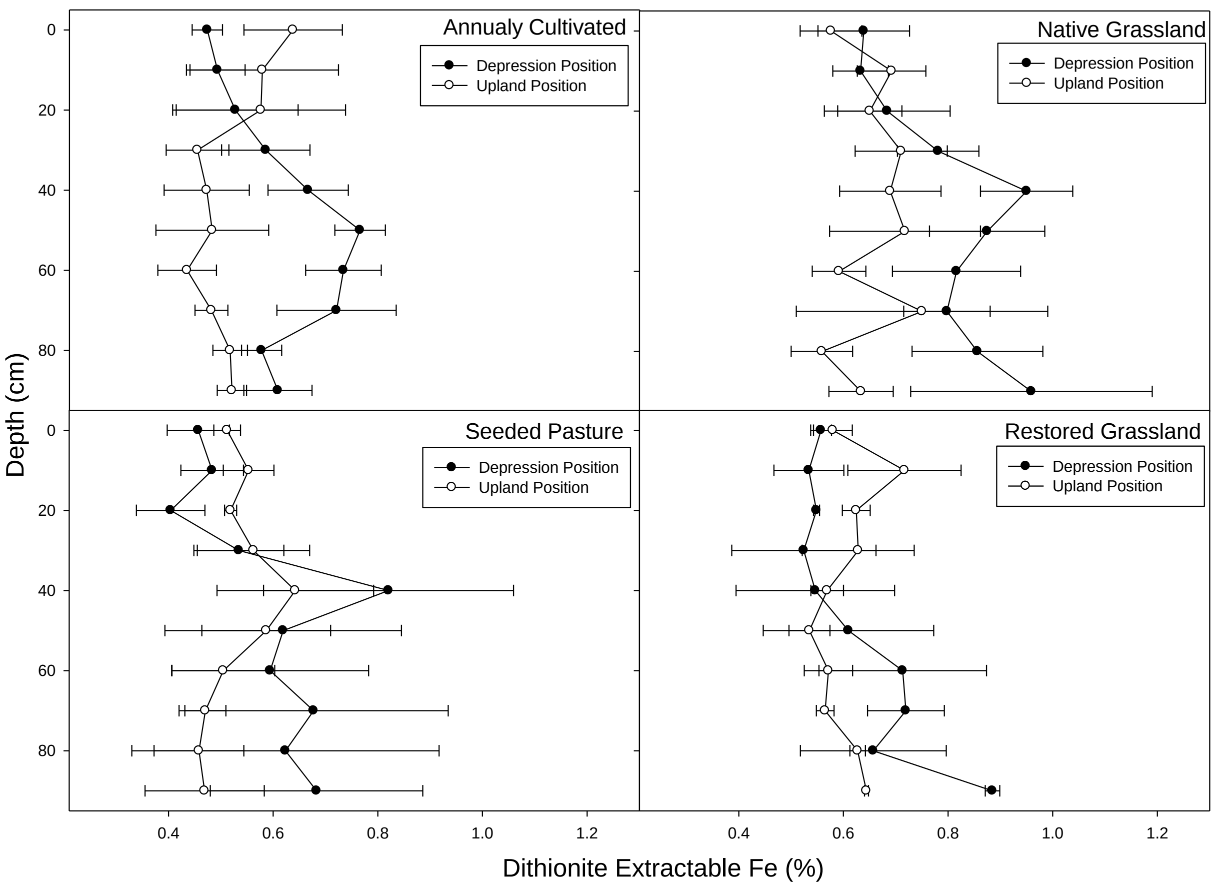

Fig. 3. 6. Soil dithionite extractable Fe (DF) profiles with respect to land-use history and pit position. Each panel represents a different land-use, with the closed circles representing the depression pit soils and the open circles representing the upland pit soils. Bars represent standard error of the mean.

A linear effects mixed model (Table 3.8) denotes that land-use and pit position are significant variables in explaining the variance of DF dataset (F-statistic = 2.8378, 4.3327; *P* = 0.0870, 0.0615 respectively). The only significant interacting effects within the LME model are between depth and pit position (F-statistic = 2.6146, $P = 0.0071$).

3.3.6 Magnetic susceptibility

The MS of non-temperature treated soils had observable differences between average upland and depression soils through analysis of their depth profiles (Fig. 3.7). Visually in these graphs, all land-uses showed similar contrasts between the differing pit positions, whereby the upland pits had consistently higher MS values then their corresponding depression pits. Additionally, MS declined with depth for the cultivated and previously cultivated land-uses (i.e. annually cultivated, restored grassland, seeded pasture). Conversely, the MS values of the native grassland depression pits increased with increasing depth.

Table 3. 8. Analysis of a linear mixed effects model using dithionite extractable Fe as a response variable and depth, land-use and pit position as explanatory variables. Individual pits and associated depression/upland transects were included as nested random variables to address within-profile and soil position relationships.

Explanatory variable	df	Denominator df	F-statistic	*P*
Depth	9	194	1.5332	0.1385
Land-use	3	11	2.8378	0.0870
Pit Position	1	11	4.3327	0.0615
Depth: Land-use	27	194	0.4870	0.9854
Depth: Pit Position	9	194	2.6146	0.0071
Land-use: Pit Position	3	11	0.3818	0.7681
Depth: Land-use: Pit Position	27	194	0.4160	0.9957

Through analysis of a LME model, pit position explained the most variability (Table 3.9; F-statistics =38.2484; $P < 0.0001$). In contrast, land-use and depth had less influence on the MS values though these variables were still significant. Figures of MS after differing temperature treatments can be found in Appendix A.

A Spearman's rank correlation test was conducted between DF and MS values after different temperature treatments; these results are displayed in Table 3.10.

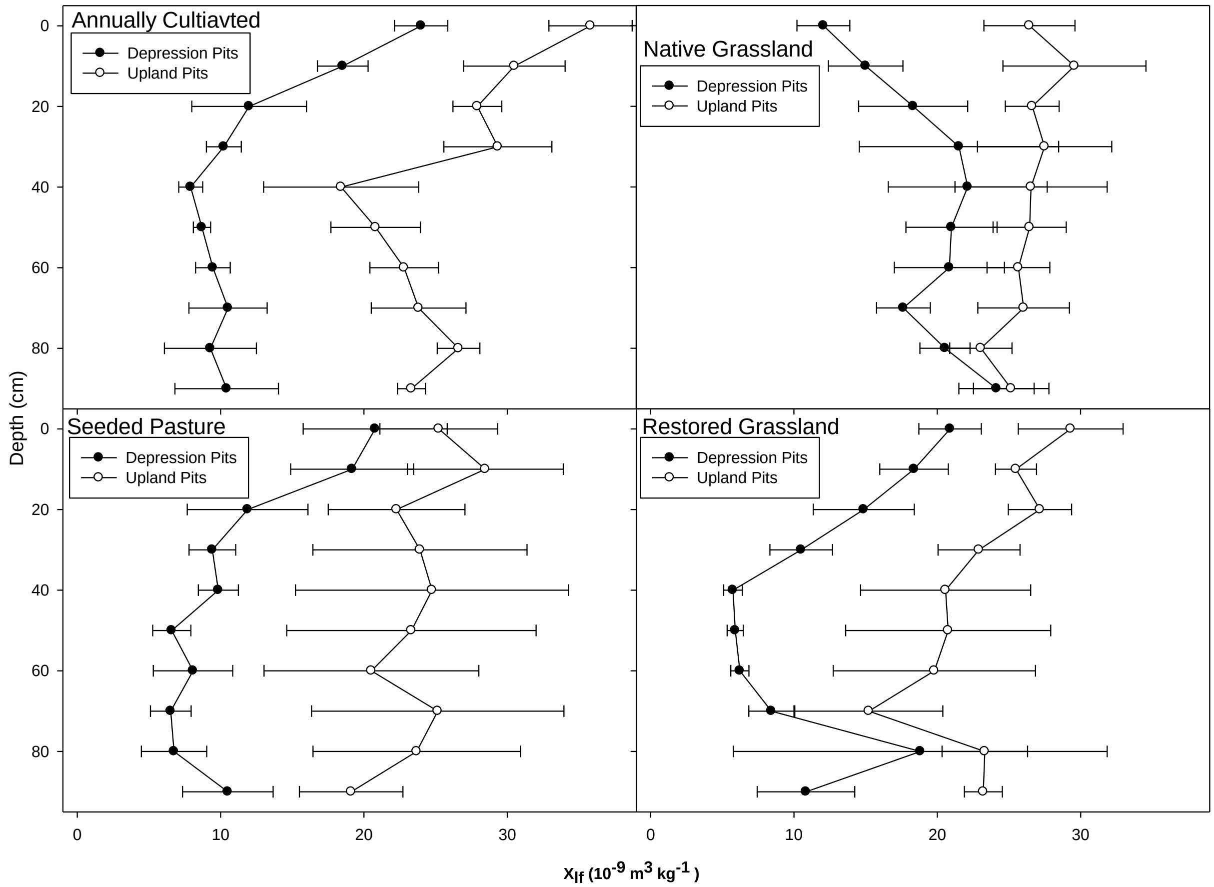

Fig. 3. 7. Magnetic susceptibility comparison of non-temperature treated soil with respect to depth in differing land-uses (annually cultivated, native grassland, restored grassland, seeded pasture, restored grassland) and slope positions (depression, upland positions). Each line represents individual soil pits. The filled circles represent the depression soil pits whereas the open circles denote the upland soil pits. Bars represent standard error of the mean.

Table 3. 9. Analysis of a linear mixed effects model with magnetic susceptibility included as a response variable and depth, land-use and pit position used as explanatory variables. Individual pits and associated depression/upland reference were included as nested random variables to address within-profile and soil position relationships.

Explanatory variable	df	Denominator df	F-statistic	*P*
Depth	9	194	8.2533	<.0001
Land-use	3	11	1.8863	0.0266
Pit Position	1	11	38.2484	<.0001
Depth: Land-use	27	194	2.5767	<.0001
Depth: Position	9	194	0.5195	0.8594
Land-use: Position	3	11	0.8823	0.4801
Depth: Land-use: Position	27	194	2.0584	0.0027

Table 3. 10. Spearman's rank correlation of dithionite extractable Fe and soil magnetic susceptibility values after contrasting temperature treatments.

Temperature Treatment	MS† at room temperature	MS after 100°C	MS after 300°C	MS after 500°C
Dithionite Extractable Fe correlation (R_s‡)	-0.021	-0.02992	0.1088	0.2449
P	0.719	0.6082	0.06161	<0.001

† Magnetic susceptibility

‡ Spearman's rank correlation coefficient

3.3.7 Wet aggregate stability

Differences among individual land-uses of wet stable aggregate sizes did not have any statistical significance (P = 0.1) though significant differences existed between the native and pooled non-native land-uses (P = 0.1) through an unpaired t-test (Table 3.11). The native grassland had the greatest proportion of the largest size fraction (>250 µm), whereas the annually cultivated soils had the smallest amount of these fractions though differences were not statistically significant (Fig. 3.8). For the two smallest aggregate size classes (53-250 µm; <53 µm), the native grassland soils had the lowest proportion whereas there were limited differences among the other land-uses.

Table 3. 11. Unpaired t-test of wet stable aggregate size fractions. Pooled cultivated land-uses represents an aggregate of the annually cultivated, restored grassland and seeded pasture land-use histories. Statistical significance was determined by a Student's t-test.

Wet stable aggregate size fraction	Mean fraction amount (S.D.) Native grassland land-use (n=5)	Pooled cultivated land-uses (n=15)	t-test significance
250 µm	80.54 (11.01)	62.54 (12.14)	*
53 µm - 250 µm	16.83 (10.48)	32.91 (10.47)	*
< 53 µm	1.88 (0.90)	4.39 (2.28)	*

* Denotes significance at P < 0.1 via an unpaired t-test.

3.3.8 Ordination analyses

Three ordinations were generated to analyze holistic and semi-holistic datasets. The first ordination used sampled soils from all pits along with their respective analyzed variables; the second ordination used data points from only depression pits along with their respective analyzed variables; the third ordination used only the soil surface values along with their respective analyzed variables with the inclusion of wet aggregate size fractions. Two axes were selected for each of the ordinations as they allow for simple interpretation and the stress values (goodness of the fit) were maintained below 10% (Clarke, 1993).

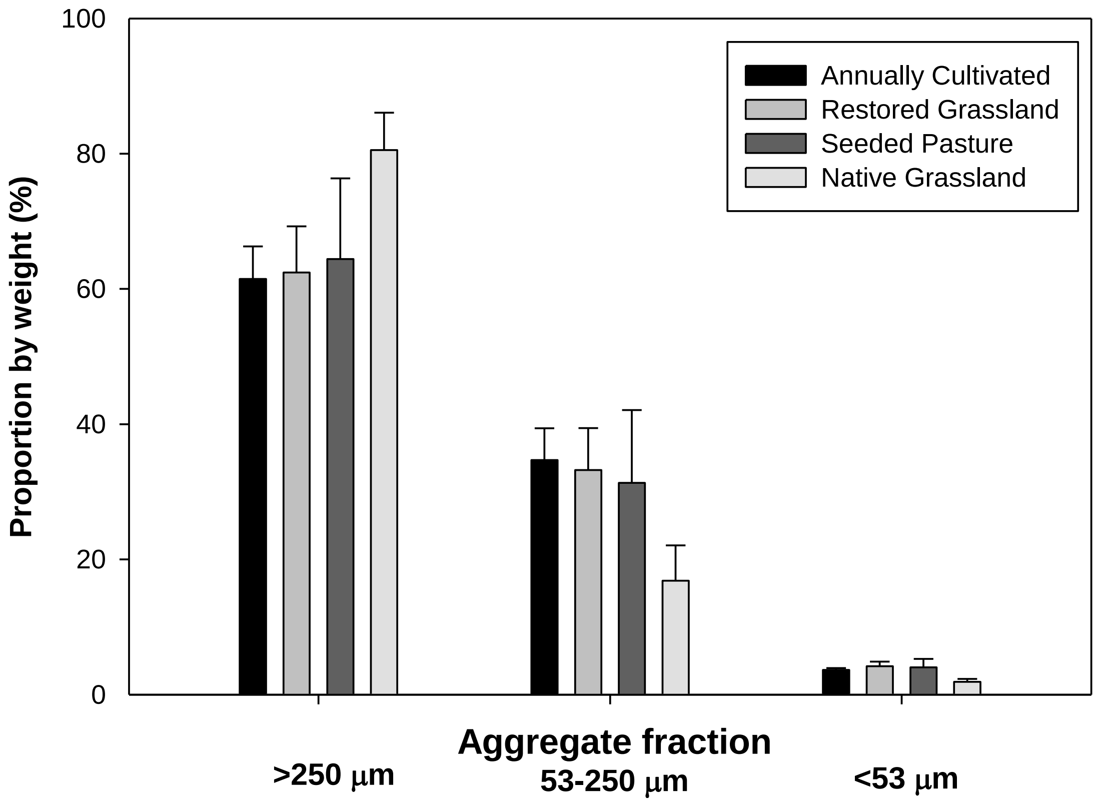

Fig. 3. 8. Comparison of wet stable aggregates by size fraction (>250 μm, 53 – 250 μm, <53 μm) with respect to land-use (annually cultivated, seeded pasture, restored grassland and native grassland). Each bar represents % average of recovered aggregates by weight. Error bars represent standard error of the mean. There were no significant differences via Tukey's HSD (*P* < 0.1) among land-use histories with respect to aggregate fraction groups.

Stress plots for each ordination were created to determine the validity of fit (Fig. 3.9). Stress plots illustrate each ordination distance against its correction to fit the specified number of axes. All three stress plots have a sufficient linear fit ($R^2 > 0.95$) and thus their ordinations accepted as reasonably true.

The first ordination of all sampled points has a clear difference between upland and depression pits (Fig. 3.10). Some other clusterings of land-use histories exist; however, they are not as pronounced as pit position differences. The variation of axis 1 is mainly driven by IC contents and MS values. The variation of axis 2 is mainly influenced by DF and OC.

The second ordination of only depression pits has multiple clusterings of several land-use histories (Fig. 3.11). The most apparent clustering is of annually cultivated, restored grassland and seeded pasture land-uses. A broader cluster of native grassland exists within the ordination. Axis 1 of the ordination is predominantly influenced by DF content whereas axis 2 is mainly influenced by frequency dependent charge (FD).

The third ordination, which uses only the soil surface (0-10 cm) depression points, has a diverse spread of points (Fig. 3.12). The NGS points are distanced from the other land-use histories. Axis 1 was mainly influenced by MS values whereas axis 2 was predominantly influenced by medium sized aggregate fraction and IC content.

3.4 Discussion

3.4.1 Introduction

The soil characteristics examined during the study were proficient at differentiating particular position of the soil pits; however, no variables through either their sole analysis (i.e. ANOVA) or a holistic approach (i.e. NMDS) were conclusively able to differentiate among the land-uses. However, some significant differences were determined through analysis of LME models. Dithionite extractable Fe, MS and IC content were able to differentiate upland soils from their lowland counterparts in most instances. The fraction of water stable macroaggregates by weight had non-significant trends that differentiated the contrasting land-uses; however, significant differences existed between pooled cultivated and formerly cultivated land-uses against the native grassland. Subsequently, a NMDS ordination revealed the presence of some data patterns through a holistic, multivariate approach.

3.4.2 Soil classification and field measurements

Gleysolic soils were identified within the depressional areas of the SDNWA; however, they were not found within the native grassland site (NGS) with the exception of one pit (Table 3.2). The NGS had similar depressional areas as those observed at SDNWA but this did not encourage the development of Gleysolic soils at the site. The soils of the NGS had some mottling development; however, these mottles were found well below the soil surface (> 50 cm) (Table 3.3). Despite spatial similarities of the sites, changes to the hydrological regimes could be caused by vegetation cover (Euliss and Mushet, 1996; van der Kamp et al., 2003), human activity (Zaidelman and Belichenko, 1999) or parent material. Bedard-Haughn et al. (2006b) used true Gleysols for their study from the NGS; however, the same wetlands could not be sampled because of flooded conditions during the sampling season of 2011.

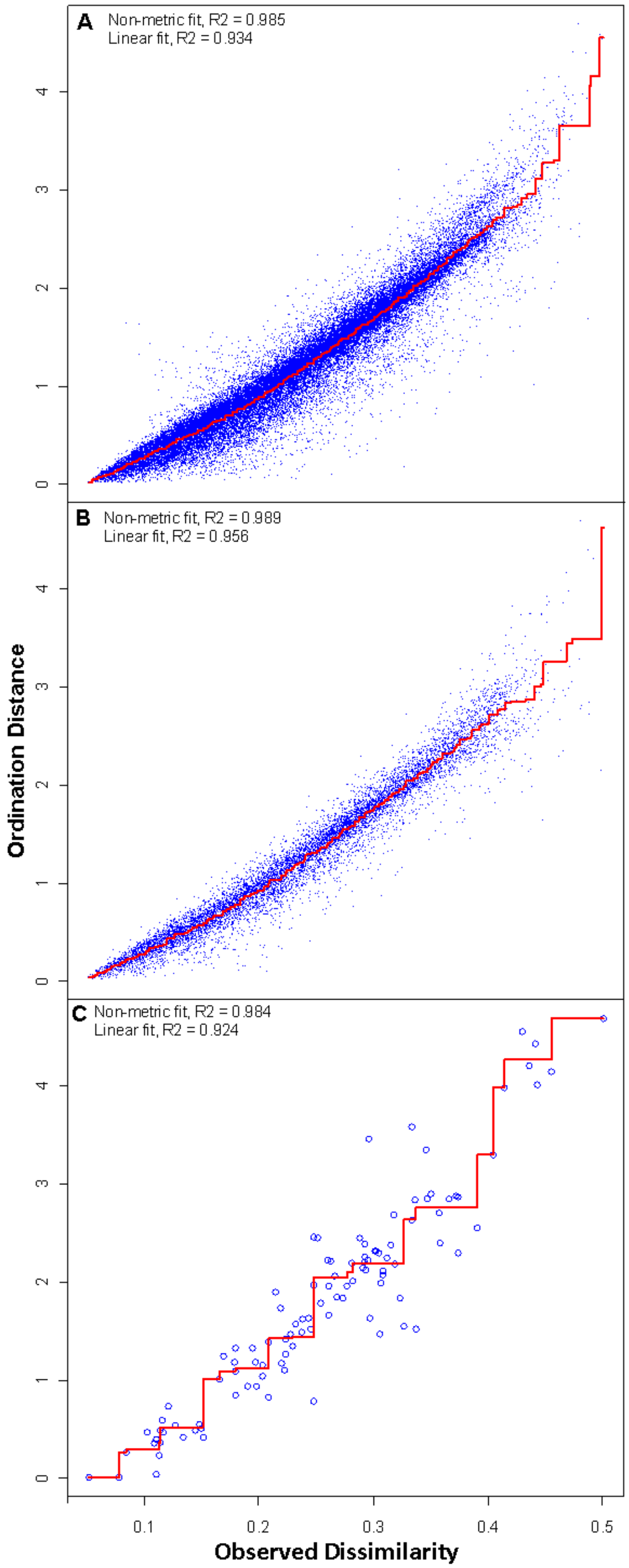

Fig. 3. 9. Stress plots of non-metric multidimensional scaling ordinations using the entire field dataset (A), using the depression pits only (B), and using only the surface depression pits (C).

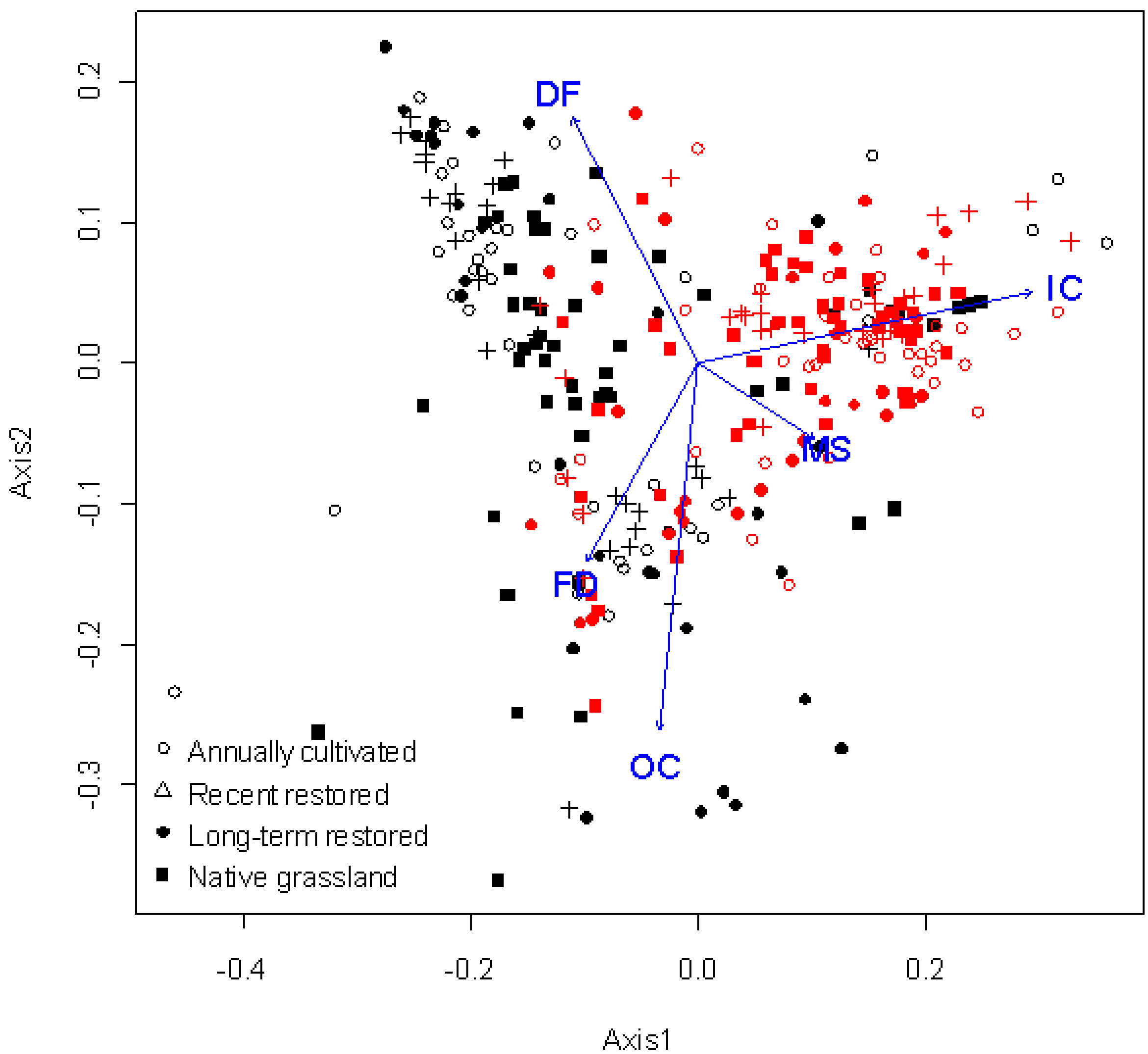

Fig. 3. 10. Ordination of entire pooled data set (both upland and depression pits). Black points represent depression pits whereas red points represent the upland pits. Blue vectors represent the influences of the soil variables on the placement of points. The blue vector magnitude corresponds to strength of correlation and its direction corresponds to the direction of the gradient, as pertaining to the positing of pits with respect to the soil variables. Abbreviations are as follows: OC = organic C content, IC= inorganic C content, MS = magnetic susceptibility at room temperature, DF = dithionite extractable Fe and FD = frequency dependent charge.

The soils within the SDNWA and NGS both were classified as Orthic Black Chernozems rather than their previously classified Dark Brown Chernozems (Miller et al., 1985; Pennock et al., 2010). This discrepancy was potentially due to the taxonomic similarities between the soil Great Groups and the variability of soil color identification based on chart quality and experience of individual (Sanchez-Maranon et al., 2005; Sanchez-Maranon et al., 2011). Additionally, the soil Great Groups are often classified on a region basis and both the SDNWA and NGS are located on the edge of the Dark Brown Chernozem and Black Chernozem regions.

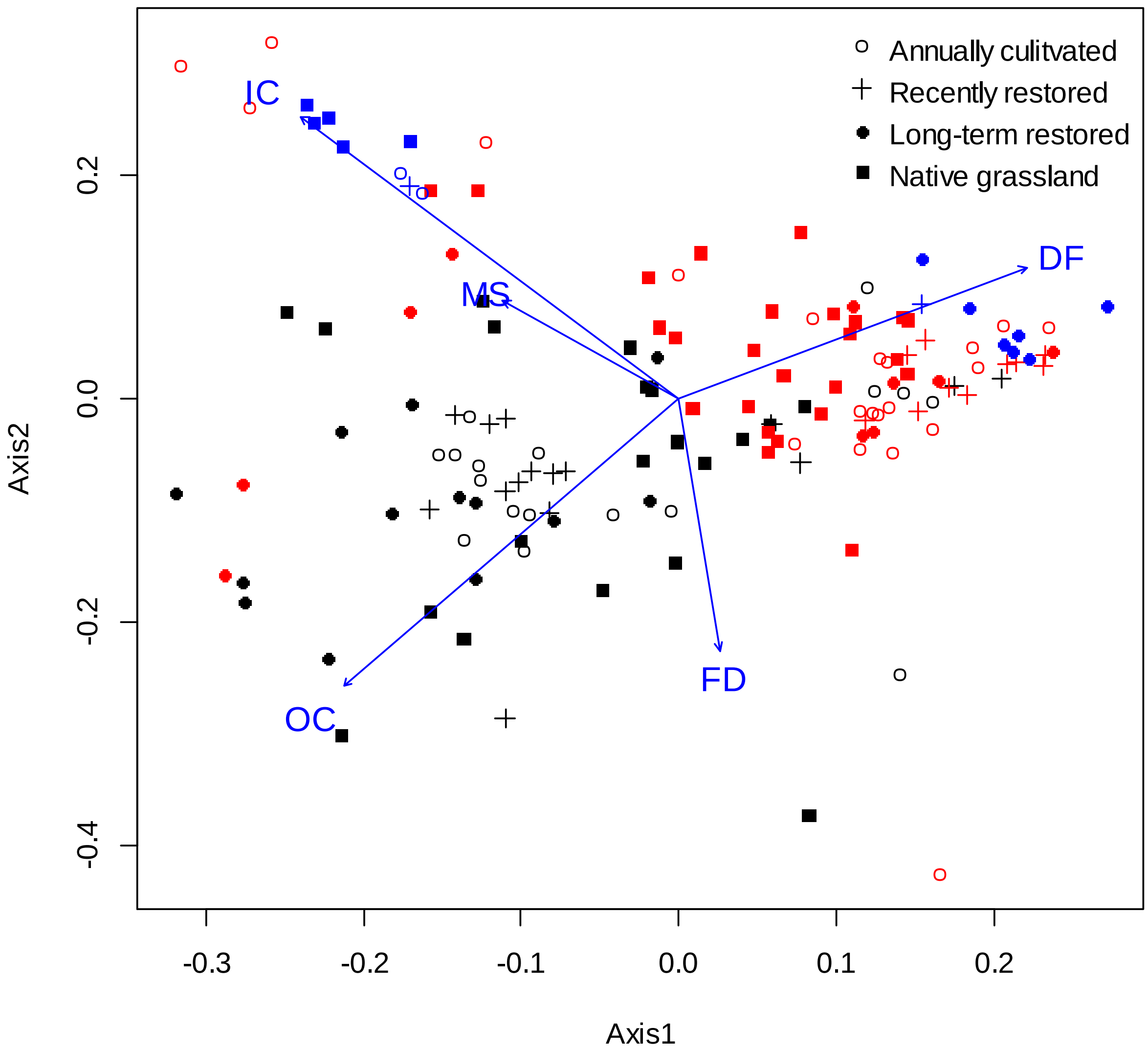

Fig. 3. 11. Ordination of pooled data set including only depression pits with horizon classification (i.e. A, B or C soil horizon). Black points represent soil points from the A horizon. Red points represent soils from the B horizon. Blue points represent points from the C horizon. Blue vectors represent the influences of the soil variables on the placement of points. The blue vector magnitude corresponds to strength of correlation and its direction corresponds to the direction of the gradient, as pertaining to the positing of pits with respect to the soil variables. Abbreviations are as follows: OC = organic C content, IC= inorganic C content, MS = magnetic susceptibility at room temperature, FD = frequency dependent charge and DF= dithionite extractable Fe.

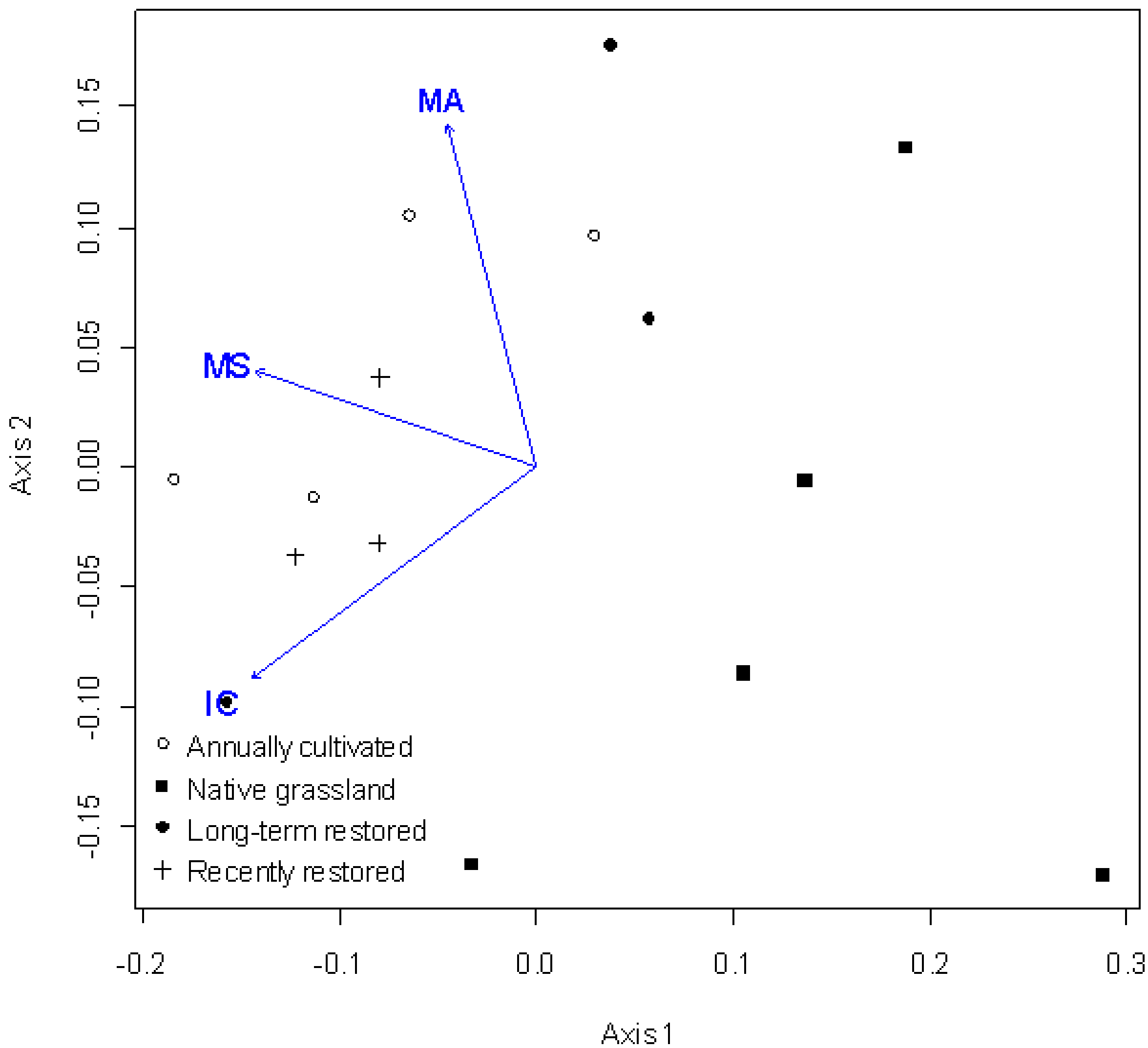

Fig. 3. 12. Ordination of surface soils (0 – 10 cm) of depression positions only with medium sized (53 µm – 250 µm) wet stable aggregate size fraction included. Blue vectors represent the influences of the soil variables on the placement of points. Abbreviations are as follows: MA = medium sized wet stable aggregates, IC = inorganic C content and MS = magnetic susceptibility at room temperature.

3.4.3 Organic carbon profiles of pits

The observed OC decline with depth is a well-documented phenomenon with OC inputs mainly located within the rooting zone of the soil (i.e. approx. depth: 0 – 30 cm; Fig. 3.3; Brady and Weil, 2001). According to the LME model, depth was the main factor of variance within the study (Table 3.5). The significant effects of pit position within the LME model can be best explained by the moisture redistribution to lowland areas that will encourage high plant productivity within these areas. Studies have reported different amounts of OC accumulation and losses based on land-use; Janzen et al. (1998)

observed that soil OC losses occurred after land conversion from native grassland to cultivated cropland. Furthermore, these different OC dynamics as affected by land-use may have caused some of the higher OC contents observed within the seeded pasture land-use relative to the annually cultivated land-use.

The curvatures of the SOC profiles among all land-use histories were similar suggesting generally consistent soil development. More subtly, the native grassland land-use had limited differences between its pit positions in comparison to the other land-uses. Slobodian et al. (2002) reported similar findings within the same area of native prairie grasslands that had comparable SOC contents, on an equivalent mass basis, which were statistically similar between upland and lowland pit positions. Slobodian et al. (2002) also observed that cultivated land-use histories had larger differences in equivalent mass SOC among their pit positions relative to those observed within the native prairie grassland land-use histories. Relatively higher evapotranspiration and limited erosion rates of the native grasslands compared to cultivated and previously cultivated land-uses may influence the lack of OC difference between the pit positions. Tillage erosion will translocate high OC material from upslope positions to accumulate in lowland areas (Lobb et al., 1995) and this would influence the differences between pit positions within the annually cultivated landscapes.

Lower amounts of SOC on an equivalent mass basis were observed within the NGS land-use relative to the SDNWA land-uses (Table 3.6). Aforementioned, these NGS values were similar to what was reported by Slobodian et al. (2002), however, they are still below the values of cultivated and previously cultivated land-use histories; similar native and uncultivated wetlands reported by Bedard-Haughn et al., (2006a) also had higher OC stocks compared to the native grassland depressions from the current study. Vast differences in OC soil stocks of the regions would suggest dissimilar levels of net primary production or available moisture (Gottschalk et al., 2012). While both the NGS and SDNWA are spatially similar to one another, past soil surveys have distinguished them as having slightly different topographic relief (Soil Working Group, 1978). These topographic differences are likely to influence the moisture redistribution of the area, ultimately changing total levels of OC stored.

3.4.4 Inorganic carbon profiles

The trend of IC occurring at higher levels within upland positions relative to their depression position counterparts, has been previously documented and can be attributed to several factors (Fig. 3.4; Miller et al., 1985; Fang et al., 2007; Heagle et al., 2013). One factor contributing to IC levels occurs when the parent material is naturally rich in dissolvable inorganic carbonates (i.e. $CaCO_3$), as is common for much of the PPR (Heagle et al., 2013). The upland soils have limited water infiltration because of moisture redistribution to downslope areas; this ultimately prevents dissolvable IC from being leached down a soil profile. Conversely, the depression areas will have higher amounts of collected moisture which will allow for increased water leaching of IC (Miller et al., 1985). Thusly, pit position was found to be the strongest indicator of IC variation through analysis of a LME model (Table 3.7).

The exception to the higher IC contents within the upland pit positions was observed in the seeded pasture land-use, where the upland position had relatively low IC contents in comparison to the depressional pits of the landscape. Abovementioned, this area is located in the higher elevated region of SDNWA where fill-and-spill events occur during the spring snowmelt (Shaw et al., 2012). These fill-and-spill events cause large amounts of solutes to be redistributed to lower elevated areas, and this prevents the upland position from accumulating IC. The higher elevated region will also be more spatially removed from the water table relative to the lowland areas, and will be less likely to receive groundwater contributions of IC. The accumulations of IC below 50 cm of the elevated region would further suggest that the water table is commonly found below the rooting zone. van der Kamp et al. (2003) observed that the ground water table of the upland cultivated area of SDNWA was more distant from the soil surface prior to spring snowmelt relative to the restored grassland area of SDNWA.

Accumulations of IC were observed just below the soil surface (10 cm) within all land-use histories except for the annually cultivated site. This IC accumulation may have occurred because of evapotranspiration of IC-rich groundwater at points just below the surface. Past hydrologic research confirms that much of the IC occurring within the depression position areas, do so because of IC-rich groundwater (Heagle et al., 2013; Miller et al., 1985). The annual evapotranspiration of this IC-rich groundwater may have caused these below surface accumulations to occur within the natural and restored grassland soils.

Conversely, in the annually cultivated site, these below-surface accumulations were not as pronounced. The hydrological effects that tillage will have on a landscape may influence this phenomenon. Most basically, soil turbation through tillage will allow for mixture of A and B horizon in the formation of a plough layer; this will dilute the observable accumulation of IC just below the soil surface. Continued tillage on the plow layer may expose the surface IC contents to rainwater, which has a slightly acidic pH (pH: 6 - 6.5) and may contribute to IC decomposition.

3.4.5 Soil Fe contents and magnetic susceptibility

The dithionite extractable Fe has been used to discriminate Gleysolic soils (McKeague and Day, 1966). During the study, depression pits were generally classified as Gleysols; within these soils, accumulations of DF were observed with respect to increasing depth (Fig. 3.6). However, the upland soil pits of each land-use history had a leached DF or a lack of major change to DF with respect to depth; these upland pits were all classified as Chernozems. Examination with ANOVA (Table 3.8) was also able to discriminate that the combination of depth and pit position groupings were significant in explaining the DF values.

The MS of the soils clearly discriminates upland from depression positions (Fig 3.7; Table 3.9); this has been observed previously on the Prairies as a means of differentiating Gleysolic soils (de Jong, 2002; de Jong et al., 2005). There was a MS decrease in all SDNWA land-uses (annually cultivated, restored grassland and seeded pasture) with respect to increasing depth whereas the opposite was true at the NGS. This difference may be due to prolonged hydrologic changes induced by tillage within the SDNWA. The effect of tillage and changes to vegetation coverage will affect the ponding durations and reduce infiltration rates (Euliss and Mushet, 1996; van der Kamp et al., 2003); this in turn will lower MS values within the soil through redoximorphic reductions of metallic ions. The annual act of tillage plays a role in aerating the soil in the plough layer (i.e. depth: 0 – 15 cm; Brady and Weil, 2001), which will cause oxidation of metallic ions and tillage translocation of aerated soil from upslope positions (de Jong et al., 1998). Also, the NGS had pits with much shallower A horizons within their upland positions (approx. 20 cm) relative to what was observed in the SDNWA sites. The shallower presence of the B horizon suggests less soil weathering and higher Fe contents, thusly leading to a higher MS value (de Jong et al., 2000).

The presence of significant correlations between DF and MS values after 500 °C along with the lack of significant correlations between DF and MS at room temperature (Table 3.10) suggest that more complete oxidation of soil through higher temperature treatments allow for MS readings to better discriminate the extractable Fe content within a soil. Studies have furthermore shown that a ratio between oxalate extractable Fe (de Jong et al., 2005) and DF significantly correlates with MS at room temperature because it corresponds to the amounts of free extractable Fe and amorphous Fe (Alekseyev et al., 1988 *in* de Jong et al., 2000).

3.4.6 Wet stable aggregates

The significantly higher fraction of soil macroaggregates (> 250 μm) within the native grassland land-use history relative to the cultivated and previously cultivated land-uses (i.e. restored grassland and seeded pasture land-uses) are indicative of the effects of tillage disruption of soil aggregation (Table 3.11). The lack of tillage within the native grassland land-use as well as their perennial vegetation cover allow for increased genesis of macroaggregates relative to SDNWA land-uses (Six et al., 2004). With the smaller aggregate size fractions (53 – 250 μm and <53 μm), the NGS has lower portions; this was expected because the NGS has higher amounts of the large sized fraction (Fig. 3.8). Since only the depression position pits were analyzed for wet stable aggregate fractions, pit position effects could not be compared with this variable.

While lower amounts of OC were present within the NGS relative to SDNWA, higher amounts of macroaggregates were still observed within the NGS. This would suggest that tillage disruption is the major factor in the amount of macroaggregates within a soil and it is subsequently more important than the presence of OM bonding materials (Six et al., 2000).

3.4.7 Holistic data analysis

Clear differences between the upland and depressional pit positions are apparent through a non-metric multidimensional scaling ordination (NMDS) (Fig 3.10). These differences are mainly driven by the MS values and the IC contents, which have been previously observed in studies to differentiate landscape position of Prairie soils (Miller et al., 1985; de Jong, 2002); furthermore, most of the patterns found by the NMDS ordination were previously described through examination of the individual variables through both depth profile graphs and ANOVA.

Other small clusters of land-uses exist within the ordination; however, no clear trends are present. The lack of obvious clusterings among the land-uses suggests that differing land-use histories do not have significant effects in altering the specific pedological variables tested. This suggests that despite some minor differences revealed among the alternate land-use histories through analysis of individual variables, there are limited differences among the land-uses, as detailed through this holistic approach.

Upon examination of the ordination generated with only the depression pits, there are clusters of the native grassland land-use and clusters of the particular horizon designation (Fig 3.11). The land-use history clusters are generally driven by IC and DF contents, which have been observed as variables among land-uses (Table 3.7; Table 3.8). Both these factors are influenced by the hydrologic regime, which can be influenced by the land-use (van der Kamp et al., 2003; Euliss and Mushet, 1996).

Horizon clusterings are also present within the depression ordination (Fig. 3.11). The A and B horizons are mainly separated from one another through OC and DF contents. Both of the pedological values are sensitive to profile depth and they often produce the visual cues that allow for profile discrimination in soils. Organic C was mainly produced through plant decomposition and will be mostly present at the surface of the soil where most plant biomass exists (Brady and Weil, 2001). The DF content is susceptible to soil weathering and downward water movement will result in DF depletions to the A horizon with subsequent accumulations to the lower B horizon (Stonehouse and St. Arnaud, 1971). Furthermore, some of the C horizons are differentiated by IC content, which again will accumulate at increased depth because of water dynamics. The inclusion of the wet aggregate stability data within an NMDS ordination revealed more significant separation of the differing land-uses. The native grassland wetland pits were broadly clustered to the edges of the ordination graph and were mainly influenced by the distribution of medium sized wet stable aggregates (53 – 250 µm) and lower MS values (Fig 3.12). The land-uses were broadly clustered together while still being spatially removed from the native grassland land-use pits.

Despite the fact that the ordinations (all-pit ordination; depression-only ordination; wet stable aggregate inclusive ordination) did not reveal any patterns not observed through examination of individual variable and ANOVA tests, it is important to examine datasets through a holistic approach to ensure that patterns are not missed. The major strength of ordination-style analyses is its ability to allow for large datasets with multiple variables to be compared in an easy, visual manor; the criticism to this is that only patterns already known are usually the first identified by the researcher. Other data patterns may go unnoticed in ordinations; however, combined with additional statistical analyses, most trends will then be identified.

3.4.8 Summary

Overall, most soil variables lacked ability to differentiate the land-uses within the study. While a LME model did identify significant differences among the land-uses with respect to some soil characteristics (i.e. OC, DF and MS), these differences were not generally observable within the depth profile figures. Wet aggregate stability showed non-significant trends in differentiating the land-uses; though significant differences were revealed when pooling the cultivated and formerly cultivated land-uses.

Most of the soil variables were adept at differentiating the pit position among all land-uses (i.e. OC, IC, DF, MS). These differences were observable through analyzing each individual depth profile as well as the LME models generated for each variable.

Holistic analysis of NMDS ordinations allowed for trends to be re-identified, however, no new patterns were discovered. The use of multivariate statistics for studies such as these is important as it ascertains that holistic patters are not overlooked.

4. GREENHOUSE GAS EMISSIONS OF WETLAND SOILS AMONG DIFFERING LAND-USES AND BIOGEOCHEMICAL CONTROLS

4.1 Introduction

Greenhouse gas (GHG) emissions are an important area of research; their inventories are required to understand the risks and potential for global climate change (Mosier, 1998). Globally, wetlands are important emitters of GHGs because of their frequent saturation and high organic matter (OM) levels, which lead to elevated emissions of both CO_2 and CH_4 (Whiting and Chanton, 2001). The wetlands of the Prairie Pothole Region (PPR) have emissions lower than most of their Canadian counterparts including those found in the northern peatlands and eastern Canada (Lai, 2009; Roulet, 2000); however, the PPR spans an extensive 900 000 km^2 (Gleason et al., 2011), which cumulatively makes them important. Methane and CO_2 are the GHGs most associated with wetlands; however, N_2O emissions should also be considered in these systems when they receive exogenous N sources.

Methane has a global warming potential of approximately 25 (in CO_2 equivalency values on a 100-year scale) and is the second greatest GHG contributor to climate change after CO_2 (IPCC Working Group, 2007). Methane contributes to climate change through radiative forcing, whereby infrared radiation is retained on the Earth's surface, and through photochemical reactions in the troposphere (IPPC Working Group, 2007; Whalen, 2005). Wetlands are known emitters of CH_4 because of their frequent water saturation and higher amounts of OM, relative to other terrestrial landscapes (EPA, 2010).

Methane production is controlled by the presence of sulfate (SO_4^-). Past studies have shown that the presence of SO_4^- suppresses CH_4 production, which leads to decreased emissions (Ro et al., 2011; Le Mer and Roger, 2001; Conrad, 1996). The reduction of CO_2 is also a pathway for CH_4 production though the presence of SO_4^- will limit methanogenesis because SO_4^- is more thermodynamically favored over CO_2 (Le Mer and Roger, 2001).

Nitrous oxide has a global warming potential of approximately 298 (in terms of CO_2 equivalency values on a 100-year scale) and is considered the third most important in climate change potential after CO_2 and N_2O. The main controls of soil N_2O production include the presence of an available N source and the saturation level of the soil. Globally, natural wetlands are low emitters of N_2O, despite their frequent saturation, because they are often low in available N contents. In the PPR, it is important to consider N_2O emissions because most wetlands are adjacent to agricultural lands and may receive N through fertilizer runoff (Hobb and Govaerts, 2010). Many PPR wetlands will annually have a dry down period where they lose their ponded water; the partially saturated soils during these dry-down periods (i.e. WFPS: 60 – 80%) are optimum for high N_2O emissions (Kachenchart et al., 2012).

A land-use change may influence multiple effects to soil including changes in: soil physical properties (bulk density, particle size, carbonate concentration), chemical properties (available nutrients, etc.) and biological properties (microbial biomass and community structure) (Doran, 1980; Balesdent et al., 2000; Six et al., 2004; Zucca et al., 2010). All these factors, in turn, can have potential effects on the GHG emission rates; however, these underlying controls (i.e. SO_4^- presence, WFPS levels and NO_3^- additions) have been less studied in their relationship to contrasting land-use histories.

The overall purpose of the study was to determine the interacting effects that differing land-uses and known GHG controls may have on the specific GHG emission of wetland soils. Two separate incubations were carried out to determine the presence of interacting effects among CH_4 and N_2O emission controls and soil land-use history with respect to their particular emitted GHGs.

4.2 Materials and Methods

4.2.1 Site characteristics and soil collection

Intact soil cores (dimensions: 10 cm x 4.7 cm cylinder tubes; volume: 173.49 cm^3) were collected from the depression centers of two comparable wetlands of differing land-use histories (annually cultivated and seeded pasture) from the St. Denis National Wildlife Area (SDNWA) in fall 2011 (Fig. 4.1). The wetlands are Class II (Stewart and Kantrud, 1971), as based upon a previous survey of the area (Hogan and Conly, 2002).

The area of SDNWA is classed as a Weyburn soil series with hummocky glacial till land forms (Soil Survey Working Group, 1988). The wetland soils of both land-uses were classified as Humic Luvic Gleysols, as per the Canadian System of Soil Classification (Soil Classification Working Group, 1998).

The site has been cultivated annually for at least the past six decades and rotations include: *Triticum aestivum* L. (spring wheat), *Brassica napus* L. (canola), *Linum usitatissimum* L. (flax), and other common crops of Western Canada (Hogan and Conly, 2002). The seeded pasture site was annually cultivated until 1982 when the site was seeded to a tame grassland mix, which includes *Bromus inermis* L. (brome grass), *Medicago sativa* L. (alfalfa) and *Melilotus officinalis* L. (sweet clover) (Hogan and Conly, 2002).

Soil cores were sampled using a slack hammer with a mounted soil corer. Sampled soil cores were kept under refrigeration (4° C) until the incubation experiments commenced. The sampled soil cores were used for both the CH_4 incubation and the N_2O incubation.

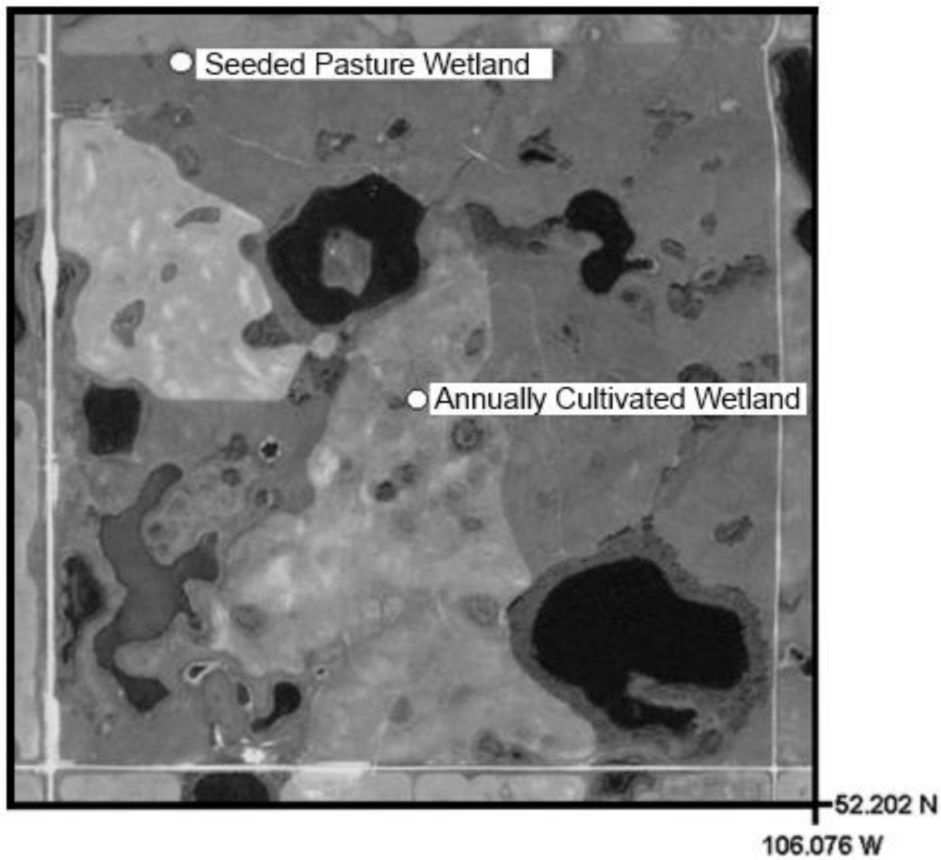

Fig. 4. 1. East section of St Denis National Wildlife Area with land-uses labeled at time of study. Sampled wetlands are labeled on the map. The coordinates of the site are 52.215° N latitude, 106.098° W longitude with a legal land description of 28 – 37 – 1 W3 (Map adapted from Hogan and Conly, 2002).

4.2.3 Methane incubation

4.2.3.1 Incubation treatments and experimental design

Intact soil cores were placed in mason jars (volume = 2.6 L) for the duration of the incubation. The mason jars had lids retrofitted with septa to allow for gas sampling of the jar's headspace. A glove box (Plas Labs, Lansing, USA) was used to purge the headspace of the mason jars of their O_2 and subsequently replace it with N_2 gas. After approximately 1 h of N_2 gas flushing, the soils cores were brought up to 120% water filled pore space (WFPS) and their specific SO_4^- treatment was added.

The SO_4^- treatment was added in solution through differing dilutions of analyzed sulfidic pond water. The sulfidic pond water was sampled from Pond 1 (SDNWA pond classification; Hogan and Conly, 2002) of the SDNWA on October 25, 2011. Table 4.1 displays the ionic concentrations of the sulfidic pond water used. Sulfate treatments S0, S10, S50, and S100 contained 0, 10, 50 and 100% sulfidic pond water respectively, with distilled H_2O making up the remainder of the solution. The incubation used a two-way factorial design using land-use history (two levels) and SO_4^- additions (four levels) as treatments (Fig. 4.2). Each treatment had 5 replicates, with an additional 3 procedural controls of empty incubated mason jars for a total of 43 incubating mason jars (2 x 4 x 5 = 40 + 3 = 43).

Table 4. 1. Selected chemical values of pond water that was added to soil cores for SO_4^- treatments S10, S50 and S100. Ions were analyzed through inductively coupled plasma mass spectrometry, pH and conductivity was measured with electronic probes. A homogenized single sample of pond water was used for the analysis (n=1).

Analysis	Result
Major anions and cations (mg L^{-1} H_2O)	
Bicarbonate (HCO_3^-)	342
Chloride (Cl^-)	19.6
Calcium (Ca^{2+})	164
Potassium (K^+)	47.9
Magnesium (Mg^{2+})	257
Sodium (Na^+)	89.8
Sulfate (SO_4^-)	1370
pH	7.95
Conductivity, µS cm^{-1}	2560

4.2.3.2 Sampling procedure and gas analysis

The incubation continued for 14 d with headspace sampling occurring at d 0, 1, 2, 3, 4, 6, 8, 10, 12, and 14. The incubation temperature was approximately 22 °C for the duration of the experiment. Gas sampling involved the removal of 20 cm^3 of headspace gas from each mason jar using hypodermic needles (Hypodermic needles with polypropylene hub, 0.9 x 25.4 mm, Covidien, Dublin Ireland). Gas samples were stored in 12 cm^3 Exetainers® (Labco Ltd, UK). The Exetainers® had been prepared by evacuating to 0.00667 kPa. Removed headspace in mason jars was replaced immediately with an equal volume of inert Ar gas to prevent major pressure changes to the soil while maintaining anaerobic conditions.

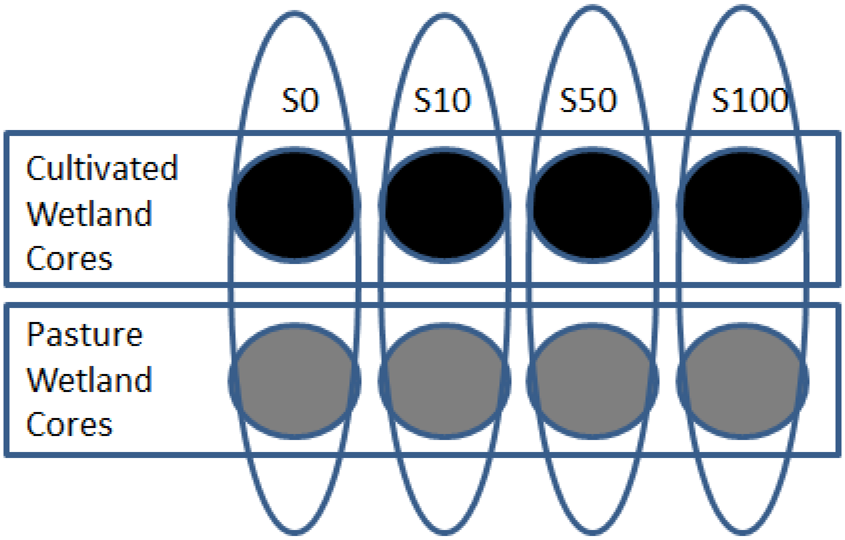

Fig. 4. 2. Schematic of the CH_4 incubation design. The study involved a two-way factorial design with land-use history and SO_4^- additions as treatments. The SO_4^- treatments S0, S10, S50 and S100 represent 0, 10, 50, and 100% sulfidic pond water respectively. Each treatment was replicated 5 times.

The gas samples were subsequently analyzed for CH_4 via a Varian CP-3800 gas chromatograph (Varian Inc., Palo Alto, USA). The CH_4 concentration was measured with a flame ionization detector. The column used was a Porapak Q8 (length = 3.66 m; diameter = 3.175 mm). The detection limit for CH_4 was 360 ppb.

Linear regression was used to determine the flux of CH_4 emissions between sampled times (Keller et al., 2009). The means of the procedural controls (empty incubated jars) were subtracted from all other gas samples. Gas emissions were calculated on a soil area basis. Briefly, the headspace sample (20 cm^3) was extrapolated to determine the gas mass within the entire headspace, minus the volume of soil and water (2.6 – 0.173 L). Gas emissions were determined per soil area (mg CH_4 m^{-2}).

4.2.2 Soil and water analysis

The seeded pasture and cultivated soil cores were analyzed for common nutrient and physical properties including: OC, IC, extractable SO_4^-, extractable NO_3^-, extractable NH_4^+, total N, total P and bulk density. Organic C and inorganic C were measured by combustion and subsequent infrared detection (Wang and Anderson, 1998). Extractable SO_4^- was determined through a 0.01 M $CaCl_2$ extraction. Soils were analyzed for total N and P through H_2SO_4 digestion (O'Halloran and Cade-Menun, 2008). Extractable NO_3^- and NH_4^+ were determined through 2 M KCl extraction (Bremner and Keeney, 1966). Nutrient concentrations from the $CaCl_2$ extraction, KCl extraction and H_2O_4 digestion were subsequently analyzed by colorimetry with a Segmented Flow Analysis Auto Analyzer (Technicon Corporation, Copenhagen, Denmark) (Wall et al., 1980). Bulk density was determined on extracted soil cores used for the incubation.

The sulfidic pond water used for SO_4^- treatments within the CH_4 incubation was analyzed at ALS laboratories (Saskatoon, SK) for multiple ionic concentrations including HCO_3^-, OH^-, CO_3^{2-}, Cl, B, Cu, Fe, Mn, P, Zn, Ca, K, Mg, Na, SO_4^- and NO_3^- along with pH, alkalinity and conductivity. Briefly, inductively coupled plasma emission spectrometry was used to measure ionic concentrations (Greenberg et al., 1992). Alkalinity was measured using acid titration (Greenberg et al., 1992). Electrical conductivity and pH were measured using calibrated probes.

4.2.4 Nitrous oxide incubation

4.2.4.1 Nitrous oxide experimental design and core preparation

The N_2O incubation was a three-way factorial design with treatments of land-use histories (annually cultivated and seeded pasture wetland soils), water filled pore space (WFPS) (60%, 80% and 120%) and NO_3^- additions (no NO_3^- added and 112 kg N-NO_3^- ha^{-1} added) (Fig. 4.3). Each treatment was replicated five times, with three additional procedural controls of empty mason jars for a total of 63 incubation mason jars (2 x 3 x 2 x 5 = 60 + 3 = 63).

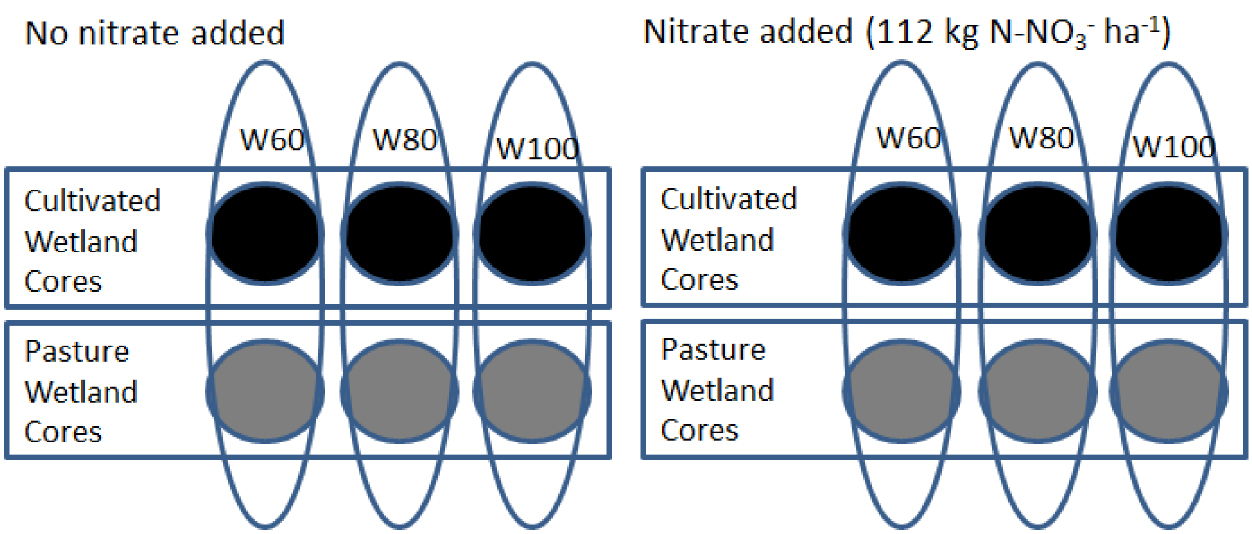

Fig. 4. 3. Schematic of N_2O incubation experimental design. Land-use history treatments used soil cores collected from differing wetlands within St. Denis National Wildlife Area. The water filled pore space treatments are denoted by W60, W80 and W120, and correspond to 60%, 80% and 120% water filled pore space. Each individual factorial treatment was replicated five times, for a total of 60 incubating soil cores.

Prior to incubation, soil cores underwent a freeze-thaw cycle to free up N for the N_2O incubation. Soil cores were removed from cool storage (4 °C) and placed in a freezer (-20 °C) for 24 h. After the freezing period, soil cores were placed back in cool storage (4 °C) for another 24 h.

After the freeze-thaw period soil cores were placed in mason jars and their respective WFPS and NO_3^- treatments were applied. Nitrate addition treatments were applied in solution with their respective WFPS treatment. The water addition amounts for the WFPS treatments were determined through bulk density calculations of the pasture and cultivated soil cores.

4.2.4.2 Sampling procedure and gas analysis

The incubation ran for a 7 d period. Each day included 2 samples, a T0 at 0 h and a T1 after 24 h. The first T0 sample was taken place immediately after the mason jars were closed with their specific treated soil cores incubating inside. The T1 sample took place after 24 h, on the next day. Following each T1 sample, mason jars were opened to the environment for 20 min and allowed a period to equilibrate with the surrounding atmosphere. After the 20 min period, jars were closed again, and the next T0 sample was taken.

Gas sampling and analysis was conducted as per the CH_4 incubation (see *Section 4.2.3.2*). A Varian CP-3800 gas chromotograph was used to measure N_2O concentrations; the detection limit for N_2O was 60 ppb.

Linear regression was used to determine the N_2O fluxes (Chen et al., 1995) between samples T0 and T1 for each specific treatment. Given that T0 samples were low, only a subsample (random 20% of total) was analyzed and the mean was used as a general T0 sample. Gas emissions were calculated on a soil area basis. Briefly, the headspace sample (20 cm^3) was extrapolated to determine the gas mass content within the entire headspace minus the volume of soil and water (2.6 – 0.173 L). Gas emissions were determined per soil area (mg N-N_2O m^{-2}).

4.2.4.3 Post-incubation analysis

After the incubation, extractable soil NO_3^- amounts were determined with a 2 M KCl wet soil extraction, using an approximate 10:1 water-soil solution by weight. Briefly, wet soil was added to distilled water at a 10:1 ratio. A subsample of the wet soil was measured for moisture content by measuring the change in mass after drying overnight in an oven (90 °C). The NO_3^- levels were determined through colorimetry with a Segmented Flow Analysis Auto Analyzer (Technicon Corporation, Copenhagen, Denmark). The NO_3^- amounts were subsequently adjusted using the known moisture content of each sample to reflect equivalent soil mass by dry weight among all samples.

4.2.5 Statistical analysis

Linear mixed effects (LME) models were used to analyze both the CH_4 and N_2O incubations. The LME models were generated using the 'nmle' library (Pinheiro et al., 2011) in R statistics (version 2.13.1; R Core Team, 2011) wherein gas emissions (mg CH_4; mg N-N_2O m^{-2}) were used as the continuous response variable; land-use and the other soil core treatments (i.e. SO_4^- additions, WFPS levels or NO_3^- additions) were included as fixed effects. Sampling day was included within the models to conduct a repeated measures test (Zuur et al., 2007). The models were subsequently analyzed by an analysis of variance test (function 'anova').

Statistical comparison of cumulative CH_4 and N_2O emissions and extractable NO_3^- amounts were conducted through a Tukey's Honestly Significant Difference test of a linear model using JMP (version 8.0; SAS Institute Inc., Cary, NC). JMP was used in place of R Statistics because its results included statistical probability letters.

4.3 Results

4.3.1 Soil core nutrient characteristics analysis

Soil cores were assessed for their nutrient properties and bulk density. The cultivated and seeded pasture soil cores had comparable amounts of OC and total N though they were different in NO_3^-, total P and SO_4^- amounts (Table 4.1).

4.3.2 Soil methane emissions with respect to sulfate additions and land-use histories

The daily CH_4 emissions were highly variable. The cause of the variation was usually due to the presence of high emitting cores within the treatment group (Fig. 4.4). Figures of the other treatment groups with each replicate represented are located in Appendix B.

There were observable differences in mean daily CH_4 emissions among the SO_4^- treatments (Fig. 4.5). The S0 treatment showed limited differences between the differing land-uses. Treatments S10 and S100 had more pronounced CH_4 emission differences between the contrasting land-use histories suggesting opposite response to the addition of SO_4^-. The cultivated soil cores showed a suppression effect within treatments S10, S50, and S100. The seeded pasture soil cores showed increased emissions for the S10 and S100 treatments, however, there was a limited effect during the S50 treatment.

Table 4. 2. Nutrient and physical properties of the cultivated and seeded pasture soil cores used for the CH_4 and N_2O incubations.

	Land-use	
Soil property	Annually cultivated	Seeded pasture
Carbon contents (%)		
Organic	4.46	5.20
Inorganic	0.763	0.0
Common ions and total nutrients (µg g^{-1} soil)		
Sulfate (SO_4^-)	17.8	47.0
Nitrate (NO_3^-)	37.1	47.2
Ammonium (NH_4^+)	7.90	18.0
Total nitrogen (N)	2838.3	2954.7
Total phosphorus (P)	634.5	114.9
Bulk density, Mg m^{-3}	1.31	1.18

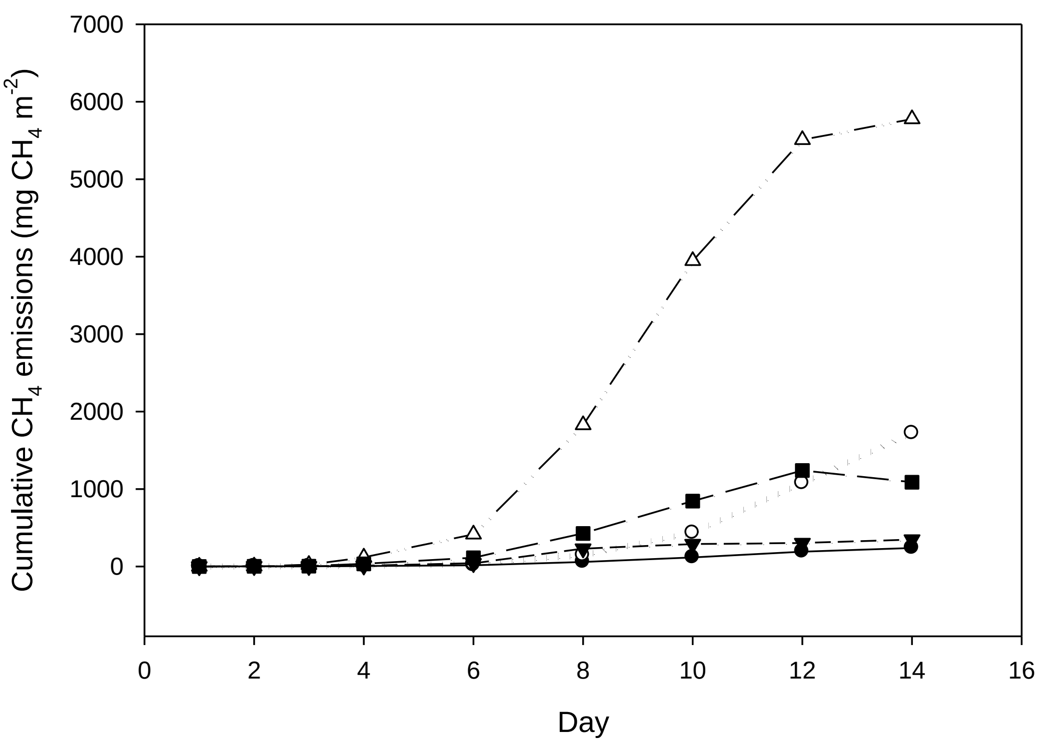

Fig. 4. 4. Cumulative CH_4 emissions of the seed pasture cores under the S0 - SO_4^- treatment with respect to day. Each point represents the emissions of a different incubated soil core (n=5).

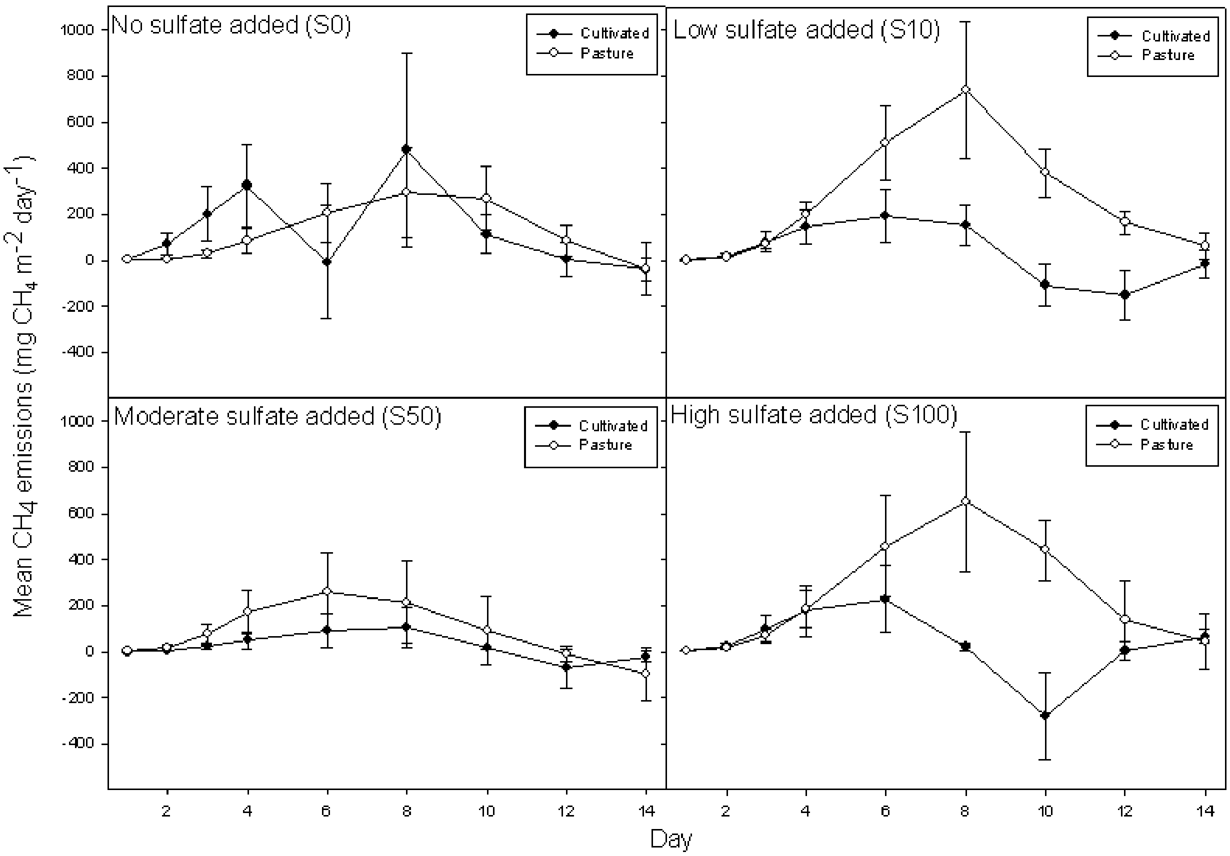

Fig. 4. 5. Mean daily CH_4 emissions of intact cores under differing SO_4^- treatments and land-use histories (n=5). Each panel represents a different SO_4^- treatment. Filled circles represent cultivated soil mean emissions; empty circles represent pasture soil mean emissions. Error bars represent standard error of the mean.

With respect to the cumulative emissions for the 14 d incubation (Fig. 4.6), there was a non-significant trend for the suppression of CH_4 emissions over the 14 d period from the cultivated soil cores with added SO_4^- (SO_4^- treatments: S10, S50, S100). In the pasture cores, CH_4 emissions were significantly increased (P = 0.1) by the S10 treatment; a non-significant trend for increased emissions was observed under the S100 treatment. The coefficient of variation values of the cumulative mean CH_4 emissions are displayed in Table 4.2.

Using an analysis of a linear mixed effects model both the SO_4^- treatments and land-use were significant factors in explaining the variation of CH_4 emissions, however, land-use had a considerably stronger effect (Table 4.3). Interacting effects of SO_4^- and land-use were present in the analysis (F-statistic = 4.68, P = 0.0032).

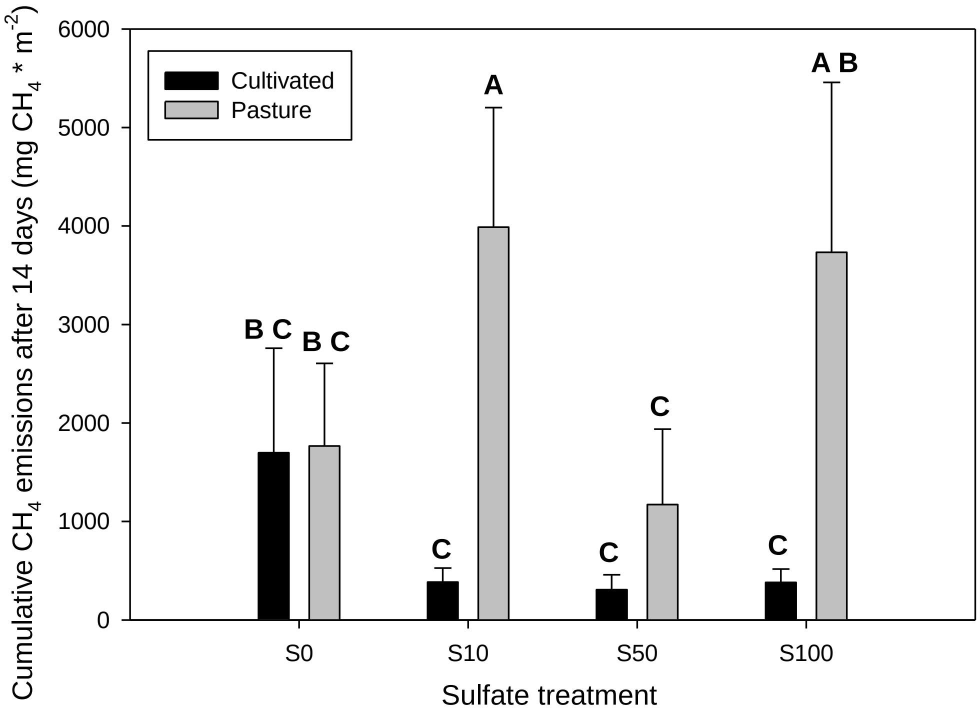

Fig. 4. 6. Final day (d= 14) mean CH_4 amounts. Black bars represent the mean cultivated soil core emissions whereas grey bars represent mean pasture soil core emissions (n=5). The same letters denote that there was no significant difference among the treatments (*P* = 0.1). Error bars represent standard error of the mean.

Table 4. 3. Coefficient of variation of mean cumulative CH_4 emissions. Each value represents the ratio of the treatment's standard deviation to its mean.

	Land use history	
Sulfate Treatment	Cultivated (%)	Pasture (%)
S0	139.8	106.2
S10	83.22	68.07
S50	108.8	146.0
S100	78.89	103.4

Table 4. 4. Analysis of variance of a repeated measures linear mixed effects model with daily CH_4 emissions as a response variable and land-use and SO_4^- treatments as fixed effects. Sampling day was the repeated measures.

Explanatory variable	df	Denominator df	F-statistic	*P*
SO_4^- treatment	3	383	3.56	0.0144
Land-use	1	383	47.88	<0.0001
SO_4^- treatment: Land-use	3	383	4.68	0.0032

4.3.3 Soil nitrous oxide emissions with respect to differing land-use histories, water filled pore space and nitrate additions

High variation existed within each of the treatment groups within the N_2O incubation. Most of this variation was driven by the presence of one or two heavy emitters (Fig. 4.7). The high emitting cores were visually no different from their low emitting counterparts. Additional figures of N_2O treatment groups are located within Appendix B.

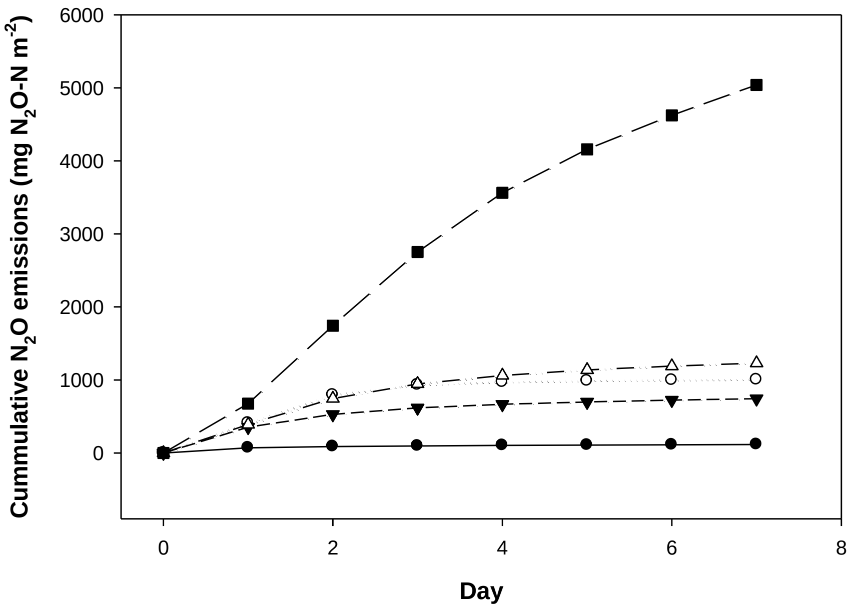

Fig. 4. 7. Cumulative N_2O emissions of the seeded pasture cores under the W60 water filled pore space treatment and no-nitrate-added treatment with respect to day. Each line represents an individual replicate (n=5).

Between the two land-uses, the pasture cores had consistently higher emissions than their cultivated counterparts at each sampling day (Fig. 4.8). The differences between the two land-uses were enhanced with the addition of NO_3^-.

Cumulative emissions graphs show more clear differences among treatment groups (Fig. 4.9). A significant difference (P = 0.1) exists between the seeded pasture and cultivated soil cores during the NO_3^- added treatment with respect to N_2O emissions. Statistical differences also exist among all WFPS treatments of the seeded pasture soil cores within the NO_3^- added treatment.

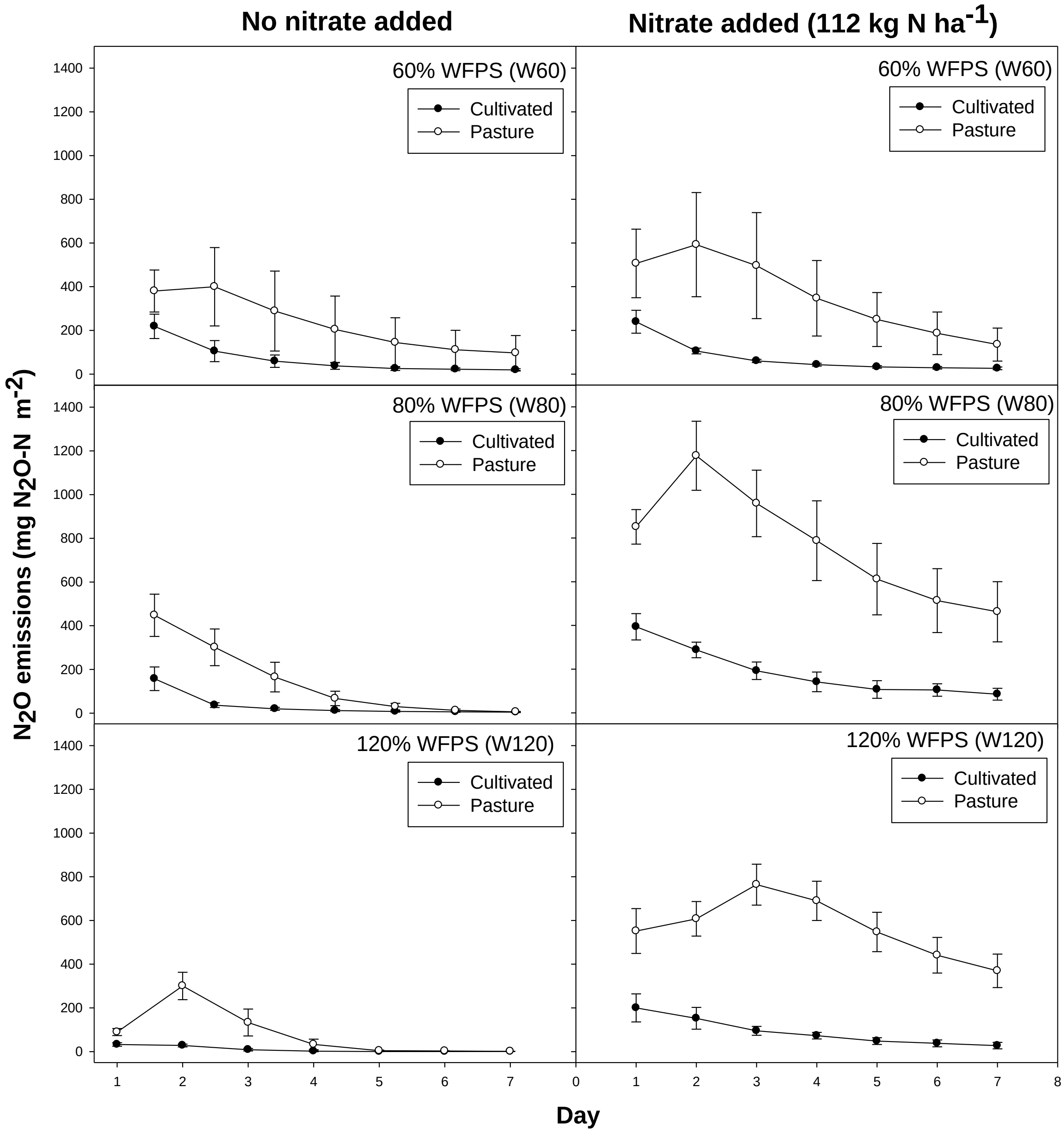

Fig. 4. 8. Daily mean N_2O fluxes of intact cores under differing water filled pore space (WFPS), NO_3^- addition treatments, and land-use histories (n=5). Filled circles represent the mean emissions of the cultivated soils whereas empty circles represent the mean emissions of the pasture soil cores. Error bars represent standard error of the mean.

Within the no NO_3^- added treatment there was a non-significant trend of decreasing N_2O emissions with increasing WFPS treatment, which was observed in both the cultivated and seeded pasture soil cores. Conversely, within the NO_3^- added treatment, the 80% WFPS treatment was the highest emitter followed by 120% and 60% WFPS respectively for both land-uses. Despite the absolute differences between the land-use histories, they had similar responses to WFPS and NO_3^- treatments.

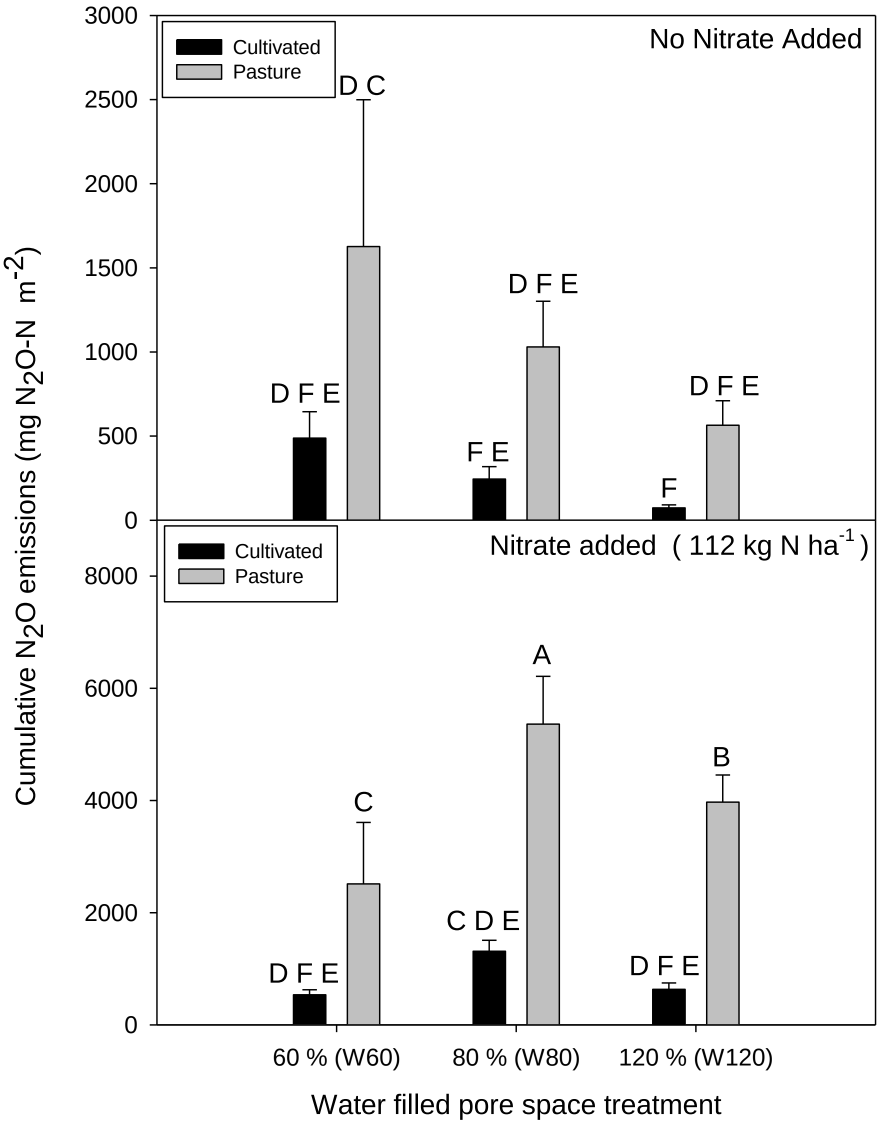

Fig. 4. 9. Cumulative mean N_2O emissions of the 7 d incubation (n=5). Each panel represents a differing NO_3^- treatment. Black bars are the cumulative mean emissions of cultivated soil cores. Grey bars are the cumulative mean emissions of pasture soil cores. The same letters denote that there is no significant difference among the treatments (*P* = 0.1) across both panels via Tukey's HSD test. Error bars represent standard error of the mean.

After the incubation, the cores without added NO_3^- were relatively depleted of NO_3^- (mean concentrations < 20 mg NO_3^--N kg^{-1}) (Fig. 4.10). There was a trend for higher amount of NO_3^- depletion with respect to increasing WFPS, which was observed for both the seeded pasture and cultivated cores. The seeded pasture cores, under higher WFPS treatments (W80 and W120), had higher levels of NO_3^- depletion relative to the pasture cores of the same treatment.

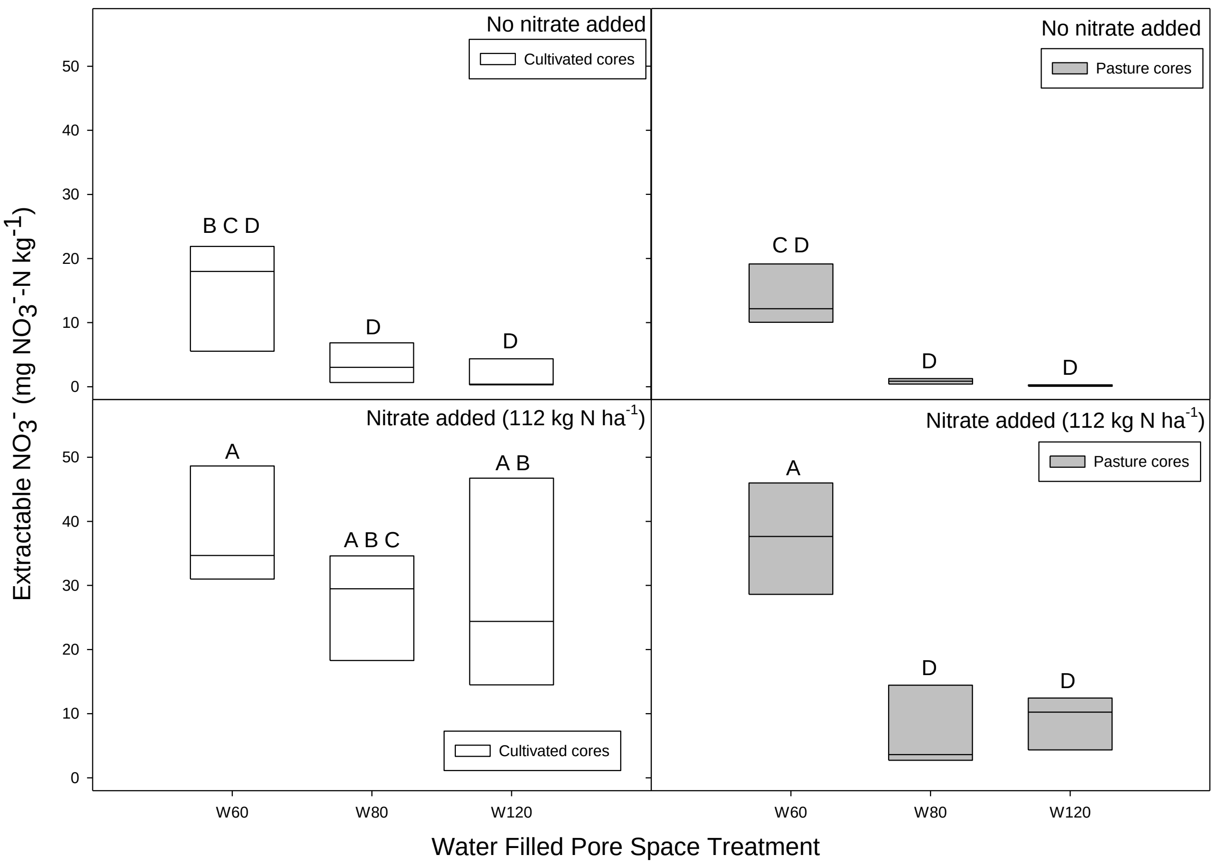

Fig. 4. 10. Box plot of NO_3^- contents of soil cores after the N_2O incubation (n=5). The solid bar within each box represents that treatments median while the boxes represent the 25th and 75th quantile. Treatments not sharing the same letter are significantly different.

An analysis of variance showed that all fixed effects within the incubation had significant effect in explaining the N_2O emissions under their specific treatments (Table 4.4). Land-use and NO_3^- additions had the greatest explanation of variance (Table 4.4; F-statistic = 226.07 and 171.95 respectively; P < 0.0001) whereas the WFPS treatments had lesser, yet still significant, amounts of explanation of variance (Table 4.5; F-statistic = 12.67; *P* < 0.0001). Significant interacting effects existed for all explanatory variables with the strongest interactions occurring between the NO_3^- addition and land-use treatments (F-statistic = 25.28; *P* < 0.0001).

Table 4. 5. Analysis of variance output of repeated measures linear mixed effects model with N_2O emissions as a response variable and land-use, water filled pore space treatments and NO_3^- treatments. Sampling day was used to make it a repeated measures test.

Explanatory Variable	df	Denominator df	F-statistic	*P*
Land-use	1	402	226.07	<.0001
Water filled pore space	2	402	12.67	<.0001
Nitrate addition	1	402	171.95	<.0001
Land-use: Water filled pore space	2	402	3.62	0.0278
Land-use: Nitrate addition	1	402	78.20	<.0001
Water filled pore space: Nitrate addition	2	402	25.28	<.0001
Land-use: Water filled pore space: Nitrate addition	2	402	8.07	0.0004

4.4 Discussion

4.4.1 Soil methane emissions

The CH_4 incubation provided evidence of interacting effects of SO_4^- and soil land-use history with respect to CH_4 emissions, satisfying the primary objective of the incubation. The interacting effects were identified through the varied responses of CH_4 emissions that both the cultivated and seeded pasture land-use histories had after receiving their SO_4^- treatment (Fig. 4.9). Interactions of the response variables (SO_4^- treatments and land-use history) were also present through an analysis of a linear mixed effects (LME) model (Table 4.5).

For the cultivated soils, the addition of SO_4^- at all three treatment levels (S10, S50 and S100) had a non-significant trend in reducing their emissions relative to their S0 treatment (Fig. 4.9). Based on the literature, this was the expected response of CH_4 emissions with respect to the addition of SO_4^-. The presence of SO_4^- within an anaerobic system had been shown to lower the amount of CH_4 emissions because the SO_4^- reduction process was thermodynamically favored over methanogenesis and would compete for substrate (Segers, 1998; Le Mer and Roger, 2001). Exogenous additions of SO_4^- cause inhibition of methanogenesis (Segers, 1998; Le Mer and Roger, 2001; Baldwin and Mitchell, 2012).

The CH_4 suppressing effect of SO_4^- additions was not detected within the seeded pasture soils under treatments S10 and S100; instead, increases in CH_4 emissions were observed within these treatment groups. This was an unexpected response, which has not previously been observed in past studies. One cause of this lack of methanogenesis suppression may because of the contrasting intrinsic SO_4^- contents between the cultivation and seeded pasture soils. The seeded pasture soils had higher SO_4^- contents prior to the start of the incubation. This higher amount of SO_4^- may have prevented the SO_4^- additions from affecting the methanogenesis rates. Within the S10 and S100 treatments, an increase in emissions was observed. This may have been due to the high inter-treatment variability of the study, particularly with the presence of high emitting cores.

The cultivated soils generally had lower CH_4 emissions within every treatment group compared to their pasture counterparts and this may have been partially affected by the differing phosphorus (P) regimes in the cultivated and pasture soils (Keller et al., 2005; Song et al., 2012). The availability of P has previously been documented to limit CH_4 emissions and was hypothesized to do so by changing C dynamics within soil (Song et al., 2012). The cultivated soil had a higher P content (Table 4.2), most likely through extensive P fertilization (Edmeades, 2003).

4.4.2 Emission variability

The high variability of the CH_4 emissions was usually caused by the presence of high emitting individual cores (Fig. 4.4). Yao et al. (2010) observed a large CV of CH_4 emissions (CV = 849%) from incubated soil cores, with the Gleysolic soil order (via FAO Soil Classification) having higher levels of variation than the other sampled orders. While this study did not attain CV > 800%, there was a CV of 146% during pasture soil S50 treatment (Table 4.3). Furthermore, Gleysols are hypothesized to be more variable emitters because of their higher contents of OM and more frequent saturation periods (Yao et al., 2010). van den Pol-van Dasselaar et al. (1999) similarly reports high spatial variation of CH_4 emissions within and among treatment groups. The variation from the aforementioned studies was postulated because of differing water filled pore space (WFPS) levels, OC contents and soil temperatures.

The soil cores were collected from either seeded pasture or cultivated wetland depressional areas. While some spatial variability would occur with respect to OC contents of prairie landscapes, the spatial similarities of surface OC contents are generally high, assuming that the landscape position is similar (Rosenbloom et al., 2006). Since the OC contents and bulk densities were not specifically measured for each individual core in the incubation, a correlation cannot be conducted to determine if a significant relationship existed among the high CH_4 emitters and soil bulk density or OC content.

The soil bulk densities were different between the two sites. The higher level of compaction within the cultivated land-use history may have led to decreased CH_4 production. Within anaerobic environments, soil compaction will reduce CH_4 consumption rates (Ruser et al., 1998; Ball et al., 1999), ultimately leading to increased emissions; on the contrary, compacted anaerobic soils may have reduced levels of CH_4 emissions because of limited gas fugacity rates (EPA, 2010). Since this study used anaerobic conditions to ensure CH_4 production, the decreased pore space within the cultivated land-use history may have lowered their CH_4 emissions relative to the seeded pasture land-use history.

Another possibility for variation may have been the presence of high emitting microsites. These highly localized regions within soils occur when ideal anoxic conditions and OC contents are present in a soil (Riley et al., 2011). Within these microsites, an ideal level of anoxic conditions and high OC amounts allow for the intense production of CH_4 through methanogenic bacteria (Riley et al., 2011). Analysis of potential methanogenesis is commonly conducted using anaerobic conditions with small amounts of soil (< 20 g soil; Keller et al., 2009). This type of analysis has not previously been measured using intact soil cores, which likely causes additional levels of variation, on a scale similar to what is observed within aerobic incubations of intact soil cores (Yao et al., 2010). The use of disturbed cores would involve the homogenous mixture of soil followed by uniform packing of the cores; these steps would eliminate the spatial variability common with sampling intact cores because the soil would have been redistributed relatively equally among all the repacked cores. The homogenous nature of repacked cores would thus have lesser emission variations compared to intact cores sampled from the same area.

4.4.3 Methane emissions from Prairie Pothole Region wetlands

The potential CH_4 emissions observed within the study were mainly within the range of CH_4 emissions observed from other PPR wetlands, albeit mostly the upper end of the range (Fig. 4.11). Since only single wetlands were sampled for each land-use history, there is limited inference space for the study's results though the wetlands can be easily compared with studies examining gas emissions of PPR wetlands. The other studies were conducted in the figure all had measured CH_4 emissions under field conditions. Conversely, this study was conducted in the laboratory under controlled conditions with O_2 initially purged from the system. The lack of entirely anaerobic conditions of the field studies allowed for certain levels of CH_4 oxidation, ultimately leading to lower levels of CH_4 emissions (Le Mer and Roger, 2001). Warmer temperatures will allow for increased biological activity, including methanogenesis (Segers, 1998). The lab study maintained a constant 22 °C temperature incubation whereas in the field the temperature would be more varied (Bates and Hall, 2012) and usually lower throughout the year (Environment Canada, 2012).

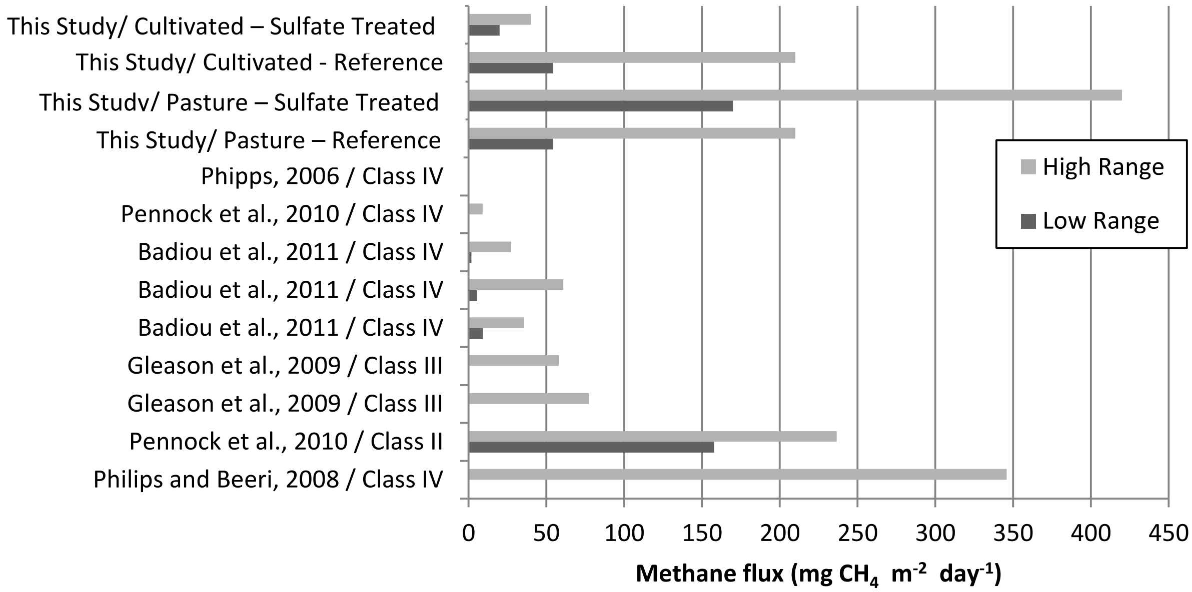

Fig. 4. 11. Mean CH_4 emissions from Prairie Pothole Region wetlands from previous field studies. Classes refer to wetland classification according to Stewart and Kantrud (1971). High range of emissions were selected by taking 75-100% quantile of mean CH_4 emissions whereas low range was selected by taking the 0-25% quantile of mean CH_4 emissions. Adapted from Badiou et al. (2011).

4.4.4 Nitrous oxide emissions among differing land-use history, water filled pore space and nitrate addition treatments

The incubation revealed the presence of interacting factors among land-use history, WFPS and NO_3^- addition treatments as denoted by the ANOVA (Table 4.5). The interactions are visually apparent within the cumulative N_2O figure (Fig. 4.9); this was observed through the shifting high emitting treatment groups with respect to the NO_3^- additions treatment groups. The presence of these interacting factors satisfies the primary objective of the study.

Several reasons exist for the higher N_2O emission from the seeded pasture soil cores. Seeded pasture soil cores had lower bulk densities than their cultivated counterparts and the increased gas diffusivity of these less compacted cores may have influenced the additional N_2O emissions (Håkansson and Lipiec, 2000). Increased OM contents of the seeded pasture soil cores may also increase the N_2O emission rate because OM contents are good indicators of the microbe community and available nutrients (Carter, 2002). The dynamic cycling of OM provides nutrients to the microbial communities.

Soil nutrient analyses suggest that the seeded pasture soil cores had higher NO_3^- contents prior to the incubation (Table 4.2); albeit, the post-incubation analysis of NO_3^- show little difference between the pasture and cultivated cores when no NO_3^- was added (Fig. 4.10). Studies have reported that the best indicator of N_2O emissions are available NO_3^- contents within the soil, as these are the substrates required for the production of N_2O via the denitrification pathway (Skiba et al., 1997; Lee et al., 2006). Another instance of this phenomenon was observed within the study through increased N_2O emissions with added NO_3^- (Fig 4.9). The sampling period of the soil cores may have influenced the lower N_2O emissions of the cultivated cores; Bedard-Haughn et al. (2006a) observed low mean N_2O emissions from cultivated wetlands during times later in the growing season (i.e. early fall; the sampling time of the incubation study) whereas uncultivated wetlands had higher mean N_2O emissions over that same time period. The WFPS treatments had similar influences across both land-use histories. In the no-NO_3^- added treatment, the highest emitting WFPS treatments was the W60 level for the cultivated and pasture soil cores whereas the lowest emitting cores were the W120 levels for both land-use histories. Under these lower NO_3^- levels, higher N_2O emissions were possibly the result of nitrification-based N_2O within the aerobic soil cores and some denitrification-based N_2O emissions from anaerobic hot spots (i.e. W60; Smith et al., 2003). The lack of emissions at the W120 treatment group suggests that nitrification derived N_2O is halted because of redox conditions; the denitrification-derived N_2O is present within the anaerobic systems but is minimal, possibly because the N_2O is being fully reduced to N_2 (Dalal et al., 2003; EPA, 2010).

With the addition of NO_3^-, the highest emitting WFPS treatment levels were W80 for both the pasture and cultivated cores, whereas the W120 and W60 levels were the mid and lowest N_2O emitters respectively. With more available NO_3^- within the system, further N_2O losses are prevalent within the W80 because these cores were incompletely saturated as to allow for partial denitrification and the subsequent escape of N_2O gas to the surrounding headspace (Dobbie and Smith, 2003; Pennock et al., 2010). Despite the change to mean cumulative emission rankings with respect to the NO_3^- addition, both the cultivated and pasture soil cores reacted similarly to each WFPS treatment.

4.4.5 Variability of nitrous oxide emissions

The variability found within the N_2O incubation was similar to that observed within the CH_4 incubation. The majority of emissions within most treatment groups were driven by the presence of heavy emitting cores (Fig 4.7). The emission variability was not exclusive to this study, with N_2O commonly being referred to as the “humbling gas” (Personal communication, Dan Pennock, June 2012). Many past studies have examined the spatial variability of N_2O emissions, particularly as it deals with the presence of high emitting microsites (Ball et al., 2000; Henault et al., 2012). Anoxic microsites will allow for intense production of N_2O through incomplete denitrification (Christensen et al., 1990). The variability within the study is likely the result of both anoxic microsites and the natural spatial variability of soil nutrients occurring along gradients (Bruland et al., 2006).

Soil compaction and differences in bulk density will cause changes to the emission variability. Agricultural compaction has been observed to greatly influence the spatial variability of N_2O emissions over small distance gradients (i.e. 10 cm) (Ball et al., 2000). For the study, the soils were extracted via slack hammers and likely some compaction occurred during the collecting phase. The different levels of soil compactions that likely occurred during the soil collection phase were a possible influencing factor of the experiments' variability. Overall, N_2O emission are well known for their variation and these are caused by many known and unknown factors; even within the Prairie Pothole Region a high range of reported N_2O emissions from wetland soils exists.

4.4.6 Nitrous oxide emissions from the Prairie Pothole Region

Previous studies within the Prairie Pothole Region have found a wide range of N_2O emissions from wetlands (Fig. 4.12). Since the N_2O incubation used only single wetlands for each land-use history, there is limited inference space although the amounts can still be compared to wetlands of the region. The range of emissions from past studies is overall much lower than what was observed during the study. The reason for the increased emissions has several explanations including an extreme freeze-thaw cycle, consistent and warmer temperatures under lab conditions and partial saturation of WFPS to encourage N_2O emissions.

The original experimental plan called for a freeze-thaw cycle to increase the available N for the N_2O incubation. The experiment used a 24-h freeze period (-20 °C) followed by a 24-h thaw period (4 °C) of all the soil cores, after which the incubation commenced (22 °C). A 24 °C temperature swing such as this is highly unlikely to occur naturally; furthermore the unnatural freeze-thaw cycle used in the experiment may have increased N availability through cell lyses (Marion, 1995; Skogland et al., 1988) beyond that of natural occurrence.

The constant temperature of the incubation may have been beneficial to N_2O production. Microbial processes, particularly nitrification and denitrification rates, are strongly temperature dependent (Lang et al., 2012; Smid and Beauchamp, 1976) and the consistent 22 °C incubation temperature is often higher than the average summer day temperature of the PPR (Environment Canada, 2012). The increased temperature allowed for increased rates of microbial activity to occur and thusly for more N_2O to be produced then what commonly occurs within the field.

The incubation conditions, such as the WFPS levels, were controlled to maximize N_2O emissions during the study in comparison to the other studies on the PPR, which were all field studies that used *ex-situ* sampling techniques. The controlled, laboratory setting of the incubation was likely a cause for higher emissions relative to those observed within the field locales of the PPR.

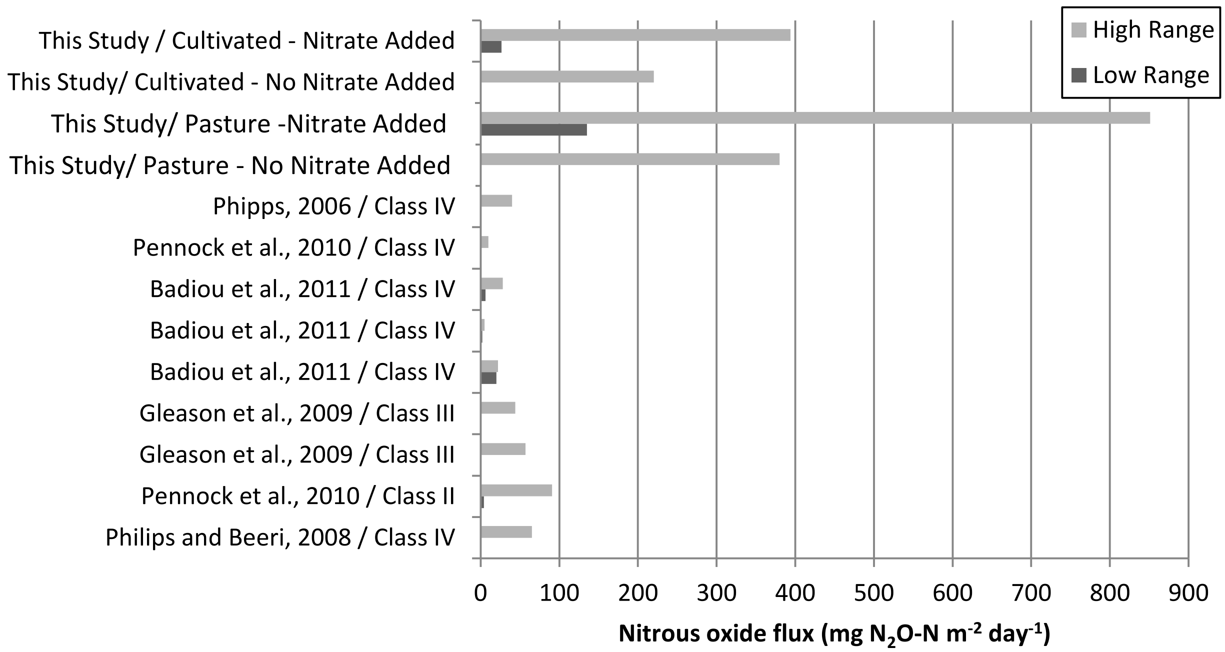

Fig. 4. 12. Mean N_2O emissions from Prairie Pothole Region wetlands from previous field studies. Classes refer to particular type of wetland according to Stewart and Kantrud (1971). High range of emissions were selected by taking 75-100% quantile of mean CH_4 emissions whereas low range was selected by taking the 0-25% quantile of mean N_2O emissions. Adapted from Badiou et al. (2011).

4.5 Summary

Within both the CH_4 and N_2O incubation, the presence of interacting effects among the land-use histories and manipulative controls were observed. In the CH_4 incubation, different responses that land-uses had to SO_4^- addition treatments confirmed the existence of interacting effects. Additionally, the results of the N_2O incubation and the additive effects of land-use history, WFPS treatments and NO_3^- additions suggest the presence of interactions. Furthermore, both interactions were confirmed through an analysis of linear mixed effect (LME) models of each incubation dataset.

The SO_4^- additions during the CH_4 incubation had significantly different responses between the two land-use histories. The seeded pasture and cultivated land-use histories had positive and negative responses to SO_4^- additions respectively, in terms of CH_4 emissions. These were postulated as being caused by the inherent levels of SO_4^- present within the soils prior to the incubation; however, it did reveal an interesting phenomenon that warrants further investigation.

Within both of the incubations, high amounts of variability were present in most treatments groups. The cause of the variation was usually the result of one or two high emitting cores within each treatment group; furthermore, this overall variation presented some difficulty in identifying significant differences among the treatments. The cause of the variation was hypothesized to be anaerobic hotspots present within some intact cores as well as spatial differences among the sampled cores. Further study is recommended to clarify the results because of the high variability observed.

In terms of previous CH_4 and N_2O studies on the PPR, the laboratory incubation yielded results in the high range and often beyond the range of the past field studies. The higher emissions are likely present because of idealized conditions (i.e. consistent temperature, saturated pore space and adequate nutrients) during the laboratory incubation and are likely not the most accurate numbers to use for estimating field emissions on the PPR.

5. CONCLUSION

Overall, both the field study and laboratory incubation revealed dissimilar changes of soil characteristics among different land-use histories of Prairie Pothole Region wetlands. Through the field study there were limited changes to the pedological features of the wetlands, however, the laboratory incubation revealed significant difference between the contrasting land-use histories with respect to their GHG emissions and the presence of interacting factors of their biogeochemical controls.

The field study demonstrated that some pedologic traits (i.e. organic carbon [OC], dithionite extractable Fe [DF] and magnetic susceptibility [MS]) had limited differences among the contrasting land-use histories through an analysis of linear mixed effect (LME) models and examination of their depth profiles. Organic C, inorganic C (IC), DF and MS were revealed to be very adept at differentiating the pit position among the contrasting land-uses; these were visible through the analysis of both the depth profile figures and LME models. Furthermore, these differences of pit position among the sampled variables were well corroborated through past studies. Holistic analysis of the entire dataset through non-metric multidimensional scaling only revealed previously identified trends within the data. This statistical technique was required for analysis because it confirmed that no major trends were overlooked through the sole analysis of individual soil characteristics.

Through the laboratory incubation, land-use history was discovered to have interacting effects with greenhouse gas emission (GHG) controls in terms of the particular emitted GHGs. Within the CH_4 incubation, the land-use histories (cultivated vs. seeded pasture land-use history) responded differently to the addition of SO_4^-. This response was postulated as due to the differing SO_4^- contents prior to the incubation; though, the contrasting response among the land-use histories confirmed that interacting effects were present.

Within the N_2O incubation, the land-use histories (i.e. cultivated and pasture land-use histories) had interacting effects in combination with their controlling biogeochemical factors (i.e. water filled pore space and NO_3^- additions) with respect to N_2O emissions. Though the controlling factors had similar responses on each of the land-use histories, interacting effects were still present through an analysis of variance.

Holistically, the experiments revealed that contrasting land-use histories have variable effects on soil factors. Pedological analysis of soils under differing land-use histories had limited significant differences among the variables, though some were still present. Contrariwise, the laboratory incubation had significant interacting effects among the contrasting land-use histories and GHG biogeochemical controls with respect to GHG emissions. The reason for the interactions are complex, however, they are likely influenced by observable differences determined through pedological study (i.e. OC content, SO_4^- content and bulk density). This suggests that adequate study is required to assess the effects that all types of land-use change may have on their terrestrial environment. The emissions of GHGs may be fundamentally more volatile than the development of observable or measurable pedological features; this may cause there to be more noticeable changes to the GHG emissions rather than pedological changes with respect to contrasting land-use histories.

Therefore, it was observed that land-use histories of PPR wetlands will affect specific soil characteristics, particularly the biogeochemical controls of GHG emissions. The absence of many significant differences of the field variables among the differing land-use histories does not confirm their lack of existence. This field study was very limited in its sampling range, given the vast size of the PPR. Future research could attempt to use a more encompassing sampling regime to determine if differing land-use histories affect the expression of hydric soil features and soil magnetic susceptibility.

Additional research is also recommended as follow-up to the GHG incubations. The unexpected response that SO_4^- additions had on the land-use histories should be further investigated to determine the actual involved mechanisms. Both incubations were plagued with high variability and further analysis would be recommended to determine if significant differences do exist among the differing treatment groups. Possibilities for follow-ups for this experiment could include the investigation of repacked cores using similar applied treatments with the goal of reducing intra-group variability; additionally, increased replicates per treatment group could be used to reduce the overall variability and increase statistical power.

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7. APPENDICES

APPENDIX A: PROFILE INFORMATION OF SAMPLED WETLANDS AND UPLANDS

Table A.1. Soil depth characteristics of the depression and upland pits of 'Annually Cultivated 1'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	2.59	0.36	0.46	28.67	29.49	29.16	24.24	3.95	4.07	5.14	6.51	CL	2/1
-	10-20	Ah	2.63	0.25	0.47	19.97	21.61	19.10	18.71	4.46	4.64	6.60	7.32	CL	2/1
-	20-30	Ah/Aeg	0.96	0.12	0.38	7.34	7.69	9.15	12.07	4.55	4.04	6.12	9.25	CL	2/1
-	30-40	Aeg/Btg	0.43	0.04	0.62	7.04	7.30	11.91	20.04	3.96	2.53	5.69	9.18	SC	5/3
-	40-50	Btg	0.45	0.03	0.71	8.09	8.43	12.03	20.68	3.21	1.41	4.87	8.88	C	3.5/3
-	50-60	Btg	0.39	0.03	0.69	8.54	8.69	14.35	18.29	3.36	0.00	3.90	7.04	C	3.5/3
-	60-70	Btg	0.34	0.01	0.89	9.79	9.68	13.69	22.99	1.41	1.96	5.54	8.70	C	3.5/3
-	70-80	Btg	0.22	0.02	1.01	9.15	10.26	14.37	19.11	0.98	3.49	4.01	7.93	C	3.5/3
-	80-90	Btg	0.21	0.00	0.63	6.84	7.70	7.60	8.79	0.54	2.63	1.09	6.10	C	3.5/3
-	90-100	Btg	0.18	0.02	0.49	7.44	7.98	9.30	5.52	1.57	6.57	0.00	0.00	C	3.5/3
Upland	0-10	Ah	1.79	0.00	0.59	36.46	38.76	28.07	31.24	4.75	4.53	5.65	6.13	C	2/1
-	10-20	AB/Bmk	0.59	1.90	0.61	29.44	32.05	42.51	25.81	4.54	4.76	5.70	7.22	C	3/4
-	20-30	Bmk	0.54	2.00	0.52	28.68	29.92	26.87	22.79	4.01	4.02	4.77	5.77	C	5/6
-	30-40	BC/Cca	0.50	3.03	0.34	19.28	20.47	21.78	14.11	2.36	2.56	3.73	4.96	C	5/4
-	40-50	Cca	0.42	2.74	0.30	22.34	23.83	18.53	15.77	3.34	2.90	4.04	5.21	C	6/3
-	50-60	Cca	0.22	3.11	0.30	19.11	21.81	18.16	10.89	0.52	1.65	2.07	3.61	C	6/3
-	60-70	Cca/Ck	0.31	2.71	0.37	22.89	24.56	20.40	15.58	1.34	0.00	1.90	5.01	C	5/6
-	70-80	Ck	0.17	2.76	0.47	22.50	25.03	20.38	15.03	2.71	3.47	3.08	4.13	C	5/6
-	80-90	Ck	0.06	2.46	0.51	31.06	31.52	32.79	22.69	2.88	0.34	2.95	3.02	C	5/6
-	90-100	Ck	0.05	2.25	0.58	23.17	23.45	44.23	14.97	1.95	1.06	2.21	4.37	C	5/6

Table A.2. Soil depth characteristics of the depression and upland pits of 'Annually Cultivated 2'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	2.53	0.57	0.45	25.15	26.41	25.06	20.47	3.61	4.22	4.50	5.01	C	2/1
-	10-20	Ah	2.44	0.82	0.37	22.48	24.48	23.10	18.88	3.31	2.67	4.67	4.72	C	2/1
-	20-30	Ah	2.34	0.70	0.40	23.95	24.11	24.24	19.87	3.13	3.69	4.38	5.04	C	2/1
-	30-40	Ah/Aeg	1.20	0.32	0.37	8.80	9.15	12.74	16.60	5.52	4.44	7.32	8.23	C	5/3
-	40-50	Aeg	0.22	0.06	0.45	5.56	5.45	14.31	18.67	9.16	0.00	9.65	9.34	C	5/3
-	50-60	Btg	0.37	0.00	0.90	8.77	9.48	32.36	61.34	4.50	4.02	6.80	11.08	HC	3/2
-	60-70	Btg	0.33	0.02	0.82	7.77	8.91	23.23	54.52	1.77	1.75	4.73	11.43	HC	3/2
-	70-80	Btg	0.30	0.02	0.73	9.22	8.74	32.34	108.25	3.51	4.15	4.52	12.27	HC	3/2
-	80-90	Btg	0.31	0.01	0.60	6.13	8.07	41.27	216.75	23.96	1.27	3.11	12.57	HC	3/2
-	90-100	Btg	0.28	0.01	0.67	7.93	9.90	39.17	247.72	4.51	17.83	2.93	12.36	HC	3/2
Upland	0-10	Ahk	3.13	1.50	0.39	28.47	30.64	28.86	26.90	3.06	3.14	3.88	4.14	L	2/2
-	10-20	Ahk	2.53	1.21	0.22	20.95	24.25	21.05	18.08	0.46	0.75	1.94	1.27	L	2/2
-	20-30	Aekg	1.24	3.63	0.26	22.92	24.12	20.85	18.42	2.08	3.27	1.32	2.89	C	5/3
-	30-40	AB	0.56	3.18	0.40	28.83	32.31	32.25	22.82	2.86	3.55	1.57	2.28	C	5/4
-	40-50	Bmk	0.61	2.66	0.39	4.89	5.24	12.52	17.09	2.21	5.00	8.67	9.72	C	6/4
-	50-60	Bmk	0.46	3.17	0.40	28.07	30.00	24.51	18.36	2.11	0.74	1.99	2.00	C	6/4
-	60-70	Bmk	0.41	2.67	0.41	26.66	28.92	25.39	20.65	1.35	1.41	2.43	2.31	C	6/4
-	70-80	Bmk	0.27	3.01	0.41	30.58	33.16	28.94	22.43	1.93	0.63	1.52	2.54	C	6/4
-	80-90	Bmk	0.16	3.16	0.43	25.04	27.32	21.14	16.33	0.44	0.84	1.32	2.66	C	6/4
-	90-100	Bmk	0.17	3.10	0.47	25.15	26.45	20.98	14.23	1.41	1.14	0.95	1.98	C	6/4

Table A.3. Soil depth characteristics of the depression and upland pits of 'Annually Cultivated 3'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3 kg^{-1}$	$m^3 kg^{-1}$	$m^3 kg^{-1}$	$m^3 kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	2.28	0.08	0.42	20.31	22.62	22.75	21.12	0.17	4.28	4.22	5.58	L	2/1
-	10-20	Ah	2.00	0.56	0.50	17.42	19.04	20.50	20.35	3.97	3.24	6.02	4.59	L	2/1
-	20-30	Ah	2.06	0.41	0.44	8.99	9.76	26.58	31.68	3.27	3.76	9.63	10.87	L	2/1
-	30-40	Aeg/Btg	0.50	0.03	0.56	9.26	9.80	27.68	34.59	4.18	4.17	9.46	11.19	C	5/3
-	40-50	Btg	0.39	0.04	0.71	9.47	10.19	20.94	25.64	3.61	3.35	6.33	10.32	C	4/4
-	50-60	Btg	0.33	0.01	0.70	10.22	10.65	15.15	18.59	2.00	3.63	3.79	9.48	C	4/4
-	60-70	Btg	0.25	0.18	0.63	12.76	14.72	13.85	12.39	1.21	1.17	2.33	3.36	C	4/4
-	70-80	Btg/Ccag	0.36	0.78	0.70	18.26	18.02	16.28	13.21	0.79	0.13	1.74	2.36	C	4/4
-	80-90	Ccag	0.30	2.01	0.46	18.87	22.73	20.45	17.17	1.22	0.92	0.76	1.28	C	6/3
-	90-100	Ccag	0.34	2.38	0.52	21.10	25.32	21.58	18.61	0.43	0.56	1.44	1.55	C	6/3
Upland	0-10	Ah	1.36	0.00	0.76	42.65	43.93	43.72	41.69	4.40	4.96	4.87	6.09	SL	2/1
-	10-20	Bmk	0.50	1.06	0.93	36.82	40.03	37.27	34.02	3.77	4.06	4.33	5.41	SL	4/6
-	20-30	Bm/Ck1	0.36	0.22	1.03	30.49	32.17	30.61	27.57	2.16	0.14	3.01	3.21	SL	4/6
-	30-40	Ck1	0.31	0.60	0.62	37.13	36.12	32.98	29.84	1.30	1.63	1.47	2.36	S	5/6
-	40-50	Ck1	0.25	1.25	0.53	30.51	32.89	28.72	24.22	1.38	1.81	1.53	1.71	S	5/6
-	50-60	Ck2	0.33	2.06	0.44	22.84	25.48	21.51	17.92	1.30	0.80	1.20	1.65	SC	5/4
-	60-70	Ck2	0.22	1.96	0.37	25.62	27.63	23.73	20.37	1.10	0.40	1.09	1.89	SC	5/4
-	70-80	Ck2	0.26	1.99	0.49	26.97	29.01	26.02	21.31	1.31	0.51	2.64	2.17	SC	5/4
-	80-90	Ck2	0.26	1.83	0.54	25.11	26.02	23.61	20.47	0.80	1.55	1.22	1.81	SC	5/4
-	90-100	Ck2	0.29	2.33	0.47	24.29	27.83	24.04	19.31	1.97	0.60	1.82	2.05	SC	5/4

Table A.4. Soil depth characteristics of the depression and upland pits of 'Annually Cultivated 4'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	3.22	0.00	0.56	21.84	21.39	24.22	22.94	4.71	4.93	6.40	7.05	CL	2/1
-	10-20	Ahk	2.51	1.34	0.63	14.22	14.78	40.91	50.26	4.67	5.03	9.65	10.24	CL	2/1
-	20-30	Ah/Aheg	0.65	0.06	0.88	7.69	8.30	40.79	77.87	2.30	1.95	6.48	10.67	C	4/4
-	30-40	Ahgb	0.56	0.09	0.78	9.00	9.68	16.87	30.09	2.37	8.25	3.33	9.64	C	2/1
-	40-50	Ahgb	0.57	0.04	0.80	8.55	9.70	13.81	21.55	2.17	1.85	3.08	8.82	C	2/1
-	50-60	Ahgb	0.50	0.40	0.77	7.27	7.86	8.56	8.42	0.30	1.47	2.75	8.36	C	2/1
-	60-70	Btkg	0.47	1.72	0.59	5.94	6.42	5.54	6.63	0.47	0.91	1.36	6.33	C	5/4
-	70-80	Btkg	0.44	2.42	0.45	5.46	5.61	5.63	6.69	0.58	2.89	5.23	9.90	C	5/4
-	80-90	Btkg	0.53	4.17	0.62	4.00	4.43	4.77	8.98	3.39	2.48	4.65	10.83	C	5/4
-	90-100	Btkg	0.45	3.81	0.76	5.99	5.92	5.74	8.33	0.65	1.94	1.34	8.21	C	5/4
Upland	0-10	Ah	2.09	0.00	0.80	32.56	29.23	29.75	31.14	4.78	4.42	5.75	6.10	SL	2/1
-	10-20	Ah/AB	1.16	1.17	0.56	34.78	34.30	34.17	31.78	11.82	5.35	6.25	7.59	SL	3/3
-	20-30	Btk	0.88	1.75	0.49	29.56	28.65	28.77	26.11	11.45	5.67	6.97	7.42	SC	6/4
-	30-40	Btk	0.85	3.44	0.46	25.47	26.83	27.26	23.17	5.33	5.73	7.32	7.04	SC	6/4
-	40-50	Btk	0.41	2.61	0.67	14.63	15.02	14.81	13.07	2.88	3.33	4.79	5.02	SC	6/4
-	50-60	Btk	0.29	1.63	0.80	13.26	14.33	13.63	11.03	1.34	1.13	2.56	2.97	SC	6/4
-	60-70	Btk	0.23	1.75	0.60	17.30	18.20	16.32	13.66	0.43	1.10	1.24	2.47	SC	6/4
-	70-80	Btk	0.21	2.25	0.56	16.38	16.43	14.82	13.09	1.46	1.30	2.12	2.96	SC	6/4
-	80-90	Btk	0.12	2.23	0.58	25.19	27.52	23.93	20.92	7.63	0.60	1.16	1.11	SC	6/4
-	90-100	Btk	0.22	2.12	0.56	20.65	19.83	16.71	13.78	10.49	0.48	2.74	2.08	SC	6/4

Table A.5. Soil depth characteristics of the depression and upland pits of 'Restored Grassland 1'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	m^3 kg^{-1}	m^3 kg^{-1}	m^3 kg^{-1}	m^3 kg^{-1}	%	%	%	%	-	-
Depression	0-10	Ah	2.24	0.34	0.60	17.07	23.88	19.93	17.23	2.94	3.24	4.16	5.03	2/1	C
-	10-20	Ahk	1.94	1.07	0.43	13.68	18.63	17.85	16.01	3.50	3.76	4.90	6.48	2/1	C
-	30-40	Ah/Aeg	0.30	0.10	0.79	6.96	8.37	9.12	11.61	2.48	3.19	5.26	6.60	2/1	C
-	40-50	Aeg/Btg	0.33	0.05	0.78	5.84	7.02	7.53	8.59	1.73	0.00	1.93	4.44	5/2	SiC
-	50-60	Btg	0.31	0.06	0.83	6.47	8.20	8.93	8.33	1.46	2.02	2.49	2.94	4/3	SiC
-	60-70	Btg/Cg	0.28	0.06	1.02	7.39	9.11	10.53	10.00	1.78	2.27	12.56	5.92	4/3	SiC
-	70-80	Cg	0.24	0.05	0.83	11.39	14.67	18.83	17.22	1.76	1.50	6.27	7.44	5/4	SiC
-	80-90	Ccag	0.35	2.48	0.52	31.85	40.52	35.01	29.13	1.13	0.69	2.19	1.85	5/4	SiC
-	90-100	Cg	0.27	0.01	0.87	14.24	18.08	15.82	11.70	0.89	1.02	1.42	4.67	5/4	SiC
Upland	0-10	Ah	2.88	0.00	0.53	22.21	26.80	30.97	29.42	4.37	3.81	6.06	7.52	2/1	SiCL
-	10-20	Ahk	1.60	1.83	0.56	23.20	28.63	38.15	41.13	6.09	4.15	7.57	9.37	2/1	SiCL
-	20-30	Bt	0.63	0.02	0.67	23.31	28.38	35.07	32.27	5.48	5.44	8.25	9.30	3/4	C
-	30-40	Bt	0.48	0.07	0.83	17.28	21.42	26.71	24.25	4.72	4.68	7.63	8.96	3/4	C
-	40-50	Bt/Cca	0.70	2.70	0.60	8.75	10.93	10.44	9.19	2.60	2.55	3.25	5.03	3/4	C
-	50-60	Cca	0.74	3.61	0.61	6.47	8.25	7.70	7.75	0.39	2.29	1.28	5.13	5/3.5	C
-	60-70	Cca	0.59	3.23	0.65	5.72	6.99	6.79	6.32	1.51	1.48	3.92	3.43	5/3.5	C
-	70-80	Cca	0.48	2.73	0.60	8.49	10.45	9.48	8.22	1.28	0.75	1.39	2.29	5/3.5	C
-	80-90	Cca/Ck	0.39	2.65	0.64	18.37	21.58	19.08	15.67	3.12	0.13	0.73	0.88	5/3.5	C
-	90-100	Ck	0.34	2.46	0.64	20.60	25.90	23.22	20.77	0.49	0.48	0.82	1.11	4/5	C

Table A.6. Soil depth characteristics of the depression and upland pits of 'Restored Grassland 2'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	2.61	0.41	0.54	21.00	31.70	30.60	26.02	3.63	3.66	4.93	5.31	SiC	2/1
-	10-20	Ahk	2.26	1.01	0.52	21.49	26.65	25.53	21.86	3.78	4.05	4.96	5.88	SiC	2/1
-	20-30	Ah	2.27	0.35	0.55	19.02	23.81	23.86	21.98	3.84	2.72	5.02	5.62	SiC	2/1
-	30-40	Ah	1.97	0.34	0.44	10.07	12.98	15.58	16.94	3.85	6.81	5.64	7.19	SiC	2/1
-	40-50	Ah/Aeg	0.74	0.07	0.60	6.83	8.41	87.78	215.09	3.81	3.37	6.27	10.50	SiC	2/1
-	50-60	Aeg/AB	0.37	0.04	0.71	6.46	7.71	27.48	147.33	1.88	2.50	2.37	10.95	C	5/1
-	60-70	AB/Btg	0.33	0.05	0.64	6.06	7.24	14.34	89.94	2.61	1.95	2.74	10.05	C	5/4
-	70-80	Btg	0.32	0.01	0.58	7.87	9.40	10.55	57.96	1.09	2.18	0.65	8.42	C	5/4
-	80-90	Btg	0.32	0.00	0.80	5.78	8.38	10.11	54.00	1.32	1.97	4.44	7.62	C	5/4
-	90-100	Btg	0.35	0.03	0.90	7.44	9.30	9.47	31.23	1.70	2.50	1.11	5.86	C	5/4
Upland	0-10	Ah	1.91	0.00	0.56	31.35	38.16	40.55	36.09	4.02	3.68	4.92	5.68	SL	3/2.5
-	10-20	Ah/Bm	0.64	1.74	0.93	28.13	33.50	41.09	38.63	2.12	2.33	6.69	7.40	SL	3/2.5
-	20-30	Bm	0.58	2.65	0.62	27.21	33.51	31.34	26.14	0.86	1.02	2.03	3.00	L	4/6
-	30-40	Bm/Cca	0.28	2.62	0.47	26.58	32.24	29.05	22.72	0.83	0.98	1.03	1.84	L	4/6
-	40-50	Cca	0.34	2.58	0.51	25.81	31.92	28.02	23.11	0.74	0.89	0.73	2.73	SL	5/5
-	50-60	Cca/Ck	0.35	2.49	0.49	27.93	34.61	29.10	23.92	0.83	0.81	0.95	2.11	SL	5/5
-	60-70	Ck	0.38	2.62	0.58	27.77	34.20	30.49	24.19	0.73	0.70	1.02	1.90	SC	4/4
-	70-80	Ck	0.20	2.65	0.54	14.73	35.71	31.16	23.59	0.70	0.77	1.02	2.17	SC	4/4
-	80-90	Ck	0.23	2.84	0.60	22.90	28.42	24.51	19.12	0.63	0.61	1.21	2.01	SC	4/4
-	90-100	Ck	0.24	2.69	0.65	24.85	31.99	27.49	20.62	1.07	0.69	0.80	1.38	SC	4/4

Table A.7. Soil depth characteristics of the depression and upland pits of 'Restored Grassland 3'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	2.76	0.30	0.54	24.63	32.96	30.91	23.09	3.18	3.65	3.83	4.96	SiC	2/1
-	10-20	Ahk	2.46	1.10	0.66	19.98	29.85	26.83	18.89	2.80	3.37	3.84	4.96	SiC	2/1
-	20-30	Ah	2.38	0.49	0.54	17.72	22.75	21.63	17.05	3.55	3.04	3.74	4.39	SiC	2/1
-	30-40	Ah	2.56	0.53	0.34	14.49	19.14	18.41	15.28	2.77	2.73	2.97	4.68	SiC	2/1
-	40-50	Ah	2.46	0.42	0.26	4.58	5.83	6.19	4.47	10.87	2.92	4.38	2.02	SiC	2/1
-	50-60	Ah/Aeg	0.32	0.05	0.29	4.78	6.13	6.74	5.16	1.67	4.17	4.72	5.32	SiC	2/1
-	60-70	Aeg/Btg	0.36	0.04	0.48	5.23	6.77	9.27	10.49	2.17	1.44	6.01	9.18	SC	5/2
-	70-80	Btg	0.46	0.03	0.74	6.02	7.66	11.52	14.52	1.76	2.92	5.58	6.21	SC	3/2
Upland	0-10	Ah	1.34	0.00	0.65	34.38	41.49	42.36	36.94	2.91	3.07	1.81	4.40	SCL	3/2
-	10-20	Ah/Bmk	0.46	1.16	0.66	25.15	29.60	56.61	50.90	1.59	2.30	9.31	9.29	SCL	3/2
-	20-30	Bmk	0.31	0.38	0.58	30.96	38.06	50.96	45.49	1.61	2.05	7.35	7.84	SCL	5/4
-	30-40	Bmk	0.51	1.76	0.58	24.88	37.03	33.78	26.28	1.27	1.75	1.48	1.01	SCL	5/4
-	40-50	Bmk	0.31	1.22	0.60	27.19	38.81	35.95	30.25	2.10	2.06	3.11	3.14	SCL	5/4
-	50-60	Bmk	0.39	1.21	0.50	27.89	33.45	30.71	25.49	1.57	1.78	2.38	2.66	SCL	5/4
-	60-70	Bmk/Ck	0.37	1.26	0.49	25.90	32.04	29.08	23.11	1.30	1.84	1.97	2.20	SCL	5/4
-	70-80	Ck	0.29	1.26	0.56	24.41	27.37	26.34	21.54	1.51	4.42	1.45	2.91	SC	4/4
-	80-90	Ck	0.23	1.41	0.65	28.68	40.64	31.22	24.92	1.18	15.52	0.83	0.44	SC	4/4
-	90-100	Ck	0.23	3.15	0.65	24.20	29.54	26.62	23.48	0.74	1.26	0.90	0.47	SC	4/4

Table A.8. Soil depth characteristics of the depression and upland pits of 'Seeded Pasture 1'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ahsa	5.04	0.00	0.39	17.48	19.09	18.91	15.13	2.60	2.57	3.78	3.43	CL	2/1
-	10-20	Ahksa	3.50	1.87	0.44	18.79	20.35	20.40	16.19	2.84	2.16	2.25	4.35	CL	2/1
-	20-30	Ahksa	3.80	0.84	0.46	19.83	20.59	21.94	16.97	2.57	3.60	4.06	4.82	CL	2/1
-	30-40	Ahksa	4.82	0.85	0.36	12.53	13.94	14.62	10.90	0.28	1.64	2.17	3.23	CL	2/1
-	40-50	Ahksa	4.44	0.97	0.35	10.79	11.49	11.69	8.89	0.57	1.41	2.55	2.98	CL	2/1
-	50-60	Ahksa	2.46	1.11	0.20	4.15	4.42	4.71	3.44	0.74	2.86	1.52	3.06	CL	2/1
-	60-70	Btk	2.28	1.07	0.22	4.67	4.93	5.12	3.88	2.25	2.75	0.00	3.10	C	2/1
-	70-80	Btk	2.18	0.54	0.20	4.25	4.62	4.76	3.60	0.00	0.76	0.78	4.00	C	2/1
-	80-90	Btk	0.57	0.67	0.21	4.35	4.38	4.45	3.29	0.51	0.51	1.04	2.10	C	2/1
-	90-100	Btk	0.48	0.85	0.31	4.21	4.64	4.70	3.45	0.48	0.94	2.38	1.95	C	2/1
Upland	0-10	Ah	3.14	0.00	0.48	23.30	26.08	27.33	21.76	2.78	3.09	3.10	3.87	SL	2/2
-	10-20	Ahk	2.03	2.08	0.52	31.88	34.46	34.66	30.33	0.45	3.10	3.89	4.71	SL	2/2
-	20-30	Ahk	2.73	0.80	0.51	25.14	25.91	26.15	22.04	3.23	2.89	4.42	4.57	SL	2/2
-	30-40	Ahk	2.34	1.15	0.38	21.70	22.88	22.32	18.21	2.97	3.38	3.94	4.01	SL	2/2
-	40-50	Ahk	1.68	1.49	0.35	22.70	23.86	22.38	17.97	1.59	2.70	3.74	3.58	SL	2/2
-	50-60	Ahk	1.44	1.61	0.34	22.81	23.39	22.36	17.64	2.16	2.67	2.81	2.97	SL	2/2
-	60-70	Ahk/Btk	0.95	2.19	0.32	17.82	18.66	17.86	13.93	2.52	3.46	3.86	4.20	L	3/2
-	70-80	Btk	0.87	1.91	0.39	22.73	24.31	22.55	18.83	3.80	3.58	3.65	4.16	L	3/2
-	80-90	Btk	0.70	1.96	0.31	21.45	21.85	20.69	17.14	3.62	3.16	4.37	3.51	L	3/2
-	90-100	Btk	0.65	2.13	0.25	17.02	17.44	16.02	12.55	1.84	1.79	2.78	2.40	L	3/2

Table A.9. Soil depth characteristics of the depression and upland pits of 'Seeded Pasture 2'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	2.60	0.00	0.41	14.23	15.36	15.33	12.27	1.53	1.75	2.49	5.19	C	2/1
-	10-20	Ahk	1.97	1.20	0.41	11.95	12.44	13.35	11.78	2.31	2.52	3.36	5.19	C	2/1
-	20-30	Ah/Aeg	0.74	0.13	0.27	5.47	6.18	6.77	5.80	3.11	3.57	4.35	4.30	SC	3/2
-	30-40	Aeg/Btg	0.49	0.07	0.64	7.01	7.40	8.17	7.59	1.32	1.97	1.89	4.59	C	4/4
-	40-50	Btg	0.42	0.04	0.98	7.10	7.39	8.43	8.76	0.97	1.62	2.07	5.32	C	4/4
-	50-60	Btg	0.34	0.03	0.68	6.90	7.07	8.68	10.11	1.77	1.43	3.35	5.24	C	4/4
-	60-70	Btg/Cg	0.26	0.02	0.82	6.01	6.44	7.72	8.58	0.00	1.52	3.83	5.17	C	4/4
-	70-80	Cg	0.19	0.01	0.74	6.21	6.46	7.55	7.76	1.44	1.38	2.38	3.42	SCL	6/6
-	80-90	Cg	0.17	0.00	0.47	4.61	4.72	5.03	4.68	0.61	1.82	1.71	3.57	SCL	6/6
-	90-100	Cg	0.10	0.05	0.73	14.12	14.25	13.52	12.09	0.26	1.02	1.48	1.06	SCl	6/6
Upland	0-10	Ah	3.06	0.00	0.49	19.27	20.60	22.88	22.82	2.69	2.00	4.68	5.71	SC	3/1
-	10-20	Ahk	2.33	1.54	0.49	17.82	19.75	24.16	27.93	2.78	2.60	5.53	8.02	SC	3/1
-	20-30	Ah/Bm	1.19	0.28	0.50	12.98	13.82	40.95	70.28	1.59	2.36	9.40	13.02	SC	3/1
-	30-40	Bm	0.68	0.17	0.75	12.23	12.95	26.05	26.62	1.61	4.13	9.93	10.99	SiC	3/3
-	40-50	Bm/Ck	0.89	0.52	0.75	9.37	9.70	14.23	14.53	1.78	2.84	7.89	8.88	SiC	3/3
-	50-60	Ck	0.92	2.20	0.68	8.51	8.76	8.79	8.61	1.32	1.75	3.56	4.61	SiC	5/4
-	60-70	Ck	0.68	2.56	0.55	9.12	9.63	8.67	8.31	1.64	0.00	1.45	3.52	SiC	5/4
-	70-80	Ck	0.48	2.28	0.51	11.26	12.00	10.68	9.46	0.95	0.31	2.49	0.84	SiC	5/4
-	80-90	Ck	0.43	1.77	0.61	12.43	13.09	10.85	9.14	0.41	0.20	1.17	1.45	SiC	5/4
-	90-100	Ck	0.38	1.52	0.63	14.18	14.78	12.44	9.77	1.03	0.33	0.99	1.29	SiC	5/4

Table A.10. Soil depth characteristics of the depression and upland pits of 'Seeded Pasture 3'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.1.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	3.68	0.56	0.58	30.67	32.77	32.07	28.93	3.38	2.92	3.94	4.19	SiL	2/1
-	10-20	Ah	3.73	0.58	0.60	26.80	27.85	28.87	24.70	4.28	3.93	4.80	5.83	SiL	2/1
-	20-30	Ah/Aeg	2.16	0.33	0.48	10.36	10.41	12.64	11.85	4.14	1.41	5.72	5.48	SiL	2/1
-	30-40	Aeg	0.65	0.71	0.60	8.75	8.96	10.16	10.96	2.84	2.16	5.47	6.25	SC	4/3
-	40-50	Btg	1.17	0.01	1.13	11.65	12.06	12.58	13.99	4.50	3.68	5.33	7.30	C	4/3
-	50-60	Btg	0.86	0.13	0.98	8.74	8.82	10.12	10.33	4.01	2.05	5.71	6.95	C	2/2
-	60-70	Btg	0.36	0.14	0.74	13.57	14.13	13.89	13.98	0.54	0.54	2.39	4.13	C	2/2
-	70-80	Btg/Cg	0.47	0.07	1.09	9.12	9.12	26.03	100.42	1.29	0.66	6.05	11.34	C	2/2
-	80-90	Cg	0.42	0.04	1.19	11.31	12.50	18.53	60.24	1.15	0.00	3.58	11.52	C	5/6
-	90-100	Cg	0.40	0.01	1.01	13.20	14.03	14.44	16.24	0.38	0.19	2.07	6.52	C	5/6
Upland	0-10	Ah	3.20	0.73	0.56	33.10	34.43	30.18	32.84	4.96	3.42	4.41	4.90	L	2/1
-	10-20	Ah	3.23	0.91	0.65	35.71	36.92	37.38	33.24	3.51	2.86	4.00	4.63	L	2/1
-	20-30	Ah/AB	2.53	0.80	0.54	28.74	31.90	31.00	27.67	2.42	1.80	3.88	4.29	L	2/1
-	30-40	Bm	0.58	0.15	0.56	37.81	39.91	37.64	34.73	2.34	2.49	3.44	4.27	CL	3/4
-	40-50	Bm	0.47	0.10	0.83	42.18	45.32	43.73	40.00	2.42	3.24	4.44	5.64	CL	3/4
-	50-60	Bm	0.41	0.52	0.74	38.63	39.52	37.13	34.43	2.68	2.86	4.06	4.75	CL	3/4
-	60-70	Cca	0.42	2.45	0.65	34.64	35.37	32.64	29.50	1.16	0.88	1.88	1.85	SC	5/4
-	70-80	Cca	0.32	2.59	0.51	41.47	44.53	37.59	33.36	0.62	0.54	1.05	0.86	SC	5/4
-	80-90	Cca	0.26	2.35	0.45	37.18	39.18	35.02	31.64	0.92	0.77	1.08	1.19	SC	5/4
-	90-100	Cca	0.17	2.94	0.53	26.14	28.61	23.47	20.77	1.01	0.86	1.48	1.66	SC	5/4

Table A.11. Soil depth characteristics of the depression and upland pits of 'Native Grassland 1'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.2.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	4.06	0.34	0.58	9.72	10.36	11.41	11.02	3.96	4.80	4.68	7.04	SiCL	3/1
-	10-20	Ah	1.54	0.20	0.54	6.86	8.27	10.27	12.92	7.11	4.26	5.57	8.43	SiCL	3/1
-	20-30	Ah/Aeg	0.81	0.09	0.43	8.99	8.14	8.18	7.69	19.49	4.04	2.55	4.40	SiC	4/2
-	30-40	Aeg	0.46	0.05	0.62	7.42	8.80	8.89	8.15	7.63	4.48	5.60	4.12	SiC	4/2
-	40-50	Aeg	0.66	0.06	0.96	15.32	16.36	16.69	15.88	5.37	5.54	6.52	7.63	SiC	4/2
-	50-60	Bt	0.97	0.12	1.01	17.34	18.54	19.10	18.39	7.56	6.60	9.57	8.78	C	3/1
-	60-70	Bt	1.23	0.16	1.21	15.66	17.54	17.97	18.46	2.61	7.03	6.41	8.85	C	3/1
-	70-80	Bt	1.24	0.19	1.02	14.87	15.07	15.40	15.44	7.34	5.50	6.25	7.19	C	3/1
-	80-90	Bt	1.34	0.24	1.24	20.33	21.31	21.58	20.46	8.10	7.01	7.54	8.03	C	3/1
-	90-100	Bt	0.68	0.19	1.85	34.22	37.98	38.47	41.36	4.79	5.10	5.26	6.31	C	3/1
Upland	0-10	Ah	2.75	0.62	0.43	24.65	26.66	24.55	20.09	2.66	1.92	2.74	3.45	SCL	2/1
-	10-20	Ah/Bm	2.52	0.66	0.57	26.21	28.59	27.69	25.68	4.76	5.07	5.53	6.49	SCL	2/1
-	20-30	Bm/Cca	1.30	0.17	0.80	33.83	36.74	27.75	38.35	5.73	5.49	7.57	4.56	SC	3/6
-	30-40	Cca	0.82	0.12	1.01	24.58	26.17	24.56	34.83	5.20	5.69	9.05	9.21	SiC	4/3
-	40-50	Cca	0.87	1.83	0.75	15.81	16.92	16.94	15.86	2.24	1.75	3.97	5.61	SiC	4/3
-	50-60	Cca	0.52	2.08	0.67	20.91	22.68	21.26	17.39	0.87	1.69	3.05	4.21	SiC	4/3
-	60-70	Cca	0.20	2.41	0.53	25.83	28.20	25.69	20.25	0.47	1.37	3.03	3.77	Sic	4/3
-	70-80	Cca	0.11	2.88	0.47	27.29	29.40	24.69	20.05	1.66	1.00	1.44	2.33	SiC	4/3
-	80-90	Cca	0.09	2.62	0.56	26.85	28.84	25.51	19.69	0.97	0.52	1.10	1.24	SiC	4/3
-	90-100	Ck	0.09	1.45	0.67	29.81	31.14	29.22	23.14	0.61	1.18	1.19	1.45	SC	4/4

Table A.12. Soil depth characteristics of the depression and upland pits of 'Native Grassland 2'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.2.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	2.01	0.00	0.41	16.48	18.05	17.04	11.82	1.01	0.75	1.66	0.78	CL	2/1
-	10-20	Ahk/Btg	1.08	1.22	0.47	19.39	20.51	19.54	14.16	1.62	1.45	2.14	9.42	CL	2/1
-	20-30	Btg	0.72	0.27	0.64	22.21	22.92	21.21	16.75	2.42	1.91	3.29	4.22	SC	3/3
-	30-40	Btg	0.30	0.16	0.87	25.64	22.26	21.66	16.54	0.58	1.87	3.16	4.67	SC	3/3
-	40-50	Btg	0.28	0.61	0.79	26.56	29.46	28.01	21.44	1.34	1.07	2.76	3.53	SC	3/3
-	50-60	Ckg	0.17	3.50	0.54	21.37	23.32	20.13	16.62	1.24	0.93	1.75	2.07	C	5.5/4
-	60-70	Ckg	0.17	3.09	0.48	23.98	26.17	22.49	20.19	1.85	1.55	1.57	2.79	C	5.5/4
-	70-80	Ckg	0.14	3.69	0.55	22.94	23.91	21.09	22.49	0.34	1.00	1.31	4.56	C	5.5/4
-	80-90	Ckg	0.06	3.54	0.55	24.17	25.25	21.06	20.33	1.31	1.27	2.57	4.81	C	5.5/4
-	90-100	Ckg	0.04	2.88	0.58	30.38	32.41	28.49	24.21	0.90	0.66	1.17	1.83	C	5.5/4
Upland	0-10	Ahk	1.31	3.39	0.46	27.61	29.59	26.71	21.60	2.35	2.31	2.47	3.81	C	2/1
-	10-20	Ah/B	3.76	0.00	0.56	32.17	35.08	38.36	34.43	4.95	5.16	6.42	6.24	C	2/1
-	20-30	Bk	0.73	0.70	0.69	24.98	27.14	27.67	24.55	3.37	3.28	4.93	4.70	C	5/4
-	30-40	Bk	0.69	0.72	0.80	21.39	22.26	24.57	21.74	3.18	2.46	5.71	6.75	C	5/4
-	40-50	Bk/Cca	0.48	2.45	0.63	16.84	18.24	22.91	18.86	1.63	1.81	7.34	7.22	C	5/4
-	50-60	Cca	0.27	2.30	0.67	24.90	26.54	28.96	26.45	1.17	0.38	4.28	4.47	SC	5.5/4
-	60-70	Cca	0.15	1.93	0.76	23.79	19.33	29.43	26.25	0.15	0.00	4.51	3.94	SC	5.5/4
-	70-80	Cca	0.20	1.33	1.71	35.80	36.89	47.40	46.33	0.71	0.52	4.75	4.52	SC	5.5/4
-	80-90	Cca	0.10	1.65	0.78	17.14	19.03	21.47	20.53	1.78	1.34	4.64	4.45	SC	5.5/4
-	90-100	Cca	0.10	1.45	0.56	26.28	28.19	26.90	24.37	0.18	1.68	3.01	2.36	SC	5.5/4

Table A.13. Soil depth characteristics of the depression and upland pits of 'Native Grassland 3'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.2.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	2.86	0.00	0.62	11.84	12.90	17.02	16.34	8.50	3.92	6.77	6.74	SC	2/1
-	10-20	Ahk	1.21	2.25	0.74	21.44	22.68	25.95	24.84	5.67	5.26	7.47	9.64	SC	2/1
-	20-30	AB	0.90	0.12	0.84	27.56	30.52	31.17	30.14	7.98	7.52	9.39	10.07	SiC	2/2
-	30-40	AB	0.59	0.09	0.77	18.89	19.67	21.92	22.50	6.06	6.09	7.06	8.38	SiC	2/2
-	40-50	AB	0.44	0.06	1.19	15.19	16.03	16.01	13.46	3.99	4.02	3.28	6.58	SiC	2/2
-	50-60	Btg	0.35	0.01	1.20	19.69	20.35	21.17	17.66	2.23	2.06	3.09	5.37	SiC	3/3
-	60-70	Btg	0.31	0.04	0.92	20.28	21.69	21.76	18.22	2.50	0.99	3.63	4.87	SiC	3/3
-	70-80	Btkg	0.28	0.94	0.68	18.89	19.99	17.14	12.82	2.00	1.78	2.09	3.61	SiC	3/3
-	80-90	Btkg	0.42	2.42	0.62	18.46	19.96	16.67	12.26	1.21	1.17	2.36	2.35	SiC	3/3
-	90-100	Btkg	0.26	2.24	0.63	29.63	32.15	28.92	23.17	1.12	1.20	1.62	1.88	SiC	3/3
Upland	0-10	Ah	3.35	0.00	0.60	29.25	30.35	30.62	24.37	2.78	3.33	3.68	5.40	L	2/1
-	10-20	Ahk/AB	2.18	1.61	0.64	28.24	30.43	29.61	24.26	3.82	4.42	4.79	5.32	L	2/1
-	20-30	AB/Btk	1.70	1.54	0.55	26.59	27.29	26.95	21.74	3.81	3.78	4.78	4.66	SiC	3/3
-	30-40	Btk	0.91	1.54	0.64	23.93	26.05	24.80	20.33	2.84	2.66	3.50	5.47	C	5/5
-	40-50	Btk	0.64	1.86	0.49	21.88	23.65	21.64	17.45	1.92	2.39	3.02	5.15	C	5/5
-	50-60	Cca	0.54	1.92	0.51	21.51	23.37	21.28	16.78	2.72	1.68	3.16	6.02	C	5/4
-	60-70	Cca	0.54	1.85	0.66	20.02	1.14	20.15	16.20	1.91	1.71	2.66	2.59	C	5/4
-	70-80	Cca	0.35	2.14	0.55	18.68	20.32	17.74	15.13	3.46	0.60	1.83	4.07	C	5/4
-	80-90	Cca	0.26	1.84	0.52	18.77	21.05	19.62	15.72	2.03	0.90	2.41	3.24	C	5/4
-	90-100	Cca	0.21	2.42	0.51	26.96	28.86	24.61	19.95	0.92	0.67	1.56	0.97	C	5/4

Table A.14. Soil depth characteristics of the depression and upland pits of 'Native Grassland 4'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.2.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	4.83	0.00	0.62	6.60	7.52	13.68	14.82	0.66	1.32	5.62	10.00	L	2/1
-	10-20	Ah	2.73	2.72	0.73	12.15	13.33	18.00	21.99	1.32	1.83	5.68	7.55	L	2/1
-	20-30	Ah	1.16	0.17	0.45	9.56	9.77	10.67	10.22	2.72	1.97	3.80	4.03	L	2/1
-	30-40	Ah	1.17	0.20	0.62	9.62	10.04	10.40	9.99	4.29	4.91	4.31	7.19	L	2/1
-	40-50	Ah	1.01	0.18	0.72	11.68	12.43	12.59	11.67	4.48	4.94	5.06	6.58	L	2/1
-	50-60	Ah	0.81	0.14	0.80	13.90	14.73	15.51	15.88	5.04	5.26	5.86	8.26	L	2/1
-	60-70	Ah/Btg	0.50	0.10	0.67	10.89	11.60	28.17	37.14	3.48	3.49	9.98	11.94	L	2/1
-	70-80	Btg	0.39	0.06	0.89	12.16	13.10	54.33	83.37	2.28	2.78	11.71	13.79	CL	4/6
-	80-90	Btg	0.30	0.06	0.94	15.27	16.33	22.69	25.37	1.42	1.18	7.20	8.67	CL	4/6
-	90-100	Btg	0.35	0.33	0.81	19.05	21.27	20.57	18.81	1.81	1.29	3.42	4.77	CL	4/6
Upland	0-10	Ah	6.46	0.00	0.65	34.99	37.31	42.61	40.57	4.56	4.33	5.67	6.55	SL	2/1
-	10-20	Ahk	2.85	3.90	0.78	46.06	48.81	48.01	43.78	3.80	4.28	4.35	4.34	SL	2/1
-	20-30	Ahk	1.69	2.51	0.74	24.45	25.52	25.78	22.06	1.24	0.92	3.27	2.39	SL	2/1
-	30-40	Ahk	1.34	3.11	0.57	21.50	23.09	25.18	20.23	0.56	1.64	2.51	2.25	SL	2/1
-	40-50	Ahk/Btk	0.38	2.21	1.04	36.33	37.67	0.00	34.56	0.07	1.26	1.30	0.87	SC	4/3
-	50-60	Btk	0.02	3.04	1.27	32.25	34.22	33.58	0.00	0.43	0.85	0.80	1.69	SC	4/3
-	60-70	Btk	0.11	2.52	0.52	25.28	26.02	24.68	20.65	0.80	1.24	1.41	1.72	SC	4/3
-	70-80	Btkg	0.14	2.62	0.48	29.01	28.43	26.39	21.33	0.81	1.22	1.29	1.77	SC	5/6
-	80-90	Btkg	0.16	2.63	0.43	27.99	28.36	25.33	19.37	1.22	1.18	1.37	0.96	SC	5/6

Table A.15. Soil depth characteristics of the depression and upland pits of 'Native Grassland 5'. Magnetic susceptibility (MS) value is reported in low frequency (0.47 kH) whereas the number after refers to its temperature treatment. For pit location, see Fig.3.2.

Pit Position	Depth (cm)	Horizon Designation	OC	IC	DF	MS@ Room	MS@ 100	MS@ 300	MS@ 500	FD@ Room	FD@ 100	FD@ 300	FD@ 500	Hand Texture	Color (10YR)
-	cm	-	%	%	%	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	$m^3\ kg^{-1}$	%	%	%	%	-	-
Depression	0-10	Ah	5.86	0.00	0.95	15.67	16.95	19.61	17.72	3.61	4.98	6.29	6.35	L	2/1
-	10-20	Ahk	2.95	3.59	0.68	15.21	16.24	16.50	15.16	3.38	4.32	5.78	6.74	L	2/1
-	20-30	Ah	2.19	0.29	1.06	23.32	24.88	25.51	24.44	5.85	6.21	7.42	8.23	L	2/1
-	30-40	Ah	1.43	0.31	1.03	46.06	48.38	51.86	50.82	7.14	7.16	8.16	9.10	L	2/1
-	40-50	Ah	1.65	0.27	1.09	41.90	43.33	46.59	47.06	7.74	7.62	9.23	10.29	L	2/1
-	50-60	Ah	1.15	0.29	0.83	32.68	36.07	36.06	37.03	7.29	7.53	8.64	10.12	L	2/1
-	60-70	Btg	0.71	0.27	0.79	33.43	34.19	35.87	36.26	6.77	6.83	8.47	9.56	C	5/4
-	70-80	Btg	0.56	0.00	0.84	19.38	19.77	40.33	56.30	4.29	2.92	9.58	12.63	C	5/4
-	80-90	Btg	0.56	0.17	0.94	24.50	25.89	31.15	32.84	4.47	6.03	7.50	10.31	C	5/4
-	90-100	Btg/Cg	0.38	0.06	0.93	17.61	18.81	17.92	14.47	1.84	2.20	3.27	5.23	C	5/4
Upland	0-10	Ah/Bm	2.35	0.00	0.74	34.14	36.56	40.09	36.33	3.08	3.34	4.35	4.66	SL	3/3
-	10-20	Bmk	1.11	1.64	0.90	33.63	32.37	32.60	1.21	0.56	2.10	2.69	5.03	SL	3/6
-	20-30	Ck1	0.68	3.60	0.47	27.36	29.26	23.46	25.93	0.95	1.56	1.14	2.18	SL	6/4
-	30-40	Ck1	0.00	3.12	0.53	21.79	24.57	22.21	19.76	0.43	0.55	1.83	2.52	SL	6/4
-	40-50	Ck1	0.00	2.93	0.54	22.74	24.49	1.20	20.33	0.50	0.86	1.17	2.50	SL	6/4
-	50-60	Ck2	0.09	2.64	0.47	29.14	31.79	28.38	25.61	1.07	3.75	1.38	2.02	SC	5/4
-	60-70	Ck2	0.07	2.56	0.48	24.57	26.70	23.62	20.80	0.49	0.95	0.98	1.33	SC	5/4
-	70-80	Ck2	0.08	2.57	0.54	25.32	28.35	13.62	22.78	0.26	1.09	1.13	1.19	SC	5/4
-	80-90	Ck2	0.04	2.63	0.51	29.11	30.33	28.68	24.00	1.03	1.09	1.03	1.32	SC	5/4
-	90-100	Ck2	0.05	2.46	0.79	25.92	28.03	25.11	21.81	0.66	0.96	1.18	1.39	SC	5/4

APPENDIX B: INVIDUAL GREENHOUSE GAS EMISSIONS OF TREATMENT GROUP

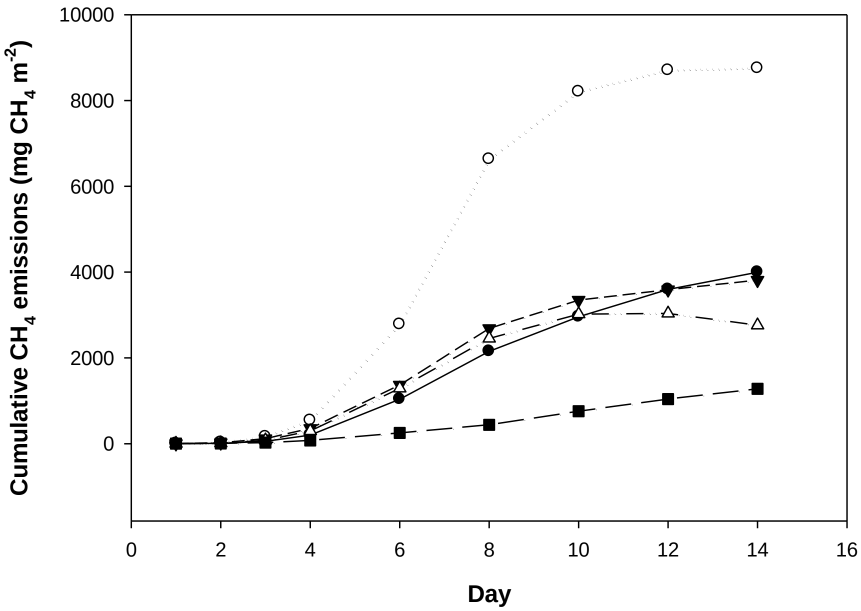

Fig. B.1. Cumulative CH_4 emissions of the seeded pasture cores under the S10 - SO_4^- treatment with respect to day. Each point represents the emissions by a different incubated soil core (n=5).

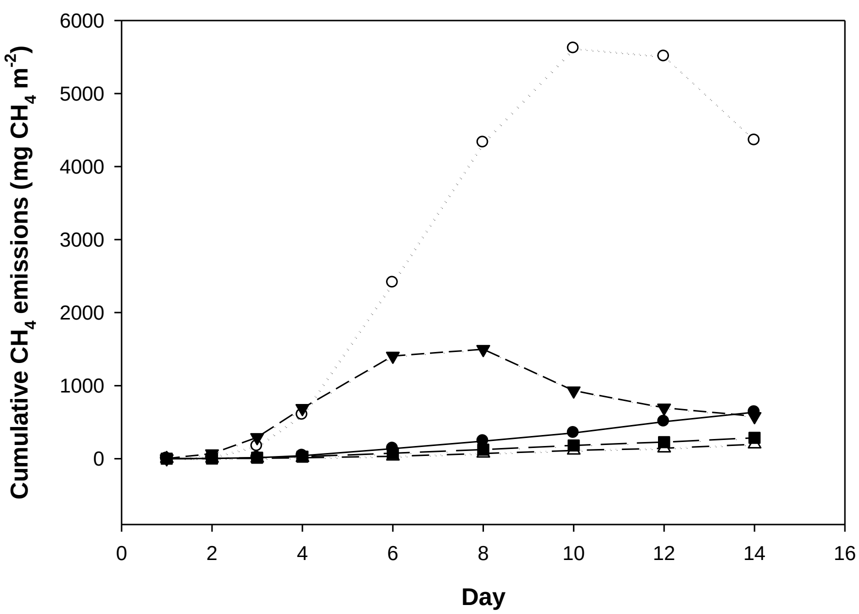

Fig. B.2. Cumulative CH_4 emissions of the seeded pasture cores under the S50 - SO_4^- treatment with respect to day. Each point represents the emissions by a different incubated soil core (n=5).

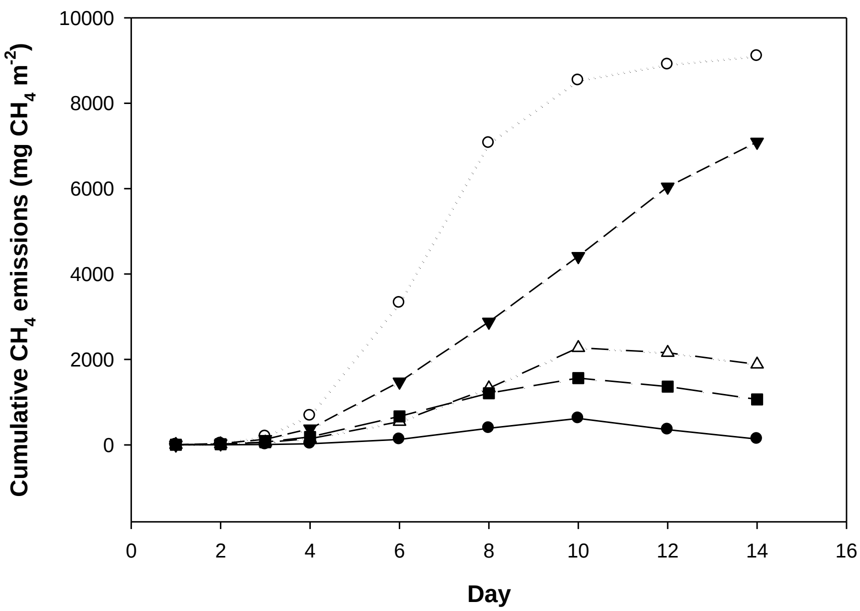

Fig. B.3. Cumulative CH_4 emissions of the seeded pasture cores under the S100 - SO_4^- treatment with respect to day. Each point represents the emissions by a different incubated soil core (n=5).

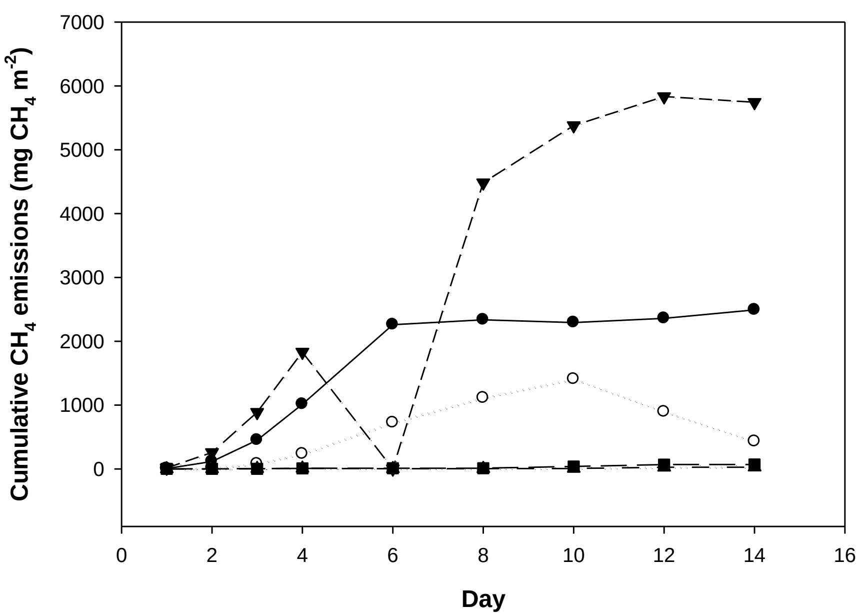

Fig. B.4. Cumulative CH_4 emissions of the cultivated grassland cores under the S0 - SO_4^- treatment with respect to day. Each point represents the emissions by a different incubated soil core (n=5).

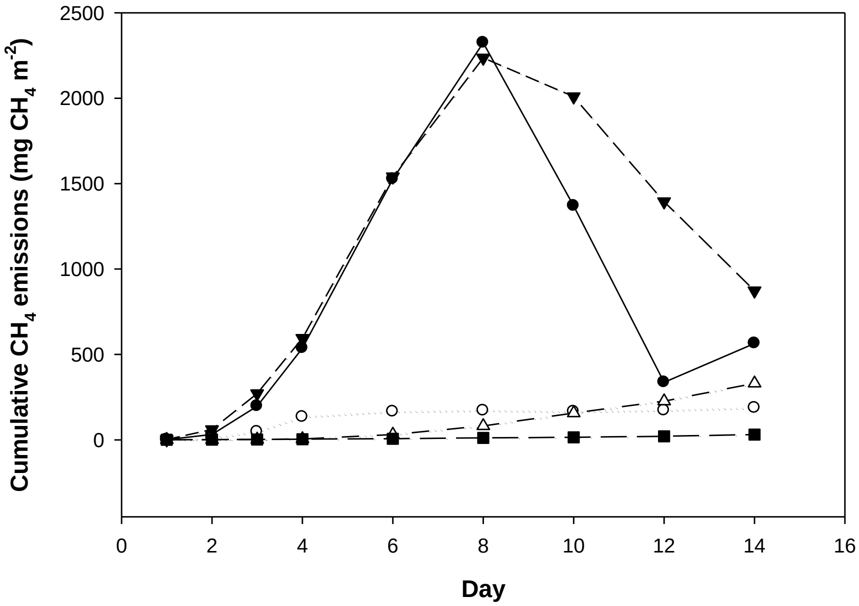

Fig. B.5. Cumulative CH_4 emissions of the cultivated grassland cores under the S10 - SO_4^- treatment with respect to day. Each point represents the emissions by a different incubated soil core (n=5).

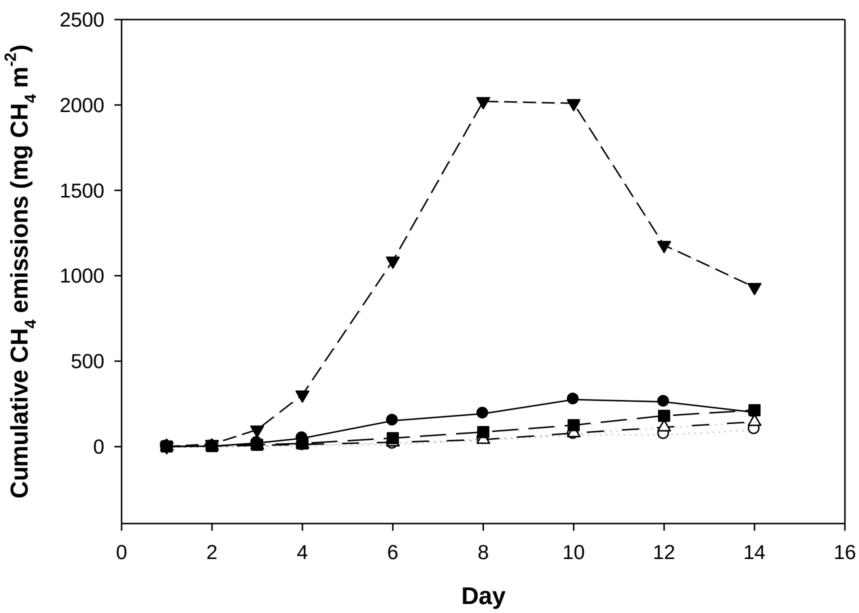

Fig. B.6. Cumulative CH_4 emissions of the cultivated grassland cores under the S50 - SO_4^- treatment with respect to day. Each point represents the emissions by a different incubated soil core (n=5).

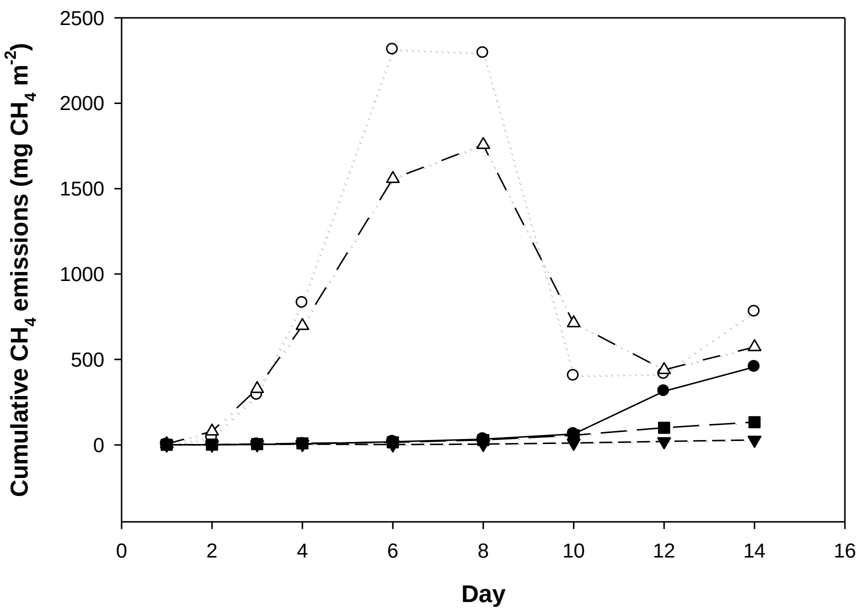

Fig. B.7. Cumulative CH_4 emissions of the cultivated grassland cores under the S100 - SO_4^- treatment with respect to day. Each point represents the emissions by a different incubated soil core (n=5).

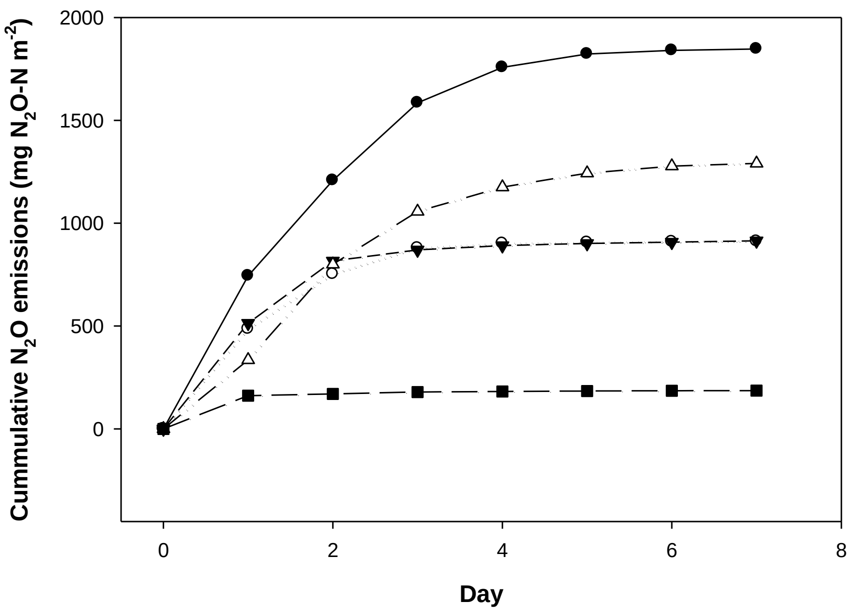

Fig. B.8. Cumulative N_2O emissions of the seeded pasture cores under the 80% water filled pore space (W80) and no NO_3^- added treatments. Each point represents the emissions by a different incubated soil core (n=5).

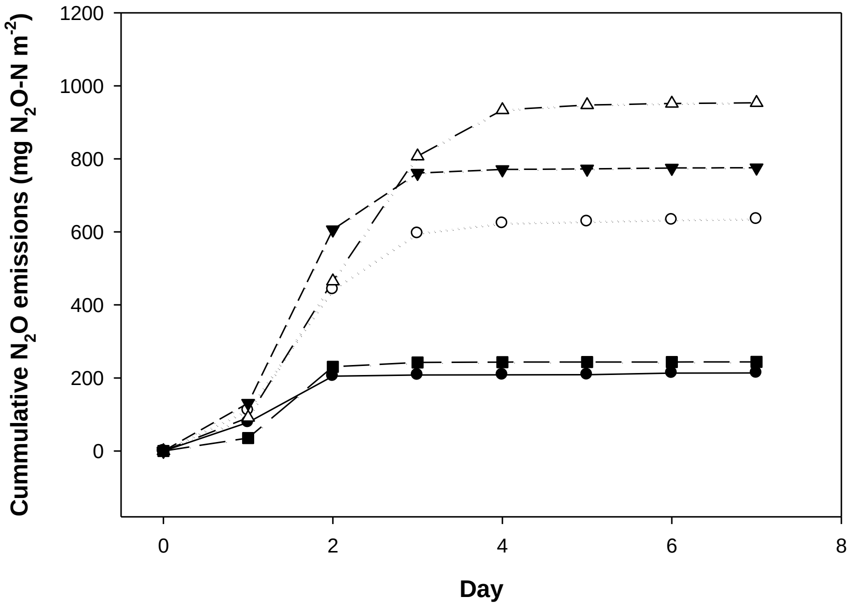

Fig. B.9. Cumulative N_2O emissions of the seeded pasture cores under the 120% water filled pore space (W120) and no NO_3^- added treatments. Each point represents the emissions by a different incubated soil core (n=5).

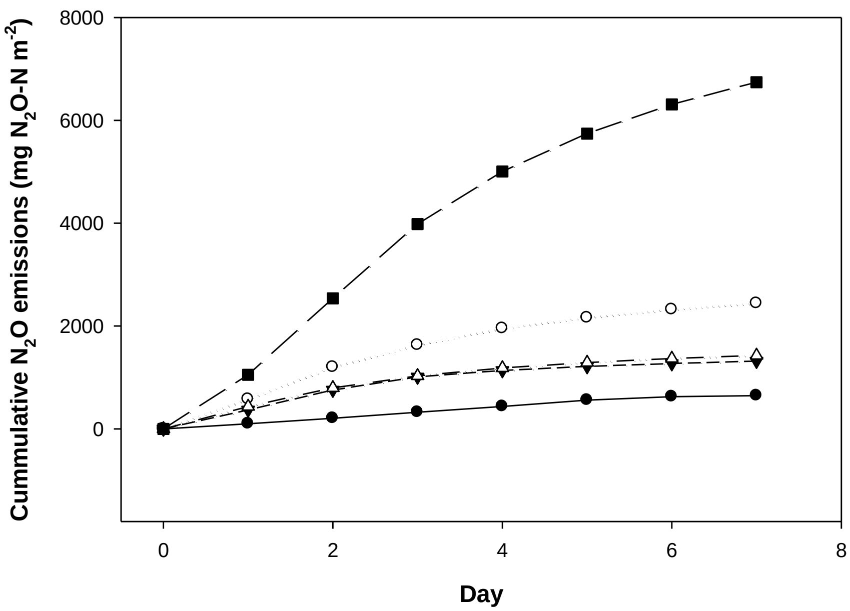

Fig. B.10. Cumulative N_2O emissions of the seeded pasture cores under the 60% water filled pore space (W60) and added NO_3^- treatments. Each point represents the emissions by a different incubated soil core (n=5).

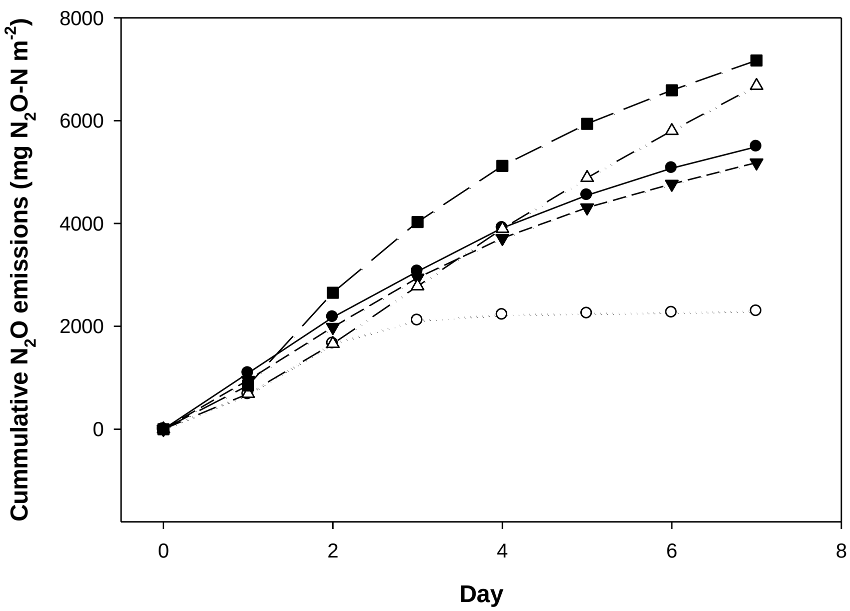

Fig. B.11. Cumulative N_2O emissions of the seeded pasture cores under the 80% water filled pore space (W80) and added NO_3^- treatments. Each point represents the emissions by a different incubated soil core (n=5).

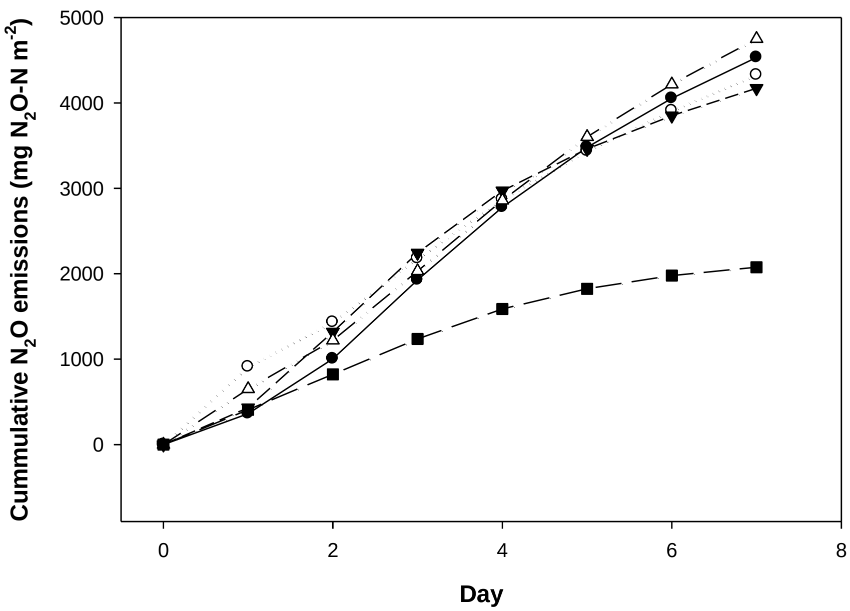

Fig. B.12. Cumulative N_2O emissions of the seeded pasture cores under the 120% water filled pore space (W120) and added NO_3^- treatments. Each point represents the emissions by a different incubated soil core (n=5).

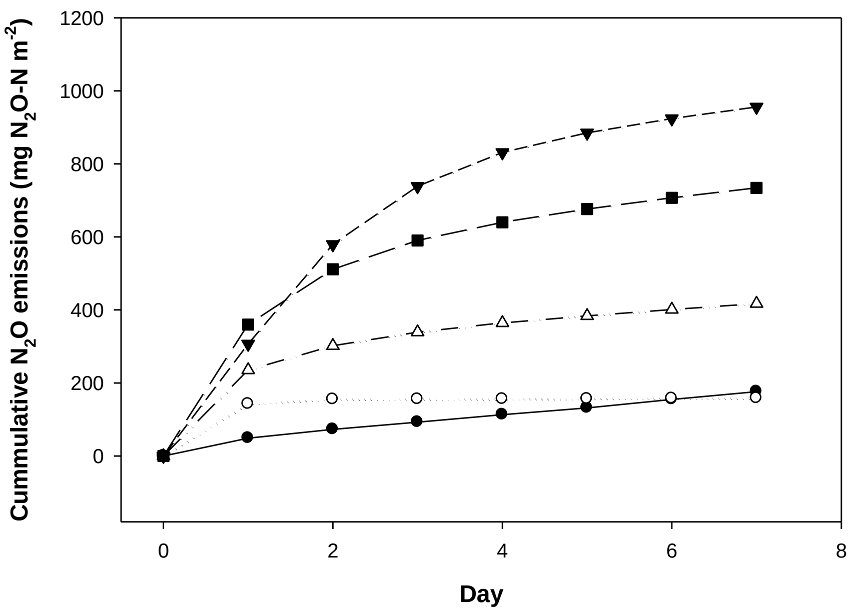

Fig. B.13. Cumulative N_2O emissions of the cultivated grassland cores under the 60% water filled pore space (W60) and no NO_3^- added treatments. Each point represents the emissions by a different incubated soil core (n=5).

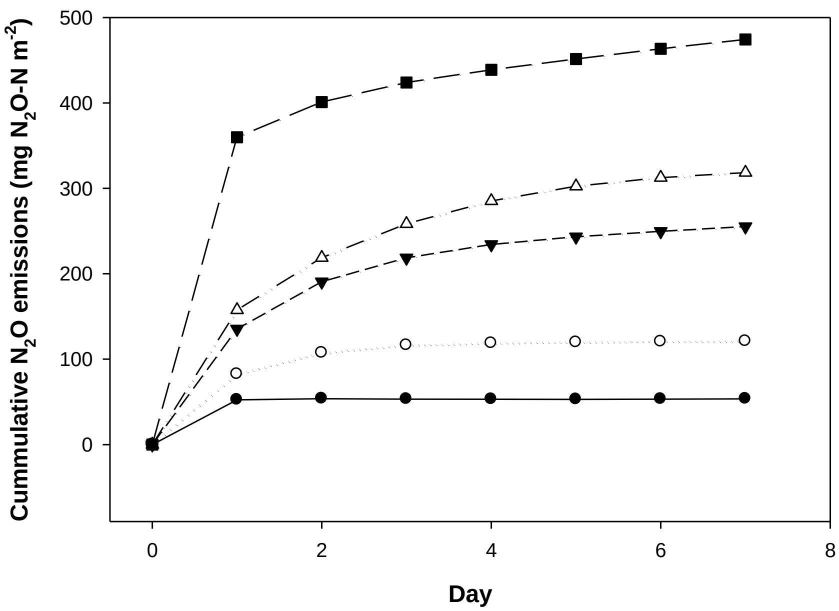

Fig. B.14. Cumulative N_2O emissions of the cultivated grassland cores under the 80% water filled pore space (W80) and no NO_3^- added treatments. Each point represents the emissions by a different incubated soil core (n=5).

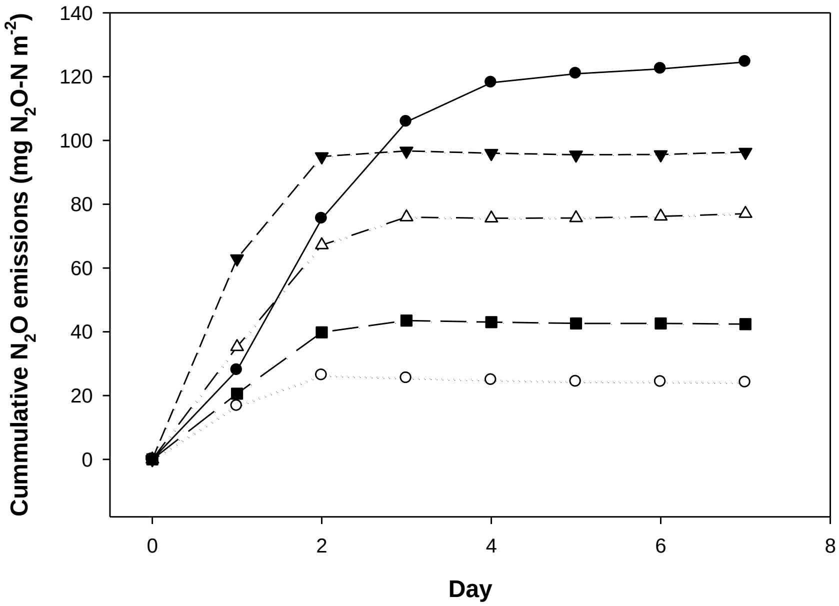

Fig. B.15. Cumulative N_2O emissions of the cultivated grassland cores under the 120% water filled pore space (W120) and no NO_3^- added treatments. Each point represents the emissions by a different incubated soil core (n=5).

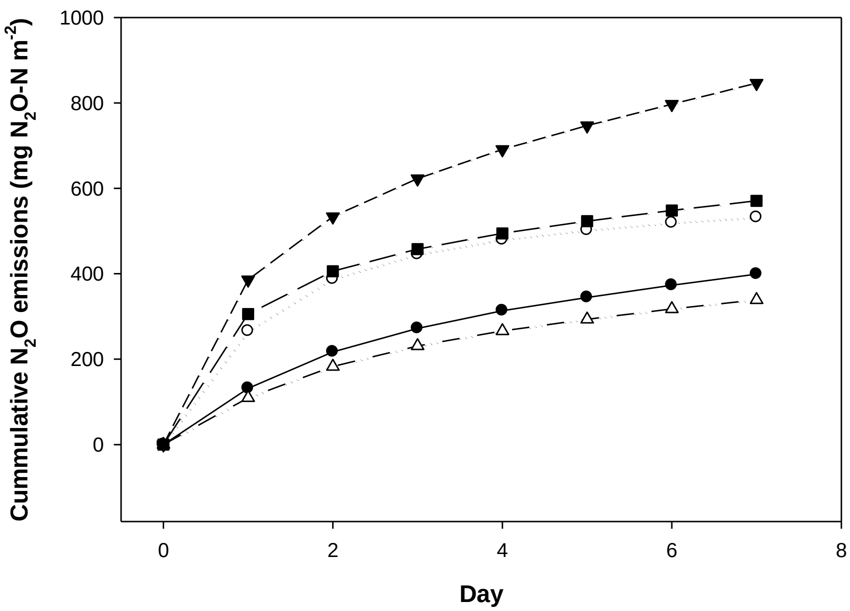

Fig. B.16. Cumulative N_2O emissions of the cultivated grassland cores under the 60% water filled pore space (W60) and added NO_3^- treatments. Each point represents the emissions by a different incubated soil core (n=5).

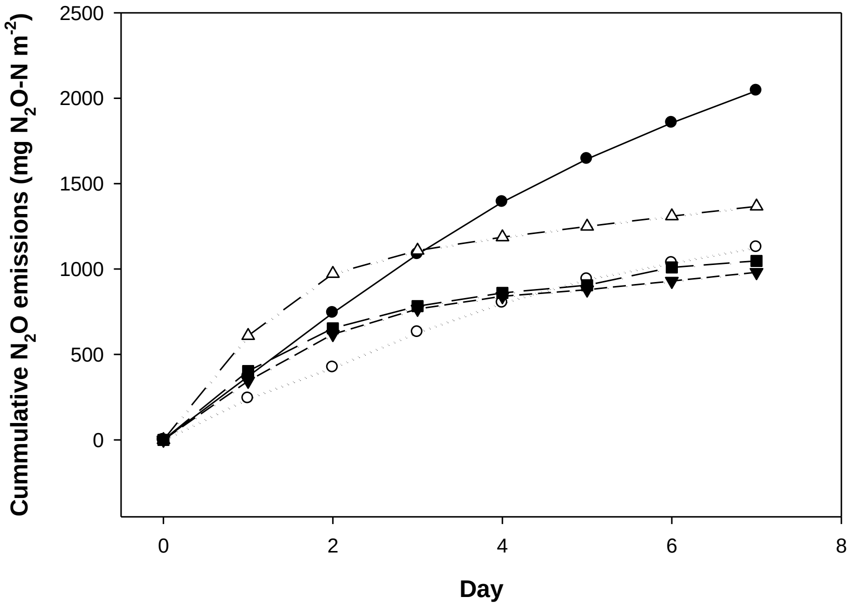

Fig. B.17. Cumulative N_2O emissions of the cultivated grassland cores under the 80% water filled pore space (W80) and added NO_3^- treatments. Each point represents the emissions by a different incubated soil core (n=5).

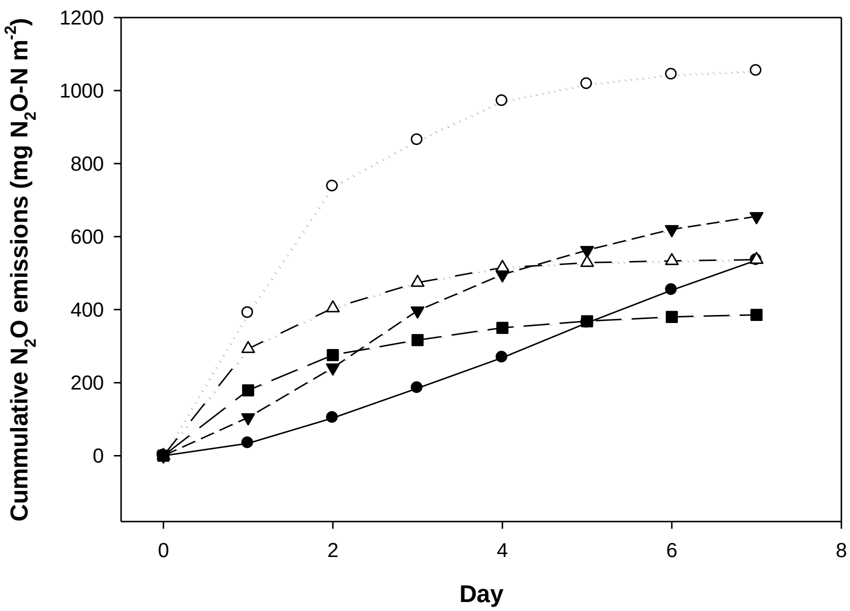

Fig. B.18. Cumulative N_2O emissions of the cultivated grassland cores under the 120% water filled pore space (W120) and added NO_3^- treatments. Each point represents the emissions by a different incubated soil core (n=5).