NITROGEN DYNAMICS FOLLOWING INCORPORATION OF 3-YEAR OLD GRASSLAND SET-ASIDES IN DELTA, BRITISH COLUMBIA

by

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ABSTRACT

The Grassland Set-aside (GLSA) Stewardship Program has been utilized by farmers in the lower Fraser River delta, British Columbia (BC), Canada since 1993. Farmers seed fields in a grass-legume mixture and leave them fallow for up to four years providing feeding habitat for raptors while subsequently improving soil quality. While the wildlife benefits have been well documented, soil quality improvement and benefits to succeeding crops are not well understood. The objective of this research is to quantify the nitrogen benefits to crop production after incorporation of 3-year-old GLSA. A regional experiment was conducted over two years, utilizing production fields transitioning from GLSA, paired with continuously cropped fields (Control) with matching management. A controlled field experiment was also conducted on a single 3-year-old GLSA, comparing fertilizer types, rates and timing of incorporation. In each experiment, soils were sampled every 10-14 days for ammonium (NH_4) and nitrate (NO_3) while ion probes, installed near the rooting zone tracked plant available nitrogen (PAN) throughout the season.

The results from the regional experiment were confounding, in 2015 showing GLSA supplied an additional 18 kg PAN ha^{-1} compared to Control but showing no PAN benefits in 2016. While the PAN supplied by the GSLA remained consistent each year, the amount supplied by Control in 2016 was relatively higher. In both years, PAN following GLSA peaked later in the season than the Control, likely due to immobilization of nitrogen facilitated by incorporation of biomass with a high carbon to nitrogen (C:N) ratio. Immobilization also delayed NH_4 release in the controlled experiment for up to 21 days and NO_3 56 days. The controlled experiment also highlighted the importance of fertilizer type to subsequent PAN, showing synthetic treatments consistently supplied more PAN than Organic.

Results from this study suggest that 3-year-old GLSAs can potentially improve PAN to subsequent crops; however, benefits provided by GLSA in Delta are dependent on a number of factors which include the C:N ratios of biomass, timing between incorporation and crop planting, precipitation and temperatures, and fertilizer type, all of which impact the timing and quantity of PAN and thus its utility to subsequent crops.

LAY SUMMARY

Grassland Set-asides (GLSA) are a conservation practice utilized by farmers in Delta, BC, to provide critical bird feeding habitat while remediating vital soil properties, often degraded from intensive farm management. In a GLSA rotation farmers take land out of production and grow a mix of grasses for up to four years before incorporating them into the soil to return to crop production. One of the reported benefits of a GLSA rotation is remediation of soil nutrients and an associated increase in plant available nitrogen (PAN) for subsequent crops. This study utilized regional on-farm and controlled field experiments to better understand the effect of GLSA rotations on PAN. Results showed that the relative benefits of GLSA for PAN are not consistent. Although GLSA have the potential to increase PAN relative to continuous cropping, this potential depends on a number of management factors that need to be considered to optimize GLSA benefits.

PREFACE

The work of this thesis is the based on collaboration between the Sustainable Agricultural Landscapes Laboratory in the Faculty of Land and Food Systems at the University of British Columbia and the non-governmental organization, the Delta Farmland and Wildlife Trust, based in Delta B.C.

With a team I was in charge of all soil and plant sampling and majority of the laboratory analysis. A subset of soil samples were sent to the Ministry of Environment in Victoria, BC for chemical analyses of selected soil properties. Plant elemental analysis of AGB was run in February of 2017, samples were prepared by myself and analyses was run in the Belowground Ecosystems Group Laboratory. I was responsible for all data collection, analysis and interpretation.

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LIST OF ABBREVIATIONS

AC - Additional carbon

AGB - Above ground biomass

AN - Additional nitrogen

C - Carbon

Con - Control

DAI - Days after incorporation

DBPI - Days between planting and incorporation

DF&WT - Delta Farmland and Wildlife Trust

DM - Dry matter

EC - Electrical conductivity

GLSA - Grassland set-asides

High - High fertilizer

Late - Late incorporation

N - Nitrogen

NH_4^+-N - Ammonium

NO_3^--N - Nitrate

MBC - Microbial biomass carbon

Org - Organic

PAN - Plant available nitrogen

PCA - Principal components analysis

PCNR - Plant carbon to nitrogen ratio

PMN - Potentially mineralizable nitrogen

PN - Plant nitrogen

RSN - Residual soil nitrogen

SOC - Soil organic carbon

SOM - Soil organic matter

TOC - Total organic carbon

TN - Total nitrogen

Typical - Typical fertilizer

WHC - Water holding capacity

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DEDICATION

I would like to dedicate my thesis and the work on this document to the many family and friends who have supported me over the past two years and willed this document to its completion. A big thank you to my Dentry's family for creating a home away from home and to my IFSA family for creating a great community and giving me a reason escape from research for a few hours a week. To my parents for both supporting me and specifically to my Mother and Sister for pushing me to put my passions before all else and ensuring I felt fully supported along this journey.

Chapter 1: Introduction

1.1 Soil Degradation in Temperate Climates

Many temperate soils are characterized by high levels of natural fertility, which make them exceptionally suitable for crop production (Robertson and Grandy, 2006). It is estimated however, that globally 0.3 - 0.8% of arable land is degraded beyond the point of agricultural utility each year (Biggelaar et al., 2004), a large part of which is driven by intensive crop management, typical of temperate agricultural production (Tilman et al., 2002).

Intensive management can be defined by the type of inputs (e.g., synthetic fertilizers), the type of crops and rotations, and the amount of mechanization. Management practices such as tillage to prepare fields for planting and control weeds can destroy soil structure, break soil aggregates and bring sub-soil to the surface. Through this type of mechanical disturbance microbial activity is stimulated as microbes gain access to oxygen and consume the carbon (C) and nitrogen (N) available in soil organic matter (SOM) for metabolic energy. Tillage thus increases microbial respiration of soil organic carbon (SOC) and the mineralization of N, potentially contributing to the loss of soil C and N pools. Tillage also modifies soil structure, reduces macro pores and may cause soil compaction. Often the use of heavy equipment can contribute to the development of a plow pan, limiting crop root penetration and causing poor internal drainage of soils (Duiker, 2004). Poor drainage can lead to anoxic soil environments and further loss of N to the atmosphere through denitrification, as microbes are forced to utilize nitrate (NO_3^-) for respiration in place of oxygen (Aulakh and Singh 1997; Inglett et al.,2005; Ratsep et al. 1994). Furthermore the short rotations times or the production of only cash crops often seen in temperate intensive cropping systems does not allow adequate time or biomass to recuperate SOM (Food and Agriculture Organization (FAO), 2002)Lack of organic inputs also contributes to the degradation of soil structure as soil organisms are deprived of the materials they need to release the vital binding agents responsible for soil aggregation (Cambardella & Elliot, 1993; Coleman et al., 2004).

Over time, physical, chemical and biological degradation caused by intensive management can ultimately result in cropping systems with low nutrient use efficiencies which in turn reduces crop productivity and farm profitability (Ratsep et al., 1994). A study by Osman (2014) estimated that compaction from mechanized agriculture alone reduced yields by 25-50% in some regions of Europe and North America. Robertson and Grandy (2006) estimated that continuous cropping in the temperate zone could lead to the total depletion of SOC within 40-60 years, while (Sainju, 2013) found lower values of SOC, soil N and a lower potential for N mineralization from conventional tillage treatments compared to no tillage, after only 21 years of continuous cropping of malt barley *(Hordeum vulgaris L.)* in Montana. The loss of SOM and the stunting of microbial activity ultimately leads to a diminished capacity of soils to supply plant available nitrogen (PAN) through the mineralization of organic N to ammonium (NH_4^+) and NO_3^-, making production more reliant on external nutrient inputs (e.g., fertilizer or manure) (Baumhardt et al., 2015). This reliance on synthetic and organic fertilizer can also reduce soil pH (Osman, 2014) further contributing to an unfavorable soil environment and the need for additional soil amendments (e.g., lime). Although there are a number of studies that have documented the relationship between intensifying production and reduced nutrient use efficiencies, Baumhardt et al. (2015) suggests that an overall decline in crop yields has not yet been observed in North America because other advances (e.g., precision agricultural, improved cultivars) which have been able to offset the considerable impacts from the loss of SOM. While there has been some movement to reduce soil degradation and protect soil fertility (e.g., widespread adoption of reduced-tillage management), the continued intensity of crop production and associated soil degradation is likely to eventually impact agricultural sustainability particularly under specific soil and climatic conditions.

1.2 Farming in the Lower Fraser River Delta and Soil Degradation

The agricultural region of Delta, British Columbia, located in the lower Fraser River Delta is one of the most productive in the province (Leonoff et al., 1992) and a clear example of soils susceptible to degradation. The region's temperate climate is typified by mild, cool winters and a long warm, dry, growing season. The soils are comprised of deep, medium to fine textured silts and clays, with a high natural fertility capable of growing a variety of crops. The intensity of production in the region has, however, been heightened by urbanization pressures, a lack of secure long term- land tenure agreements and short term rentals resulting in limited cropping rotations and a narrow focus on high value potato production, one of the most tillage intensive crops. The combination of short rotations and extensive tillage particularly on saturated soils, has contributed to the considerable loss of SOM and soil degradation in the area (Bomke and Temple, 1990).

The soil and climate which make the region so agriculturally productive are also contributing to its degradation (Bertrand et al., 1991). Delta's fine silts and clays are naturally poorly drained, are in close proximity to the ocean and have been known to be saline. The use of heavy farm equipment on saturated production fields and the lack of vegetative cover over the winters has contributed to compaction and reduced SOM (Principe, 2001). A 1992 survey reported that one out of three farms in the region suffered from poor soil structure and low levels of SOM (Leonoff et al., 1992). To address this situation and ensure the continued viability and success of the farming industry there has been growing focus on protection and remediation efforts to improve the soil quality of already degraded soils but also to deter the further degradation of the regions inherently high quality soil.

1.3 Grassland Set-Asides as a Remediation tool

Grassland set-asides (GLSA) (also known as grassland-arable rotations and grass-leys) are a management scheme that replaces crop production on arable land with perennial grasses for various economic and ecological purposes, often to improve soil quality after it has been degraded (Baer et al., 2000). Farmers adopting GLSA aim to reduce mechanical disturbance, provide above ground vegetative cover and promote root growth. GLSA have been shown to improve soil structural quality (Haynes and Swift, 1990) increase SOM and thus the pool of organic N, (Gebhart et al., 1994) often increasing the availability of N to subsequent crops, and lowering fertilization requirements to reach optimal yields (Johnston, 1990). They have also been shown to simultaneously provide critical wildlife habitat (Henderson et al., 2000) and are increasingly being used as a wildlife conservation tool. Although GLSA systems employ similar concepts and mechanisms, they will often vary from one another in management and utility, dependent on the location in which they are being employed (Yates, 2014). Some allow for natural regeneration, while others are planted with differing compositions of grass and legumes. They often vary in interval time, short rotations span between 1 and 5 years, while more permanent schemes are utilized from 10 - 30 years (Johnson, 2005). Some GLSA incorporate animal grazing and annual mowing, while others operate with as little intervention as possible after grass establishment (Yates, 2014).

Between 1988 and 2008, the European Union utilized a set-aside program as an economic tool to control the supply of cereal crops (Chalmers et al., 2001), while the United States in 1985 established a reserve program, comprised of millions of hectares of GLSA to reduce soil erosion and to promote wild bird habitat (Johnson, 2005). In Canada, three GLSA programs have been utilized since 1988, to control soil erosion as well as create bird habitat. Of these three programs, only one remains operational today, the GLSA stewardship program used by farmers in the community of Delta, BC (Yates, 2014).

1.4 Grassland Set-Asides in Delta

The GLSA stewardship program has been utilized by over 60 farmers in Delta since 1993. The conservation non-governmental organization, the Delta Farmland and Wildlife trust (DF&WT) provides farmers with a cost share to set-aside, typically degraded parcels of land, and seed them in a mix of grass and legume species for between one to four years and in some circumstances up to six years (Delta Farmland and Wildlife Trust, 2011).The goals of the program are to provide wildlife bird habitat in a critical nesting area, the Pacific flyway, while also allowing farmers the opportunity to remediate soils suffering from structural and nutrient degradation (Delta Farmland and Wildlife Trust, 2011). The wildlife benefits of the program have been well documented, showing increased bird population and diversity with GLSA adoption (Merkens, 2005), less clear have been the impacts on soil remediation. A study by Hermawan and Bomke (1996) showed improved soil aggregation following a 3-year-old GLSA and a recent study by Yates (2014) showed higher aeration porosity and improved aggregate stability following GLSA between two to six years, but given the small sample size and variation in GLSA durations included in the study, did not show conclusive evidence of remediation. While there is some indication that these GLSA are likely to improve soil quality after three years it is unclear how these benefits will impact subsequent crop production, in particular soil N dynamics. Higher concentrations of SOM has been shown to increase rates of N mineralization and PAN (Nevens and Reheul, 2002; Zhao et al., 2016), while in combination with synthetic fertilizer applications, have been shown to increase N mineralization (Zhang et al., 2015), improve crop productivity and reduce long term losses of SOM (Ladha et al., 2011), in some cases even improving SOM formation (Moran et al., 2005). At the same time, it is well know that incorporating organic materials with high (>25) C:N ratios (e.g., GLSA biomass) can temporarily immobilize N (Trinsoutrot et al., 2000; Vinten et al., 2002). How the combination of increased SOM and incorporation of potentially high C:N grasses impact N dynamics in terms of the timing and quantity of PAN after GLSA in Delta is unknown.

1.5 Objectives and Hypotheses

The overarching objective of this study was to determine the impact of 3-year-old GLSA on N dynamics in the production season following the transition of GLSA to cropping. The specific objectives of the study were to:

1. Evaluate the impact of transitioning a 3-year-old GLSA to crop production in terms of the timing and quantity of PAN in the first production season;
2. Elucidate the effect of fertilizer rate and type (organic vs. conventional) and differing times of GLSA incorporation on the timing and quantity of PAN.

This study included two experiments. The first, described in chapter two, was conducted across 8 paired operational fields that had been either in continuous vegetable cropping (Control) or GLSA for the last three years (GLSA) and were sampled over the 2015 and 2016 growing seasons. The second experiment, described in chapter three, was a controlled field experiment established in an existing 3-year-old GLSA. In experiment one I tested the following hypotheses:

H_1: GLSA fields will have higher SOC and total N concentrations than Control fields due to three years of increased C and N additions from grass and legume litter and roots and decreased losses given the elimination of tillage.

H_2: GLSA will supply more PAN on average and cumulatively than Control fields over the season following incorporation.

H_3: The high C:N ratio of the incorporated GLSA will delay PAN until later in the season due to immobilization, resulting in higher amounts of residual soil N in the soil profile after crop harvest.

In the second experiment I tested the following hypotheses:

H_4: Fertilizer application rates will have a significant impact on the timing of PAN. Higher rates of fertilizer will reduce the duration of N immobilization and supply more PAN earlier and in greater quantity than typical application rates.

H_5: Delaying the incorporation of the GLSA will delay the availability of N resulting in lower and later PAN than typical incorporation timing.

H_6: Fertilizer type will affect N dynamics following incorporation. Organic amendments will delay the availability of PAN compared to conventional treatments which will result in earlier and greater availability of PAN.

This study will contribute to a more thorough understanding of the effects of GLSA on soil remediation and benefits to farmers for subsequent crop production specifically related to N dynamics. It will also provide specific management recommendations to farmers following re-introduction of GLSA fields to crop rotation in order to maximize N utility and minimize N losses to the environment.

Chapter 2: Materials and Methods

2. 1 On-Farm Regional Assessment of Grassland Set-asides

2.1.1 Site and Experiment Description

The study was conducted from April 2015 until September 2016 on 16 fields in eight sites. All sites were located in the lower Fraser River delta in the municipality of Delta, British Columbia (49.0847° N, 123.0586° W), 30 km south of the city of Vancouver (Fig 2.1). At each site, a field coming out of GLSA was paired with a nearby Control field that had been in continuous vegetable crop production for the last three years.

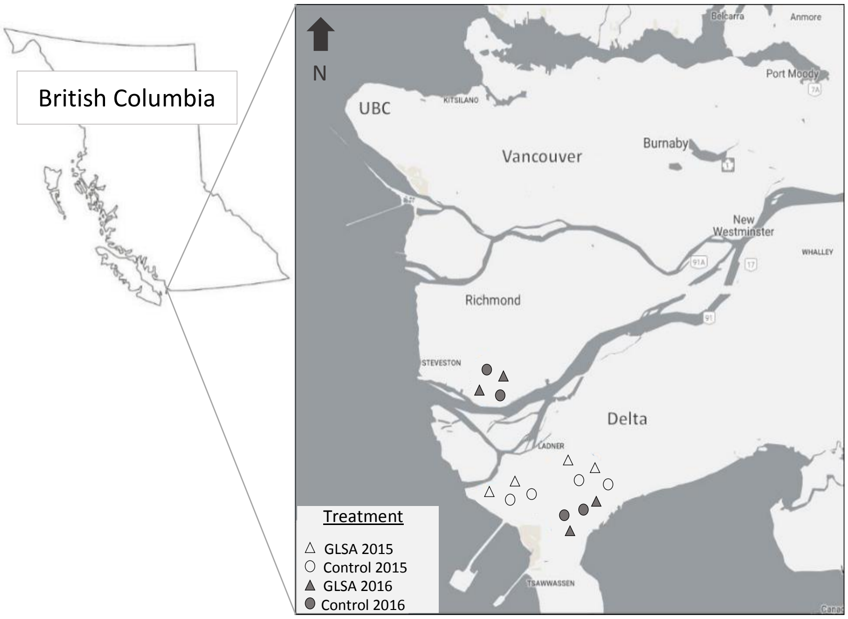

Figure 2.1: Map of the Lower Fraser River and location of study sites located in Delta, BC

The paired GLSA and Control fields were replicated in four sites in the production season of 2015 and then again at another four sites in 2016. Each field pair was selected to be: no more than 3 km apart; on a similar soil type; planted to the same crop; and managed as similarly as possible. The GLSA fields in both years (a total of eight) were planted with a DF&WT designed grass mix (Delta Farmland and Wildlife Trust, 2011), comprised by seed weight of 25% Orchard Grass (*Dactylis glomerata*), 28% Tall Fescue (*Festuca arundinacea)*, 15% Timothy-grass (*Phleum pretense)*, 15% Chewing's Fescue (*Festuca rubra subsp. Commutate)*, 15% Creeping Red Fescue (*Festuca rubra)* and 2% Double Cut Red clover (*Trifolium pretense)* and were set aside for the previous three years. Biomass of the GLSA was assessed prior to mowing, all other observations of each field were started following GLSA cessation, once fields were prepped and planted in a vegetable crop (either beans, potatoes or broccoli). In each growing season, GLSA fields were incorporated 11-59 days before crop planting based on the weather and each farmer's schedule. Incorporation and field preparation of GLSA and Control fields included mowing, pulvi mulching, subsoiling and disking numerous times depending on the site. Farmers tried to keep the management of each paired field (site) as similar as possible. Nutrient management varied by site and included both organic and synthetic fertilizer being applied at various rates (see appendix Table A1 for management details). Study sites were located on silty loam to silty clay loam Gleysols in various soil series with a range of baseline soil properties (Luttmerding, 1981). The average temperature in 2015 was 11.4^{o}C with an annual precipitation of 1141 mm (Min. Of Environment, 2016). The 2015 temperature was 9% higher and precipitation 4% lower than the 30-year historical average. In 2016, the average temperature at sites was 11.2^{o} C with a reported annual precipitation of 1315 mm, 7% and 10% higher, respectively than the 30-year historical average (Fig 2.2).

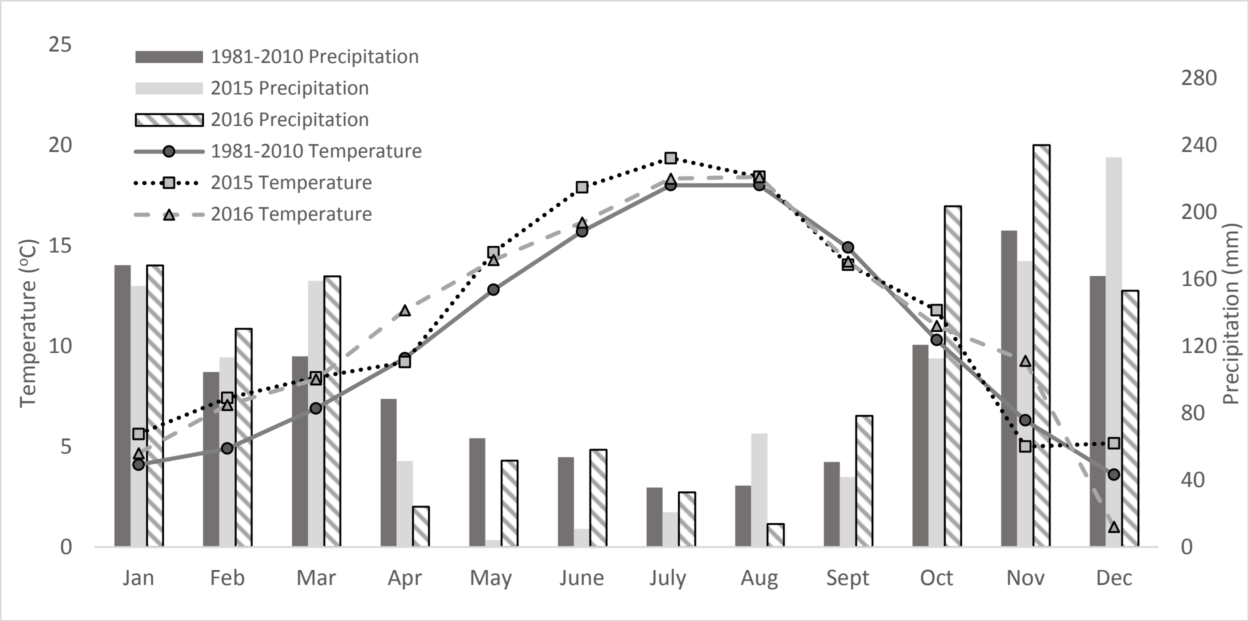

Figure 2.2: Total monthly precipitation and mean monthly temperature data from Vancouver International airport weather station (Min. of Environment, 2016)

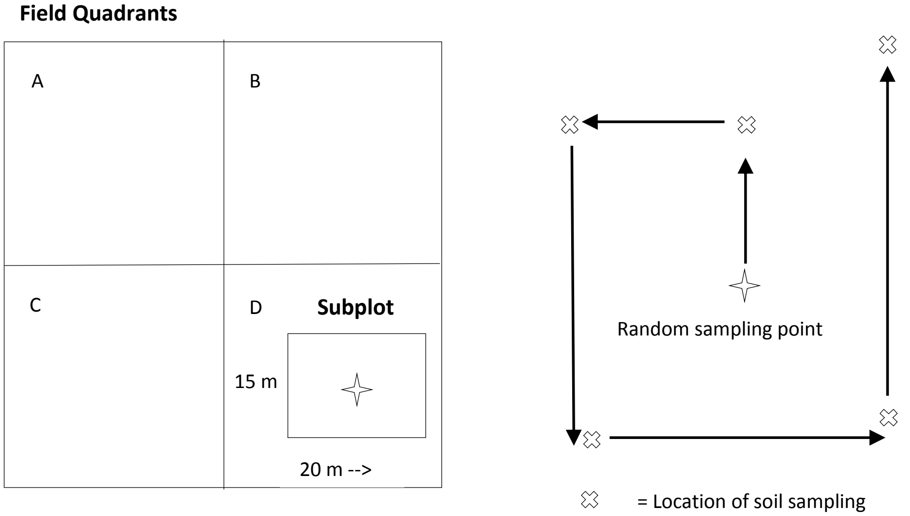

Figure 2.3: Fields spatially stratified into four quadrants and further divided into smaller subplots. Random sampling points indicate where sampling began within each subplot. From this point, a walking pattern was utilized to capture a representative composite soil sample.

2.1.2 Field Sampling

To account for the high spatial variability expected when sampling fields as large as 14 hectares, fields were divided into four equally sized quadrants. Within each quadrant a 15 x

20 m subplot was located randomly using ArcGIS (ESRI 2015. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute) at least 10 m from the field edge. The center of the subplot was used as a starting location for a concentrically increasing walking pattern used to collect soil samples (Fig 2.3). Six soil sub-samples were taken from both the bed and alley of the field and from 0-15 cm and 15-30 cm depths using a Oakfield soil probe and composited by depth for each subplot. Sampling frequency was every two to three weeks in 2015 and every four-weeks in 2016 starting after crop planting and continuing until crop harvest. Harvest dates ranged between 57- 123-days after planting. Paired fields were always sampled on the same day; however, due to normal farm operations, mainly pesticide application and irrigation, not all study sites were sampled on the same day as re-entry times were anywhere from 48-72 hours. Given the constraints of farm operations, soils which were sampled within two weeks of one another were grouped into discrete sampling periods and statistically analyzed as a temporal replication in order to better understand how PAN availability changed throughout the growing season.

2.1.3 Above Ground Biomass Carbon and Nitrogen

Prior to GLSA incorporation, at 12 randomly selected locations, above ground biomass (AGB) was harvested from 1 m x 1 m plots. After weighing wet samples, biomass was dried at 60^{o}C between four to six- days to determine dry matter content (DM). Composite subsamples of AGB from each site were then ball milled and analyzed for carbon (C) and nitrogen (N) using high-temperature flash combustion (Kirsten and Hesselius, 1983) with an Elemental Vario El Cube elemental analyzer (Elementar Analysenysteme GmbH, Hanau, Germany). GLSA C and N concentrations were multiplied by the AGB harvest to determine the additional carbon (AC) and additional nitrogen (AN) added to fields as incorporated residue.

2.1.4 Baseline Soil Properties

Baseline soil samples taken from each field at the 0-15 cm depth and air dried for one week, crushed using a wooden rolling pin to pass through a 2 mm sieve and percentage coarse fraction was calculated for each sample. Subsamples of 100-grams were taken from 25 % of the samples and sent to the Technical Service Laboratory of British Columbia Ministry of Environment and analyzed for soil organic carbon (SOC) and total nitrogen (TN) by dry combustion method (Nelson and Sommers, 1982) and for soil texture using a hydrometer method (McKeague, 1978). The same subset of samples were analyzed at UBC for active soil pH and electrical conductivity (EC) in distilled water at a suspension ratio of 1:2 (McLean, 1982) and for exchangeable pH in 0.4 M $CaCl_2$ at a suspension ratio of 1:20 (Whitney, 1988). All soils were then analyzed using Fourier-transformed mid-infrared spectroscopy (FT-MIR) with a Tensor 37 HTS-XT spectrometer (Bruker Optics, Billerica, MA, USA). Partial least squares (PLS) regression using Quant package in OPUS 7.2 (Bruker Optik GmbH, 2012) was used to develop predictions of soil properties from the relationship between FT-MIR spectra and laboratory results. These models were then used to predict soil properties for the remaining 75% analyzed only by FT-MIR (Yang and Mouazen, 2012).

2.1.5 Plant Available Nitrogen and Residual Soil Nitrogen

Soil samples were transported in coolers to the University of British Columbia (UBC) and extracted using 2*M* potassium chloride (KCl) and then frozen until analysis. Plant available nitrogen (PAN) in terms of nitrate N (NO_3^--N) and ammonia N (NH_4^+-N) were analyzed colorimetriclly using a 99 well microplate absorbance reader (Biorad iMark,Hercules, CA,USA) following the methods of Doane and Horwath (2003). A fresh 20 g subsample of soil was oven dried at 105^{o} Celsius (221^{o}F) until reaching a stable weight to determine soil gravimetric water content (Blake and Hartge, 1986). The final soil sample for each site was taken at harvest or immediately following harvest and analyzed as the residual soil nitrogen (RSN) that would be susceptible to leaching during heavy winter rains. Samples were taken down to 1 m in 2015 at 0-15, 15-30, 30-60, 60-100 cm increments. In 2016 final samples were taken only down to 30 cm. Concentrations were converted areal values (kg ha^{-1}) using bulk density calculated with a pedo-transfer function (Equation 2.1) proposed by (Alexander, 1980).

Equation 2.1: $BD = 1.72-0.294(\%OC)^{0.5}$

Where:

BD = bulk density

OC= concentration of soil organic carbon

2.1.6 Cumulative Nitrogen Supply

Ion exchange membranes were used to determine in situ cumulative PAN over the growing season. Probes with a surface area of 10 cm^{2} , see Eq. 2.2, made from ion resin membranes which adsorb cations and anions, were installed vertically into the top 15 cm of the soil profile. Two probe pairs were placed in each subplot, in close proximity to the random sampling point, one on the planting bed and one in the alley. Probes were installed and retrieved at two to four week intervals and once removed were cleaned using a brush and distilled water. Initially probes purchased from Western Ag Innovations Inc. (Saskatoon Canada) were used starting in the middle of the 2015 growing season for up to 3 time points. Probes were then sent to the Western Ag laboratory for analysis after which ion exchange probes constructed from membrane sheets purchased from GE Power & Water (Ion probes) and utilized for the remainder of the study. Ion probes were brushed clean of soil and extracted together in 2*M* KCl. Cumulative NH_4^+-N and NO_3^--N supply were determined colorimetrically as described above. Once extracted, probes were prepared for re-use by shaking for an hour in a 0.5*M* hydrochloric acid (HCL) solution and recharged by shaking five times in fresh 0.5*M* sodium bicarbonate ($NaHCO_3$) solution (Qian and Schienau, 1996). The correlation between Western Ag probes and GE ion probes was assessed (r^2=0.7) and then used as an equivalent method. Western Ag probes were converted to the same scale as GE ion probes and cumulative PAN was reported over the season. Values of adsorbed PAN were converted from µg ml^{-1} to µg $10cm^2$ using the following equation (Western Ag Innovations Inc., 2010):

Equation 2.2: $$\mu\mathrm{g\ PAN\ 10cm^2} = \frac{\frac{PAN\ \mu g}{ml} * \frac{eluate\ ml}{probe} * \frac{\#\ of\ probes}{tube}}{20\ cm^{-1}} * CF$$

Where:

PAN = either NO_3^--N and NH_4^+-N

Elutant = the volume of extraction per probe

\# of probes = are the number of probes extracted together per individual falcon tube

CF = a conversion factor of 10

2.1.7 Crop yield

At the end of each growing season, 12 subplots of 1 m^2 were harvested to estimate crop yield. Crop subsamples were dried using a Labconco Model Freeze drier (Labconco, Kansas City, MO, USA) at -55°C for between three to five days to determine DM content. Due to the different variety of crops and cultivars grown in the 2015 field season, direct yield comparisons were only made between treatments in the 2016 season. Relative maximum yield calculations were used to assess any correlations between fields planted in different crop cultivars to the effect of nitrogen availability in both field seasons (Equation 2.3). The yield of individual quadrants was subtracted and then divided from the field maximum yield.

Equation 2.3: $$\text{RMY} = \left(1 - \left(\frac{MY-QY}{MY}\right)\right) \text{ x } 100$$

Where:

RMY = relative maximum yield (%)

MY= maximum yield

QY= Quadrant yield

2.1.8 Statistical Analyses:

Baseline soil properties were tested using a linear model (LM) for differences between treatments and years. An ANOVA was used to determine significant effects using treatment, year and the interaction between treatment and year as fixed effects and block as a random effect. Significant differences between treatments and year were differentiated utilizing the Tukey's Honestly Significant Difference (HSD) test. To determine differences in available soil nitrogen and cumulative nitrogen supply between GLSA and Control sites, a linear mixed effects (LME) model was used. All statistical analyses were computed using R Version 3.2.2 (R CoreTeam, 2015) and the (NLME) package version 3.1 (Pinheiro et al., 2017). The LME model allowed for correlation between temporally repeated measurements collected over the season utilizing an autocorrelation structure and also allowed for correlation between samples from the same spatial locations. All depths and fields seasons were analyzed separately as climate, management and patterns greatly differed. In cases where the data was non-normal it was transformed using a log base 10 transformation to meet the assumption of homoscedasticity. Residual soil nitrogen was also analyzed using a LME; model however, the model excluded any time correlation as analyses was run solely on the final sampling point. A Type 3 ANOVA was used to test for significant differences ($p<0.05$) between main effects (GLSA, Control). A correlation matrix was run using Pearson's correlation and utilizing the Corrgram package (Wright, 2017) between various soil properties, sampled and climate variables. A principal components analysis (PCA) was then utilized, and plotted with management variables such as baseline soil properties (TN, SOC, pH, EC and texture) and plant available nitrogen data to help explain any variation in the data using the (FactoMineR) package (Lê, Josse, and Husson, 2008). Variables that were expected to be co-correlated were excluded from the analysis e.g. (TN and SOC).

2. 2 Controlled Field- Level Experiment

2.2.1 Site and Experiment Description

The experiment was conducted from April to August of 2016 on a single 3-year-old grassland set-aside (GLSA) planted in the same grass mix described in 2.1.1. The field was located in the lower Fraser River delta in the municipality of Delta, British Columbia (49.0847° N, 123.0586° W) (Fig 2.1). An area of ~100 m^2 of the field was utilized for this experiment (Fig. 2.4) and the rest was left in set-aside. The site was on Guichon Orthic-Humic Gleysol with a silty clay loam texture in surface and sub surface layers (Luttmerding, 1981). The 2016 climate record of a nearby weather station indicated an average temperature of 11.2^{o}C and annual precipitation of 1,316 mm at the site, 9% and 4% higher than the 30-year historical average respectively (Fig. 2.2)(Min. of Environment, 2016).

Five replicated treatments were established for the experiment that included a combination of incorporating the aboveground biomass (AGB) of the GLSA either at a typical time or late and the synthetic or organic fertilization at the same time as incorporation. Synthetic fertilization done with a granular all purpose blend ammonium sulfate $(NH_4)_2SO_4$ fertilizer with an NPK content of 13-16-10 + 11 (Sulfur). Organic fertilization consisted of a composted chicken manure which contained 1% total nitrogen (TN). A control was also established, which had no fertilizer application and the AGB removed. The five treatment levels were:

(1) High fertilizer (High): Granular fertilizer applied at 200 kg ha^{-1} of plant available nitrogen (PAN) and AGB incorporated

(2) Typical fertilizer (Typical): Granular fertilizer applied at 100 kg ha^{-1} of PAN and AGB incorporated

(3) Late incorporation (Late): Granular fertilizer applied at 100 kg ha^{-1} of PAN and AGB incorporated 14 days after other treatments

(4) Organic (Org): Composted chicken manure applied at 100 kg ha^{-1} of PAN and AGB incorporated

(5) Control (Con): No fertilizer applied and no AGB incorporated

Treatments were applied in a randomized complete block design to account for any spatial variability within the field; blocking by distance from the adjacent road edge.

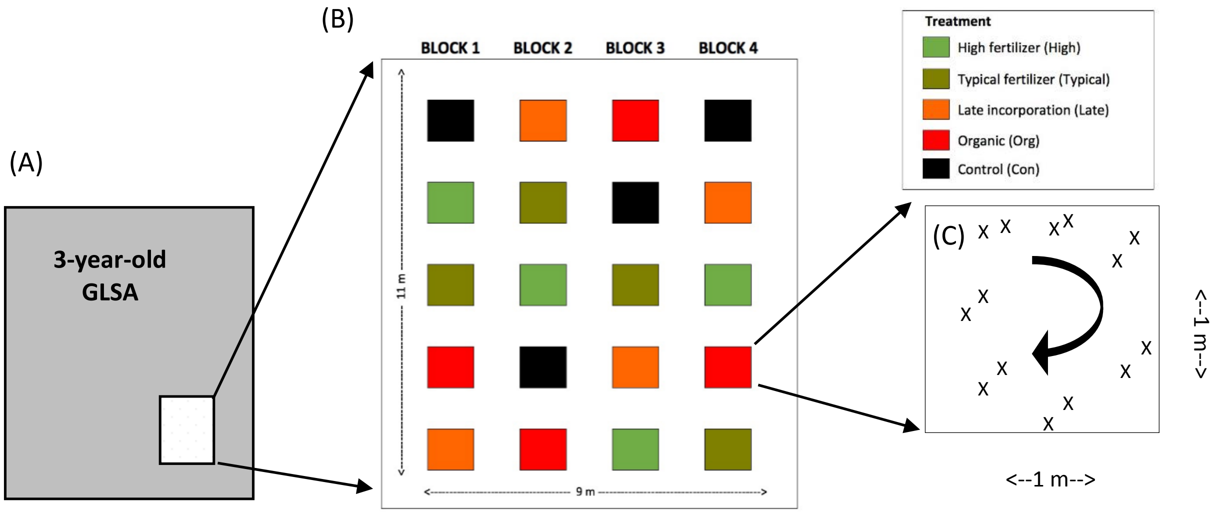

Figure 2.4: A schematic of the ~100 m^2 portion of a 3-year-old GLSA utilized for the experiment (A), illustrating the treatment layout (B) and the clockwise sampling scheme (C) indicate where samples were taken over the growing season in each plot

plot had a 1 m buffer to allow for easy sampling, minimize disturbance and ensure the accurate incorporation of GLSA and application of fertilizers or compost (Fig. 2.4).

The grass in the entire experimental site was mowed using a hand held four stroke brush cutter, ensuring only the AGB residue associated with each 1 m^2 plot stayed within the plot edges. Mowed grass residue was then incorporated by plot using a Mid-Tine Rotor-Tiller with a width of 66 cm and tilling depth of 30 cm. Three passes were made with the rototiller to ensure complete incorporation of AGB and root residue to simulate field preparation typical of farmers in the area. Grass from Con plots were mowed, collected before tilling, dried in an oven at 60^{o}C for three days and weighed to estimate dry AGB.

2.2.2 Field Sampling

Soil samples from plots were collected from 0-15 cm and 15-30 cm depths using an Oakfield soil sampler. Plots were sampled seven times throughout the growing season beginning at the north side of the plot and continuing in a clockwise direction. Two samples per sampling time were taken and mixed to create a composite sample for each depth. Sample timing commenced 7 days after incorporation (DAI) and continued in 7 day intervals until 21 DAI at which point sampling frequency was extended to every 3 weeks until 131 DAI. Initial higher frequency samplings were utilized to observe the rapid nutrient dynamics after biomass and fertilizers were added (Rayns et al., 2009). Reference to DAI when reporting results were made to the relative incorporation date of each treatment, which differs only in the case of the Late incorporated treatment. Soil baseline characteristics, AGB, additional nitrogen (AN), plant available nitrogen (PAN) and cumulative nitrogen supply were all sampled using the methods outlined in chapter 2.1.

2.2.3 Laboratory Analyses

Soil baseline characteristics, AGB, AN, PAN and cumulative nitrogen supply were all analyzed using the methods described in sections 2.1.4 and 2.1.5. Short term aerobic incubations were run at four time points throughout the season (7, 22, 76 and 131 DAI) to assess potentially mineralizable nitrogen (PMN). Subsamples of 8 g collected at 0-15 and 15-

30 cm depths were put into specimen cups and brought to 50% water holding capacity (WHC). Values for WHC were calculated from the mean of the WHC of 10 GLSA fields located within 1-5 km of the study site (Lussier et al. in prep). Samples were left to incubate in the lab for 14 days in a dark cupboard box and every 3-4 days' moisture was adjusted to keep constant. Temperature in the lab room ranged from 21-25^{o}C throughout the incubation. After 14 days samples were extracted with 2*M* potassium chloride (KCl) and then frozen until analysis (Parfitt et al., 2005; Scott et al., 1998). Values for PMN were determined by analyzing samples colorimetrically as described for PAN analysis in section 2.1.5. The PMN rate was then calculated as (Curtin, 2007):

Equation 2.4: Potentially Mineralizable Nitrogen Rate = $\frac{Ni - Nf}{Incubation\ days}$

Where:

N_i = Initial mineral N extraction

N_f = Final mineral N extraction

Incubation days = 14

2.2.4 Statistical Analyses:

To determine differences in available soil nitrogen and cumulative nitrogen supply between treatments effects (High, Typical, Late, Org or Con) a linear mixed effects (LME) model was used with treatment, date and the interaction between treatment and date as fixed effects and block as a random effect. Depths and sample dates were analyzed separately as there was a significant interaction between sample date and treatment. Non-normal data was log10 transformed to meet assumptions of normality and homoscedasticity. Models which did not meet these assumptions even after transformation were analyzed using the non-parametric Wilcox test function. A Type 3 ANOVA was used to test for significant differences ($p<0.05$) and differences between treatment means were then determined using Tukey's Honestly Significant Difference (HSD) test. All analyses were computed using R Version 3.2.2 (R Core Team, 2015) and the (NLME) package version 3.1 (Pinheiro et al., 2017).

Chapter 3: Results and Discussion

3. 1 Results of On-Farm Regional Assessment of Grassland Set-asides

3.1.1 Above Ground Biomass and Additional Carbon and Nitrogen

In both years at incorporation the GLSA biomass was composed primarily of grasses with only trace amounts of clover present (<2%). The amount of AGB and the associated amount of C and N that was incorporated varied by year. In the 2015 season, 2,662 to 7,725 kg ha^{-1} of AGB was incorporated into the soil, whereas the 2016 season, 4,161 to 6,667 kg ha^{-1} was incorporated. The C and N concentrations of AGB also varied by year, in 2015 the average C content was 41% and average N was 1.45% compared to 2016 where C was 42.5% C and 1.84% N. Thus, the average C:N ratio varied widely at 31 and 25 in each season, with the C:N ratio significantly higher in 2015 than 2016 (Table 3.1) ($p<0.05$) respectively. In 2015, an average of 2,446 kg C ha^{-1} and 86 kg N ha^{-1} was incorporated as residue and then in 2016, 2,439 kg C ha^{-1} and 101 kg N ha^{-1}.

Table 3.1: Above ground biomass (AGB), carbon to nitrogen (C:N) ratio, and additional nitrogen (AN) means and associated standard errors of the grassland set-aside in both 2015 and 2016 growing season. Different letters indicate significant differences ($p<0.05$).

Year	AGB kg ha^{-1}	C:N ratio	AN
2015	6024 (637)	31 (2.3)a	86.4 (12.5)
2016	5709 (345)	25 (2.2)b	101.4 (6.6)

3.1.2 Baseline Soil Properties

There were no significant differences found between baseline soil properties at the 0-15 cm depth (Table 3.2). Soil SOC ranged from 2.46 % to 2.91%, while TN ranged from 0.21 to 0.26%. The average pH across all the fields in both seasons was 5.63 and the EC 1.94 ds m^{-1}.

Table 3.2: Baseline soil property means and associated standard errors from 0-15 cm depth taken in 2015 and 2016 seasons showing: soil organic carbon (SOC), total nitrogen (TN), electrical conductivity (EC). Statistical analyses were run but no differences were found between any baseline soil properties ($p<0.05$).

Year	Treatment	SOC %	TN %	pH	EC ds m^{-1}	Sand (%)	Silt (%)	Clay (%)
2015	GLSA	2.54 (0.3)	0.22 (0.02)	5.82 (0.04)	2.7 (0.6)	6.9 (0.7)	65.7 (0.8)	28 (0.9)
	Control	2.46 (0.4)	0.21 (0.03)	5.85 (0.04)	2.85 (1.6)	8.7 (1.9)	64 (1.2)	27.3 (1)
2016	GLSA	2.73 (0.5)	0.23 (0.04)	5.29 (0.34)	1.03 (0.2)	7.9 (0.6)	65.5 (0.7)	27.7 (0.9)
	Control	2.91 (0.5)	0.26 (0.04)	5.58 (0.2)	1.2 (0.3)	6.8 (0.9)	64.2 (0.6)	28.9 (0.6)

3.1.3 Plant Available Nitrogen and Residual Soil Nitrogen

The pattern of both the timing and overall average PAN between GLSA and Control differed between the 2015 and 2016 growing seasons, following GLSA incorporation (Fig 3.1 and 3.2). In 2015, average available soil NO_3^--N in the 0-15 cm depth was significantly ($p<0.05$) higher at sample one and again at sample four and six (Fig. 3.1.A). The greatest difference was observed at sample four with the GLSA supplying 29 kg ha^{-1} more than control fields. Sample six was indicative of RSN of the GLSA and Control at the end of the 2015 season and showed GLSA left 8 kg ha^{-1} more residual NO_3^--N in the soil after harvest. Overall the seasonal average NO_3^--N in 2015 was 26% greater in GLSAs than Control ($p<0.05$) (Fig. 3.1.B). In the 15-30 cm depth the seasonal average NO_3^--N was 19% greater in GLSAs ($p<0.05$) (Fig. 3.1.D) but was only significantly higher in sample four (Fig. 3.1.C). In contrast, during the 2016 field season NO_3^--N in the 0-15 cm depth was 41 % higher in Control than GLSAs ($p<0.001$) (Fig. 3.1.F). Control fields were also 25% greater ($p<0.01$) in the 15-30 cm depth compared to GLSA (Fig. 3.1.H). At both depths during the 2016 season, NO_3^--N was only significantly higher in sample two (Fig. 3.1.E and G).

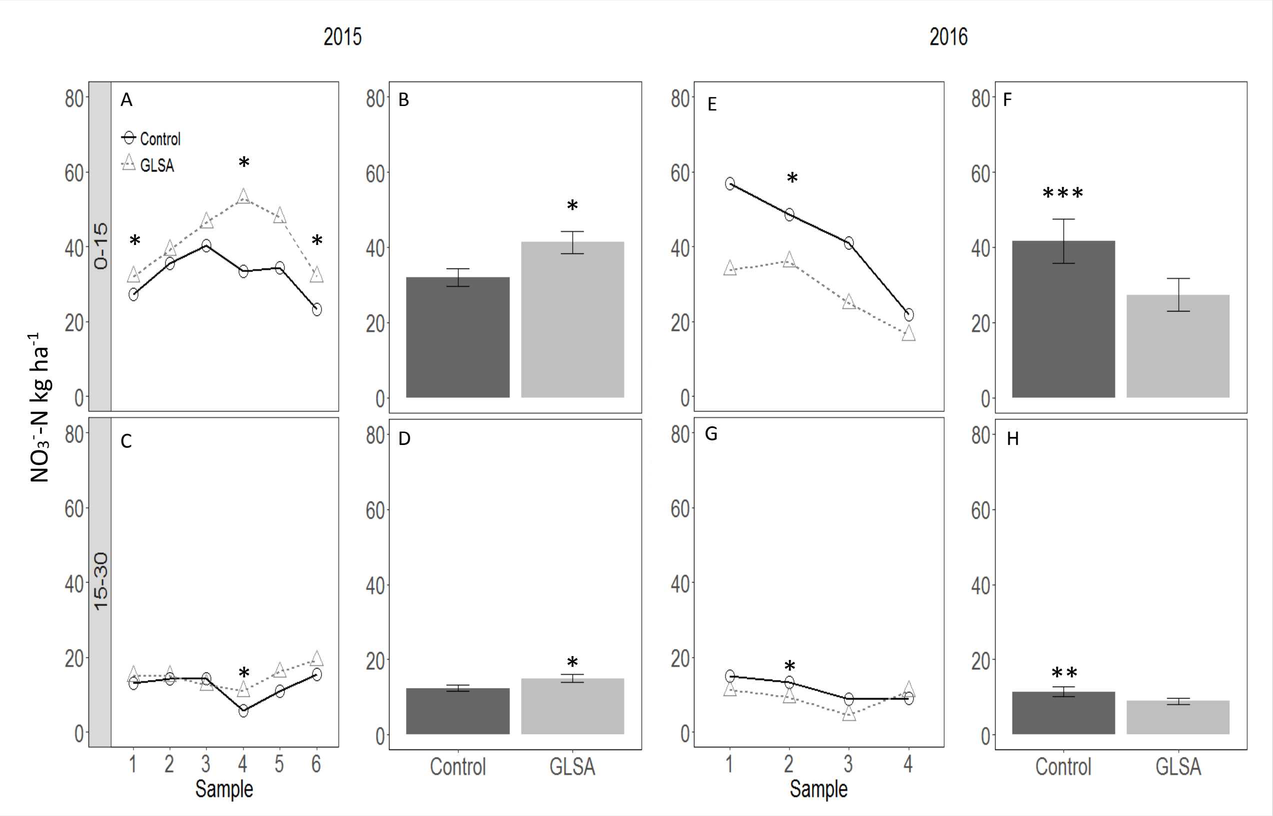

Figure 3.1: Soil nitrate (NO_3^--N) from the 0-15 cm depth by sampling time (A) and seasonal average (B) and the 15-30 cm depth by sampling time (C) and seasonal average (D) for 2015; the 0-15 cm depth by sampling time (E) and seasonal average (F) and the 15-30 cm depth by sampling time (G) and seasonal average (H) for 2016. Error bars represent one standard error of the mean. Significant differences between GLSA and Control averages are indicated by *($p<0.05$), ** ($p<0.01$), and *** ($p<0.001$).

Average NH_4^+-N during the 2015 season followed a similar trend to NO_3^--N in both soil depths. At samples one, four and five, NH_4^+-N was significantly higher ($p<0.05$) in the GLSA than the control in the 0-15 cm depth (Fig. 3.2.A) and the overall seasonal average NH_4^+-N was 20% higher in GLSAs than control fields ($p<0.01$) (Fig. 3.2.B). In the 15-30 cm depth NH_4^+-N was only significantly higher in GLSA at sample three (Fig. 3.2.C) and the overall seasonal average NH_4^+-N was not significantly different between the two treatments (Fig.

3.2.D). In 2016, there were no significant differences in NH_4^+-N either by sample period or overall average for both depths (Fig. 3.2.E-H).

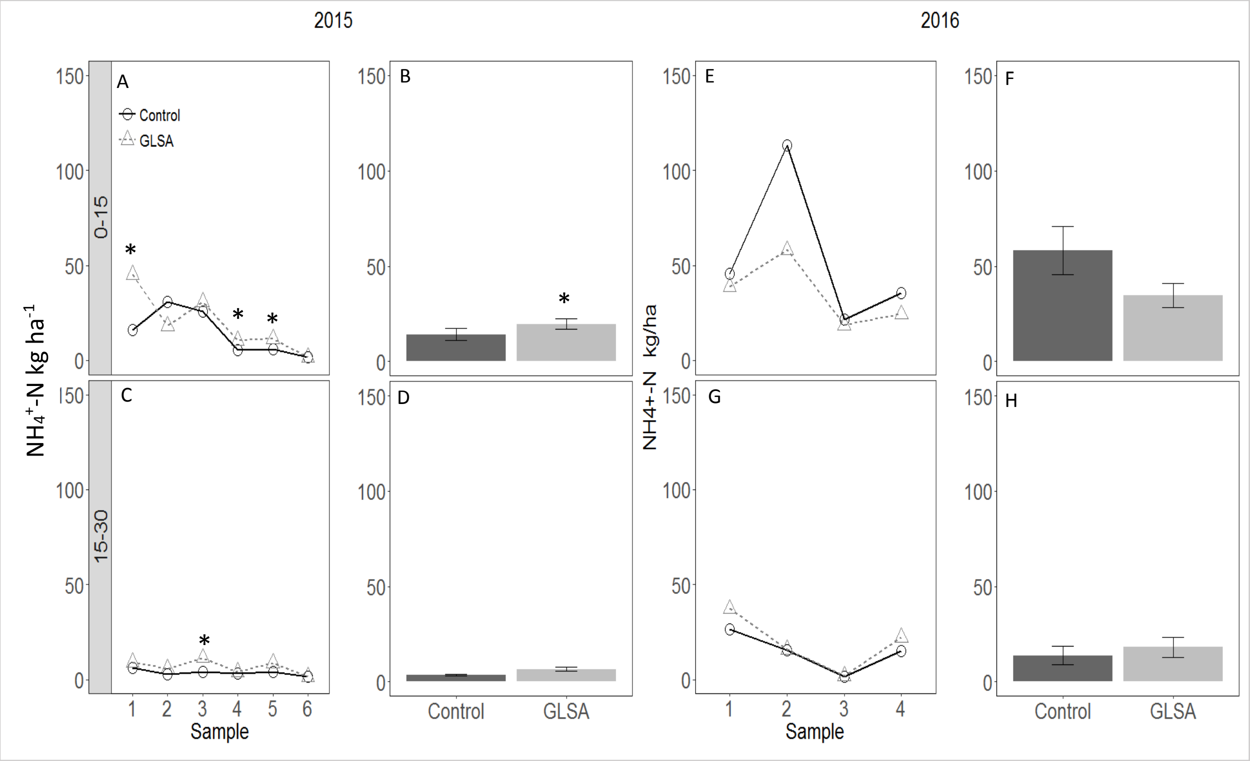

Figure 3.2: Soil ammonium (NH_4^+-N) from the 0-15 cm depth by sampling time (A) and seasonal average (B) and the 15-30 cm depth by sampling time (C) and seasonal average (D) for 2015; the 0-15 cm depth by sampling time (E) and seasonal average (F) and the 15-30 cm depth by sampling time (G) and seasonal average (H) for 2016. Error bars represent one standard error of the mean. Significant differences between GLSA and Control averages are indicated by *(p<0.05).

3.1.4 Cumulative Plant Available Nitrogen Supply

In the 2015 growing season, cumulative probe NO_3^--N was not significantly different until sample five ($p<0.001$) where GLSA sites supplied 67% more NO_3^--N than Control fields (Fig. 3.3.A). In contrast, during the 2016 growing season Control sites supplied 80% more NO_3^--N by the end of the season ($p<0.01$) (Fig. 3.3.B). There were no significant differences observed in cumulative NH_4^+-N in the 2015 season but by the end of the season in 2016 the Control had three times more NH_4^+-N ($p<0.01$) than the GLSA (Fig. 3.3.C and D).

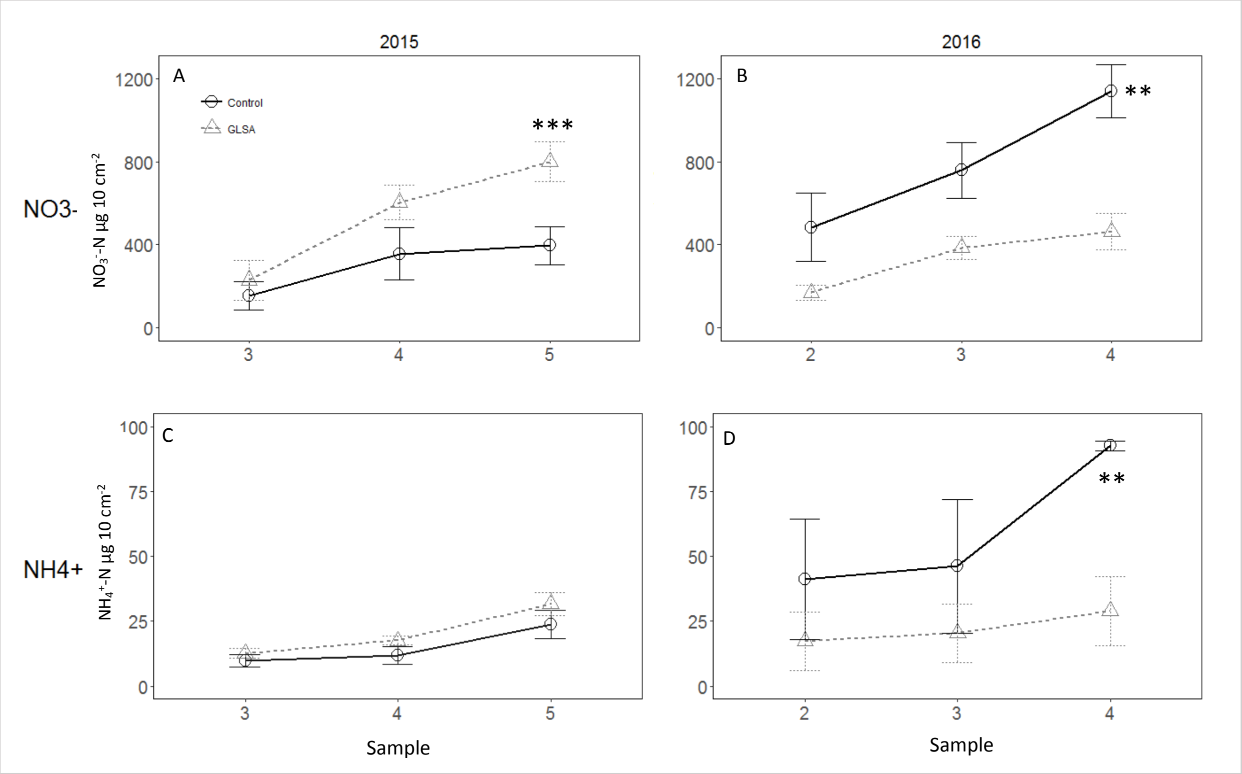

Figure 3.3: Cumulative nitrate (NO_3^--N) supply over the 2015 growing season (A) 2016 growing season (B); and cumulative ammonium (NH_4^+-N) supply over the 2015 growing season (C) 2016 season (D). Error bars represent standard error of the mean. Significant differences are indicated by *($p<0.05$), ** ($p<0.01$), and *** ($p<0.001$).

3.1.5 Crop yield

Of the three sites harvested in the 2016 season, two were planted in Yukon potatoes with yields ranging from 33,156 kg ha^{-1} to 38,201 kg ha^{-1} and one planted in broccoli with yields ranging from 337 kg ha^{-1} to 1104 kg ha^{-1}. There were no significant differences in crop yield between treatments.

3.1.6 Principal Component Analysis

A PCA grouped by GLSA and Control indicated substantial overlap between these groups (data in appendix Fig A1), but when the same data was grouped by crop type and growing season some differentiation was apparent (Fig. 3.4.A). Dimension 1 explained 28.4% of the variation with high positive loadings (>0.5) for average soil NH_4^+-N and clay content which characterized potato crops from the 2016 season, which clearly separated out from the other crops and seasons. These correlated negatively to pH along dimension 1, and characterized bean fields from 2015 and broccoli fields from 2016. Dimension 2 explained 24% of the variation with high loadings for SOC and sand content, and negatively correlated to silt content. Overall, the PCA of crop type and growing season (Fig. 3.4.A) illustrated a clear separation of the 2016 potato fields, but no clear distinction of the other groups. When the results were analyzed separately for GLSA and Control a much clearer pattern emerged. When results for the GLSA sites alone from both seasons were plotted and grouped by crop and fertilizer type (Fig. 3.4.B) there was a clear separation of fields that were in organic beans, organic broccoli and conventionally grown potatoes. Dimension 1 explained 34.1% of the variation with high positive loadings for average NH_4^+-N, SOC, AN and plant nitrogen (PN) and soil clay content characterized primarily by potato crops with conventional fertilizer applications. High negative loadings for plant C:N ratio (PCNR), average NO_3^--N and days between planting (of the crop) and incorporation (DBPI) of the GLSA were also displayed along this dimension and characterized by bean crops with organic amendments. Dimension 2 explained 23.8% of the variation with high loadings for average NH_4^+-N, SOC, AN and PN and additionally high positive loadings for AGB and AC, which explained variation in both the organic bean and conventional potatoes and were negatively correlated with fields of organic broccoli (Fig. 3.4.C). When Control fields alone were plotted and grouped by crop type and fertilizer treatments the majority of conventional potato fields clearly separated out from the organic beans and broccoli which in this case were completely overlapping. Dimension 1 explained 34.3% of the variation with high positive loadings for pH and SOC characterized somewhat by organically amended fields. A high negative loading for sand content was also found along this dimension. Dimension 2 explained 25.9 % of the variation in the plot with high positive loadings for silt and clay and high negative loadings for average NH_4^+-N explaining much of the variation in potato crop fields with conventional fertilizer applications.

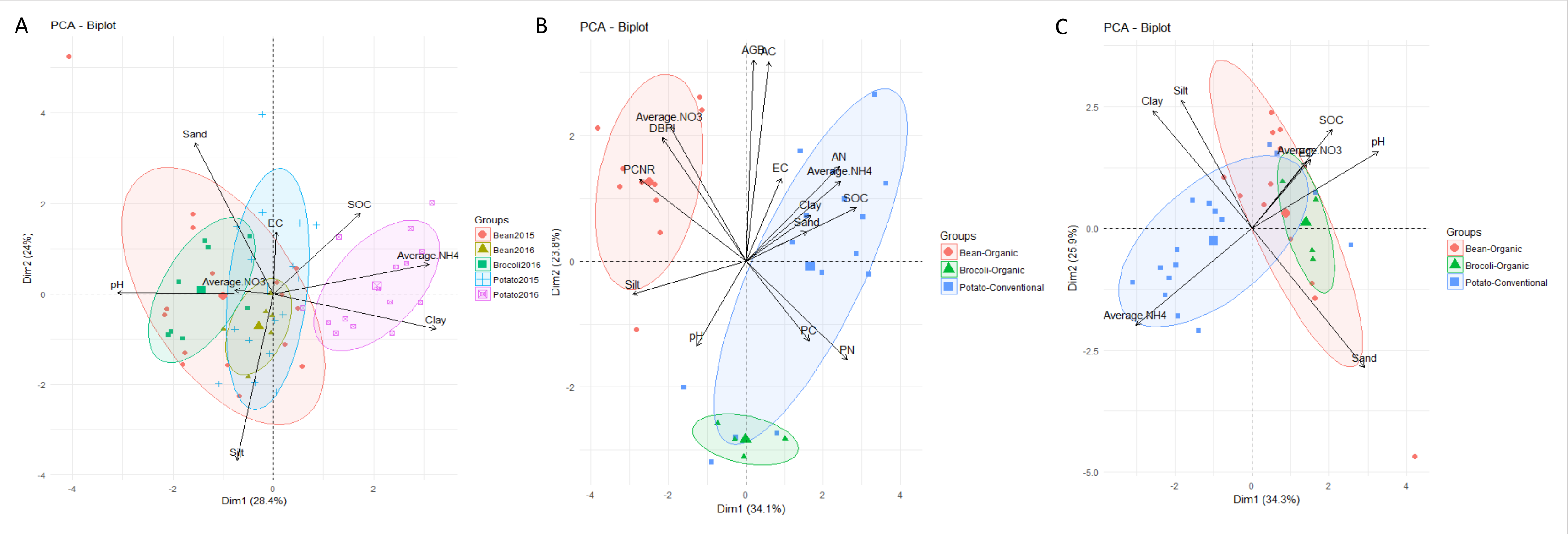

Figure 3.4: Principal Component Analysis (PCA) biplot with variables (SOC: soil organic carbon, EC: electrical conductivity, pH: soil pH, AGB: above ground biomass, AC: additional carbon, AN: additional nitrogen, PC: plant carbon %, PN: plant nitrogen %, PCNR: plant carbon to nitrogen ratio, DBPI: days between planting and incorporation, Sand, Silt, Clay, Average NO3: nitrate (NO_3^--N), Average NH4: ammonium (NH_4^+-N) for fields treated in GLSA and Control grouped by crop type and growing season (A); for GLSA fields only grouped by crop and fertilizer type (B); for Control fields only grouped by crop and fertilizer type (C).

3.2 Discussion of On-Farm Regional Assessment of Grassland Set-asides

3.2.1 Timing and Quantity of Plant Available Nitrogen

Despite a lack of difference in SOC or TN between continuously cropped fields and fields transitioned to cropping after three years of GLSA, significant treatment effects, albeit contrasting, were observed for both NO_3^--N and NH_4^+-N in the 2015 and 2016 growing seasons. In both seasons, NO_3^--N availability in the GLSA did not peak until several weeks after the Control, whereas NH_4^+-N availability peaked before the Control in 2015 and at the same time in 2016. In 2015, NO_3^--N was, however, found to be significantly higher in GLSA early in the season, seven days after planting (DAP), again at 46-56 DAP and at the final sample, 80-100 DAP. NH_4^+-N was also found to be significantly higher in GLSA seven DAP and again between 46-68 DAP. In 2015, GLSA supplied on average 13 kg ha^{-1} more NO_3^--N and 5 kg ha^{-1} of NH_4^+-N down to 30 cm over the season. Ion exchange probes which tracked cumulative PAN supply corroborated this trend in 2015, and showed in the 2016 season, overall the GLSA supplied significantly less PAN than Control. These results show that although PAN mineralization may peak later in the season in GLSA compared to the Control, the GLSA can still contribute to higher seasonal average PAN or GLSA may indeed reduce PAN compared to the Control.

These confounding results were inconsistent with other GLSA studies which found only increased PAN benefits for crop production. Chalmers et al. (2001) for example followed fields after incorporation of 3-year perennial rye grass and perennial grass-white clover mixed GLSA on various soil types in England and found PAN benefits early in the production season of 30 kg ha^{-1} down to 90 cm depth compared to annually cropped fields. Another study by (Lloyd, 1992) using a balance sheet approach and an nitrogen cycling model, assessed the relative PAN supply of five-year old, grazed GLSA following spring and autumn ploughing and estimated PAN benefits of only 22 kg ha^{-1}, while a study on a sandy loam soil in Ghent, Belgium tracked PAN in the first growing season following spring ploughing of a 3-year-old grazed GLSA and found a N benefit of 124-150 kg N ha^{-1} compared to continuously cropped fields (Nevens and Reheul, 2002). A study by Torstensson (1998) on a sandy loam soil in Sweden looked at the effects of different GLSA and green manure compositions with varying incorporation times on available N and found an additional 110 to 200 kg PAN ha^{-1} (down to 90 cm).The highest amounts were found in green manure treatments of pure White clover (*Trifolium repens*) followed by White clover, Red clover (*Trifolium perenne*) mixed with a small percentage of Rye grass (*Lolium perenne*). While many of these studies assessed PAN far deeper than my study, it is clear that benefits accrued here were not as large as observed elsewhere.

One explanation for the limited PAN benefit seen in this study could be the dominant grass composition and high C:N ratio of the GLSA compared to other studies which have much higher concentrations of nitrogen fixing legumes. The biomass composition and C:N ratio of the GLSA can play a vital role in the quantity and timing of nitrogen availability (Vinten et al., 2002). The C:N ratios observed in this study in both years was higher than the 25:1 and should result in N immobilization. Incorporating primarily high C:N grasses tend to mineralize less N compared to those composed of leguminous crops (Ruffo and Bollero, 2003) and the amount of available N can often depend heavily on the percentage composition of legumes (Eriksen, 2001; Linden and Wallgren, 1993). Torstensson (1998) on a GLSA in Sweden found varying C:N ratios of different plant compositions ranging from 12-25 with the lowest ratios found in material containing white clover (*Trifolium repens*) and the highest found in grass species; Timothy grass and Meadow-fescue (*Festuca pratensis*). The same study also found a considerably higher PAN in the soil profile after the incorporation of pure white clover GLSA compared to a white clover with grass mixed GLSA while Chalmers et al. (2001) incorporated biomass residues with a much higher clover composition (24-60 %) than the current study resulting in higher PAN. Eriksen (2001) in Denmark, found that cultivation of temporary GLSA resulted in a nitrogen contribution of 15-25 kg ha^{-1} more from grass-clover GLSA compared to grazed GLSA fields. In contrast to all these findings, Davies et al. (2001) found that pure grass GLSA in Scotland mineralized an additional 205 kg N ha^{-1} in the first year after the incorporation compared to grass-clover GLSA, although they hypothesized to see the opposite. The authors attributed these findings to a significantly higher percentage of Total-N in the grass residue compared to the clover.

In this study, the percentage of clover in the biomass immediately before incorporation was < 1 % of the total composition. The lack of clover survival after three years in GLSA is expected as it comprised only 2% by seed weight of the original planting mixture supplied to farmers for set-aside establishment (Delta Farmland and Wildlife Trust, 2011) and given that GLSA fields are not commonly managed while in set-aside (e.g. fertilized, cut or grazed). Grazing has been found to benefit the spread of clover (Swift and Vipond, 1991) and could potentially help maintain or even increase clover proportion in the GLSA. Increasing the percentage of legume seeds in the GLSA planting mix or allowing grazing could help build the capacity for soil mineralization (Christensen et al., 2009).

Another explanation for the varied performance of the GLSA in the two years could be the timing of farmer incorporation of GLSA. In 2015, GLSA fields were incorporated by the middle of May due to considerable rainfall in April, forcing farmers to delay operations until soils were dry enough to handle heavy machinery without compaction. In 2016, set asides were incorporated almost a month earlier, by the middle of April, due to a drier spring and the earlier workability of fields. This may have resulted in the clear difference in the timing of the peak PAN in the GLSA, where delayed incorporation resulted in the later peak seen in 2015, which may have resulted in an asynchrony with plant uptake. The high composition of grasses and higher C:N ratio of the GLSA biomass in 2015 could also explain the delayed mineralization. Further, the PCA analysis highlighted the importance the timing of GLSA incorporation as critical to PAN timing and quantity. The DBPI in our study ranged from 11-59 days with the largest gap found in fields planted with beans (i.e. 32-59 days after incorporation). The larger gap in DBPI correlated to high values of average NO_3^--N, which could have resulted from the increased time for mineralization of organic N in AGB to NH_4^+-N and then to NO_3^--N where high carbon residues were incorporated or from missing earlier spikes of NH_4^+-N in fields when planting was delayed.

In the current study, GLSA fields performed similarly to one another in both seasons supplying almost identical amounts of PAN on average down to 30 cm depth (81 in 2015 and 80 kg PAN ha^{-1} in 2016). The difference in relative N benefits between 2015 and 2016, could be explained by a difference in soil quality of the fields included in the study, particularly the Control fields in 2016 which appeared to be less degraded than other fields in my study. The 2016 Control fields, although not significant for any individual property, tended to have higher values of SOC, TN, lower pH and lower salinity values and on average supplied almost two times as much PAN (124 kg PAN ha^{-1}) than 2015 Control fields (60 kg PAN ha^{-1}) and 40 % more than GLSA fields in either year. Variable degradation on different fields could be driving this observation as total net mineralization and immobilization dynamics are not only affected by incorporated residue, but by background mineralization of humus (Torstensson, 1998) and a higher level of organic matter could have increased N mineralization rates in 2016 (Sincik et al., 2008).

The results of the PCA provide some support for these explanations of varied levels of degradation in our study sites and also illustrate the potential impact farm management can have on subsequent N dynamics. The PCA indicates fields planted in potato crops, which were all conventional, particularly those in 2016, were distinct from fields that were cropped using organic methods. While there is some indication that the potato fields in 2016 may have been less degraded there are also corresponding differences in the soils and management in these fields that could also help explain why the PAN in the Control was higher in 2016 than 2015. The distinction of the 2016 potato fields was largely driven by loadings of average NH_4^+-N, SOC and clay content. It may be that clay content is a key factor explaining the relative differences in PAN between the two years. Given that soils are more likely to retain nutrients and protect SOM in aggregates, the relative benefits of short-term GLSA rotations would not be as great as those in soils with lower concentrations of clay (Bot and Benites, 2005; Rice, 2002).

3.2.2 Implications of Nitrogen Dynamics

Synchronizing nitrogen availability and crop demand is imperative to maximizing crop benefits and minimizing detrimental impacts to the environment when transitioning GLSA fields back into crop production. Nitrogen, if synchronized correctly to crop demand in an available form, can be utilized efficiently to increase crop yields and minimize fertilizer applications rates for farmers (Waddell et al. , 2000). In this experiment, three sites were harvested for crop yield in the 2016 season for comparison of GLSA and Control, however no significant differences between treatments or any strong correlations with average seasonal or cumulative PAN were observed. Other studies have found that green manure and GLSA containing legumes which contribute additional PAN following incorporation have had positive impacts on subsequent crop yields. A study by Sincik et al. (2008) in Turkey, on a Vertisolic typic soil type with a sandy loam texture and a long term average precipitation of 163 mm found potato yields increased by 12-15% following incorporation of green manures; Common vetch (*Vicia sativa L.*) and Faba bean (*Vicia faba L.*) when compared to non-nitrogen fixing cover crop Winter wheat (*Triticum aestivum L.*) due to higher PAN. A study by Nevens & Reheul (2002) showed similar results with silage maize grown on incorporated 3-year-old grazed GLSA, significantly out yielding paired control sites by 85% with no additional fertilizer application, while Neeteson (1989) investigated the impact of red clover and Alfalfa (*Medicago sativa L.*) on subsequent potato crop yields and found higher potato yields following leguminous crop rotation due to additional N benefits of between 67-99 kg N ha^{-1} compared to oats (*Avena sativa L.*). Given the marginal PAN increase observed in 2015 in my study and lack of PAN increase or differences in crop yield in 2016 the benefits of GLSA for subsequent cropping remain unclear. The climate greatly differed from 2015 to 2016 as indicated by (Fig 2.2) with 2015 being a drier and warmer spring, the driest on record in British Columbia and 2016 being a colder and wetter spring, however, this did not appear to affect GLSA ability to mineralize N, as GLSA performed similarly in both seasons. Thus, it is likely that the difference in relative performance is due to difference in Control fields sampled in this study. This regional assessment of GLSA was based on a relative assessment to paired Control fields and therefore the GLSA performance is contingent on the level of degradation of paired fields. A more representative way then to assess the impact of the GLSA as a remediation tool and benefits to subsequent crops may be to focus specifically on comparisons to more highly degraded fields in the region.

To better understand the impact of GLSA on crop yield further research needs to be conducted following GLSA incorporation, with similar crop varieties grown as they respond variably to PAN (Sincik et al., 2008), and with similar past farm management and baseline soil properties.

Nitrogen can also have adverse effects if made available at the wrong crop growth stage and can lead to negative impacts on crop yield, crop quality and to the surrounding environment. Nitrogen abundance can reduce starch content in potatoes, cause excessive vine growth and potentially delay crops reaching maturity (Riley, 2000). If N release is delayed by immobilization and if not taken up by the crop, it will remain in the soil typically in the form NO_3^--N , which is known to be highly susceptible to leaching into the ground water (Linden and Wallgren, 1993; Stark and Porter, 2005; Waddell et al., 2000).

In this experiment, during the 2015 season, GLSA fields left an average of 13 kg NO_3^--N ha^{-1} more RSN at the 0-30 cm depth compared to Control, while in 2016 no significant differences in RSN were found. Many studies have found GLSA fields to increase the likelihood of ground water contamination, especially in the first year back in a crop rotation. For example, a study on 3-year-old grass clover GLSA on sandy soils in Denmark observed large amounts of N leaching between 63-216 kg N ha^{-1} in the first year after spring ploughing (Berntsen *et al.*, 2006), while a study at the Rothamsted Experimental station with 30 year average annual precipitation of 650 mm, observed losses estimated at 118 kg N ha^{-1} in the first winter after incorporation of a 3-year-old rye-grass-clover GLSA (Johnston et al., 1994). Alternatively, Vinten et al. (2002) on a study in Scotland with average annual rainfall of 870 mm on a sandy loam topsoil over a sandy clay to clay loam found only minimal N leaching (6.4-19.6 kg N ha^{-1}), over three years after ploughing of grazed grass clover GLSA. The study also found that tile drainage leaching correlated well (r^2= 0.83) with the amount of RSN in the soil measured in the autumn of the same year. In the current study, a much lower leaching potential for GLSA fields going into the winter was observed in both years, which could be a result of the lower clover content in these set-asides and more efficient use of N by the crop. Further studies should attempt to track mineralized N over the winter season to better evaluate the environmental impact of GLSA.

The specific timing and quantify of N mineralization and immobilization is crucial to crop health and yield, the regional study discussed in this chapter showed some patterns of PAN response to the incorporation of a 3-year GLSA. The subsequent study explored GLSA incorporation in a more controlled design, at a plot scale with fixed sampling dates to elucidate the relationship between timing and fertilizer quantity and type on N mineralization and availability to crops.

3. 3 Results of Controlled Field- Level Experiment

3.3.1 Above Ground Biomass and Baseline soil properties

Similar to the field study described in Chapter 2, the incorporated AGB was largely comprised of grasses with an average C content of 43% and average N content of 1.56%. The average C:N ratio was 28.5 and AGB on average supplied 48 kg ha^{-1} of AN to the soil. Baseline soil properties in the 0-15 cm depth were similar in all blocks; SOC was on average 2.53% while TN was 0.24%, the average pH was 4.94 and the EC 0.98 ds m^{-1}.

3.3.2 Plant Available Nitrogen

The timing of PAN supply differed between treatments at multiple sample times in the study at the 0-15 cm depth (Fig. 3.5.A and B). No differences in either NO_3^--N or NH_4^+-N were observed for the 15-30 cm depth (data not shown). Differences in in NO_3^--N between treatments did not occur until June 22 (Fig. 3.5.A) 56 DAI when the High and Typical treatments had significantly higher ($p<0.05$) soil NO_3^--N than the Late, Org, and Con. June 22 was clearly the peak of NO_3^--N availability when High treatment was 56 kg NO_3^--N ha^{-1}, and Typical was 37 kg NO_3^--N ha^{-1}, 3.6 and 2.4 times, more than Con respectively. The Late treatment which was incorporated two weeks after other treatments, had significantly ($p<0.05$) lower NO_3^--N on June 22, 21 DAI than the other synthetic fertilizer treatments and was not different from the Org and Con. As expected, given the application of NH_4 based fertilizer, available NH_4^+-N was significantly different among treatments earlier than observed for NO_3^--N (Fig 3.5.B). In samples taken on May 18th (21 DAI), High and Typical treatment NH_4^+-N was 25 and 11 times more than the Con respectively and differed significantly from all other treatments ($p<0.05$) but not from one another.

By June 1st,35 DAI, the NH_4^+-N in the High and Typical treatments dropped substantially while the Late treatment on the same date but at 21 DAI increased, all three supplying close to ten times more NH_4^+-N as Con and four times as much as Org treatments ($p<0.05$). By June 22nd,56 DAI, High and Typical treatments peaked for the second time and the Late treatment at 42 DAI had it highest observed peak all season, all three were again significantly different from the Org and Con ($p<0.05$). At this sampling point the High and Late treatments supplied 36 and 27 times more than Con while the Typical treatment had 16 times more NH_4^+-N than Org and Con treatments.

Between the middle of June until August 31st, NO_3^--N and NH_4^+-N availability both decreased substantially (Fig 3.5.A and B), as did soil moisture (from 22 to 16%). In samples taken on August 3rd, 98 DAI the High treatment supplied five times more NO_3^--N than Org treatments (Fig 3.5.A), but was not significantly different ($p<0.05$) than any other treatment including the Con. When the final sample was taken on September 5th, 131 DAI, NO_3^--N in all treatments increased slightly, following an increase in soil moisture to 20% and at this point, High and Typical treatments had significantly ($p<0.05$) higher NO_3^--N than Con and Org treatment. High treatments supplied three times and Typical 46% more than Con but no more than the Late treatment at 117 DAI. At the same sampling point, the High treatment also supplied 25 times more NH_4^+-N, than Con treatments and significantly more than all other treatments ($p<0.05$) (Fig 3.5.B) except for Typical which supplied 11 times more than

Con and differed significantly from both the Org and Con ($p<0.05$) but not from the Late. The Org treatment was not significantly different from the Con treatment at any sampling date throughout the experiment in either NO_3^--N or NH_4^+-N or in the seasonal averages of NO_3^--N, NH_4^+-N or PAN down to the 30 cm depth (Table 3.3).

Overall the seasonal average PAN was greatest in the High treatment which supplied significantly more ($p<0.05$) (Table 3.3) PAN than all other treatments, and five times more than the Con treatments whereas the Typical and Late treatments were 3.2 and 2.7 times higher and significantly more ($p<0.05$) than the Con but not than one another. The High treatment also supplied significantly more ($p<0.05$) seasonal average NH_4^+-N and NO_3^--N compared to the Late, Org and Con treatments down to 30 cm depth and only significantly more ($p<0.05$) than the Typical treatment in NH_4^+-N at 15-30 cm depth where values were low. Similar to seasonal average PAN results, Typical and Late treatments supplied similar amounts of seasonal average NO_3^--N, NH_4^+-N than one another, but contrastingly also supplied similar amounts to the Org and Con treatments, except in NH_4^+-N at 0-15 cm depth, where they supplied four and six times more ($p<0.05$) than Org and Con treatments.

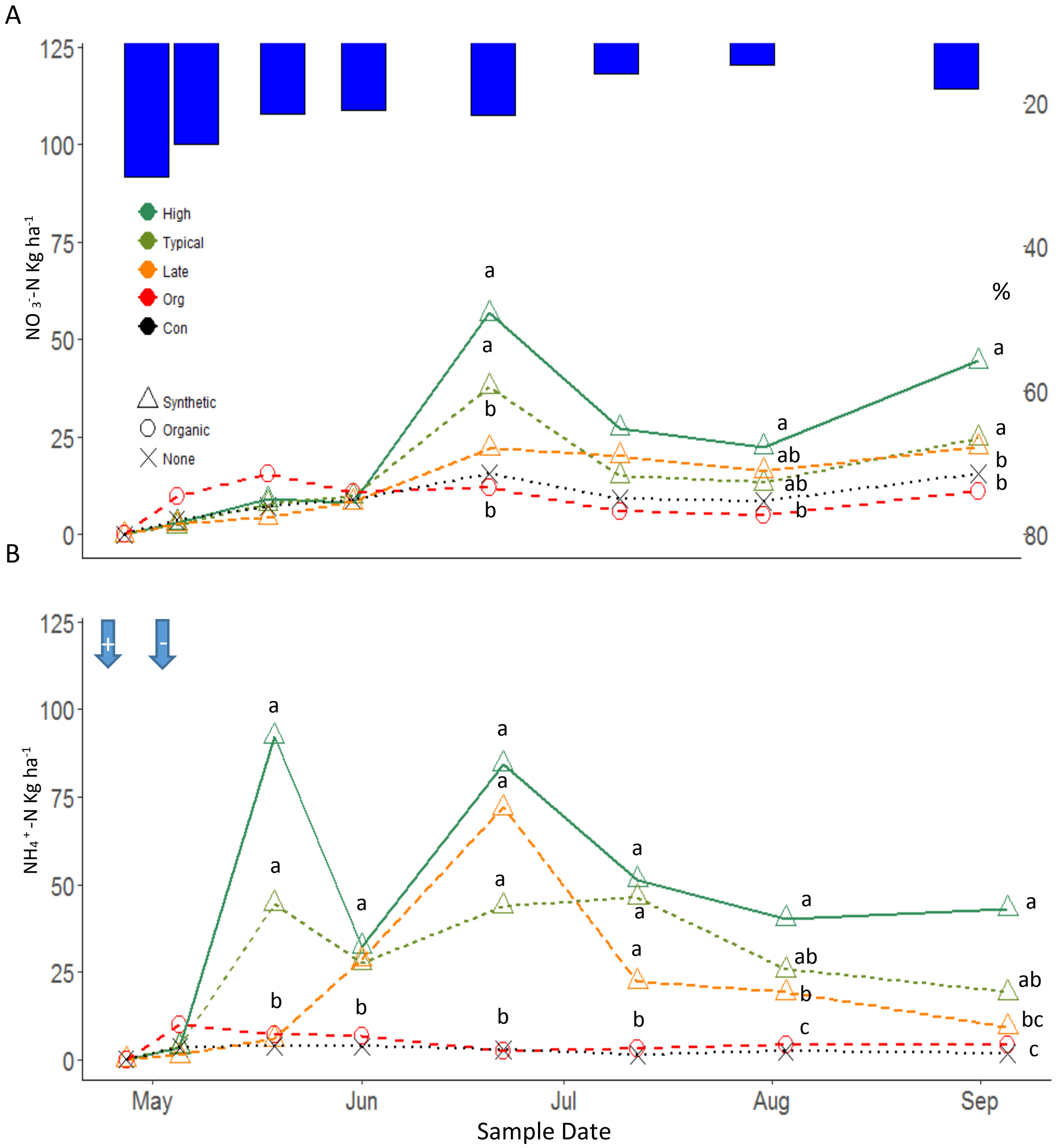

Figure 3.5: Comparison of plant available nitrogen at the 0-15 cm depth for High fertilizer(High), Typical fertilizer (Typical), Late incorporation (Late), Organic (Org) and Control (Con) treatments showing: Average soil nitrate (NO$_3^-$-N) over the growing season (lines and left axis), and average soil moisture for all treatments (bars and right axis) (A) and average soil ammonium (NH$_4^+$-N) (B). Triangles indicate synthetic fertilizer, open circles are organic fertilizers and X symbols no amendments. Incorporation of the grassland set-aside and fertilizer application is indicated with dark arrows where + for all treatments except for Li (-) which was incorporated 14 days later. Results are means of four replicates and different letters indicate significant differences (p<0.05).

Table 3.3: Seasonal averages for nitrate (NO_3^--N), ammonium (NH_4^+-N) at the 0-15 and 15-30 cm depth and their total plant available nitrogen (PAN) for 0-30 cm and associated standard errors in brackets for High fertilizer (High), Typical fertilizer (Typical), Late incorporation (Late), Organic (Org) and Control (Con) treatments. Different letters indicate significant differences ($p<0.05$).

Treatment	NO_3^--N kg ha^{-1} 0-15 cm	NO_3^-N kg ha^{-1} 15-30 cm	NH_4^+-N kg ha^{-1} 0-15 cm	NH_4^+-N kg ha^{-} ^{1}15-30 cm	Total PAN kg ha^{-1}
High	21.5 (3.9) a	3.1 (0.5) a	43.3 (6.7) a	3.7 (1.5) a	71.3 (1.8) a
Typical	13.8 (2.4) ab	1.9 (0.5) ab	26.4 (4.5) ab	1.4 (0.26) ab	43.6 (3.7) b
Late	12.1 (2.3) b	2.5 (0.5) ab	19.8 (6.8) b	1.6 (0.5) ab	36 (6.4) b
Org	8.8 (0.9) b	2.1 (0.4) ab	4.7 (0.6) c	0.9 (0.1) b	16.4 (0.8) c
Con	8.6 (1) b	1.8 (0.3) ab	2.3(0.3) c	0.7 (0.1) b	13.4 (1.2) c

3.3.3 Cumulative Nitrogen Supply

Cumulative NO_3^--N supply (Fig 3.6.A) showed no significant differences between treatments ($p<0.05$) until the middle of July. Between June 1st until July 22nd probes adsorbed a much higher rate of available ions in all treatments, increasing cumulative NO_3^--N substantially compared to previous sampling points. The Con and Org treatments were close to 25% greater, the Late treatment was five times greater and the High and Typical treatments were six and seven times greater than the previous sampling periods. Starting July 12th, 76 DAI, significant differences ($p<0.05$) were observed that remained consistent, and increased only incrementally, until the last probes were extracted on September 5th at 131 DAI. The final sampling point represented the total cumulative NO_3^--N supply and here the High treatment supplied three times more cumulative NO_3^- -N than Org and Con treatments ($p<0.05$). There were no differences in cumulative NO_3^--N supply between the Org and Con treatments and also no significant differences between the High and Typical treatments as was also observed in soil NO_3^- -N averages. The Typical treatment also supplied 2.5 times more cumulative NO_3^--N than the Org treatment slightly higher than the seasonal soil NO_3^- -N average but total cumulative NO_3^--N was not different between the High and Late treatments.   Results of cumulative NH_4^+-N supply (Fig 3.6.B) showed NH_4^+-N increased steadily beginning at plot incorporation until the end of the season. On June 1st, 35 DAI, High and Typical treatments supplied significantly more cumulative NH_4^+-N than Org and Con treatments ($p<0.05$). By June 22nd High, Typical treatments 56 DAI and Late at 42 DAI all supplied significantly ($p<0.05$) more NH_4^+-N than the Org and Con treatments and the High treatment was also significantly higher than the Late treatment. By July 12th and again on August 1st, High, Typical and Late treatments were all significantly ($p<0.05$) higher than other treatments. At the final sampling point, a large spike in cumulative NH_4^+-N in all treatments was observed. The final sampling point was indicative of total cumulative NH_4^+-N supply and showed that High treatments supplied significantly ($p<0.05$) more cumulative NH_4^+-N than all other treatments except for the Typical, and supplied six times more NH_4^+-N than the Con, whereas the Typical treatment supplied three times more than the Con treatment. These results were corroborated by our seasonal average NH_4^+-N data although soil averages showed the High and Typical treatments supplied much higher amounts, 16 times and six times more respectively than Con treatments. There were no differences between the Late, Org, or Con treatments in total cumulative NH_4^+-N where the seasonal soil averages showed Late treatments to supply significantly higher ($p<0.05$) amounts than Org and Con treatments.

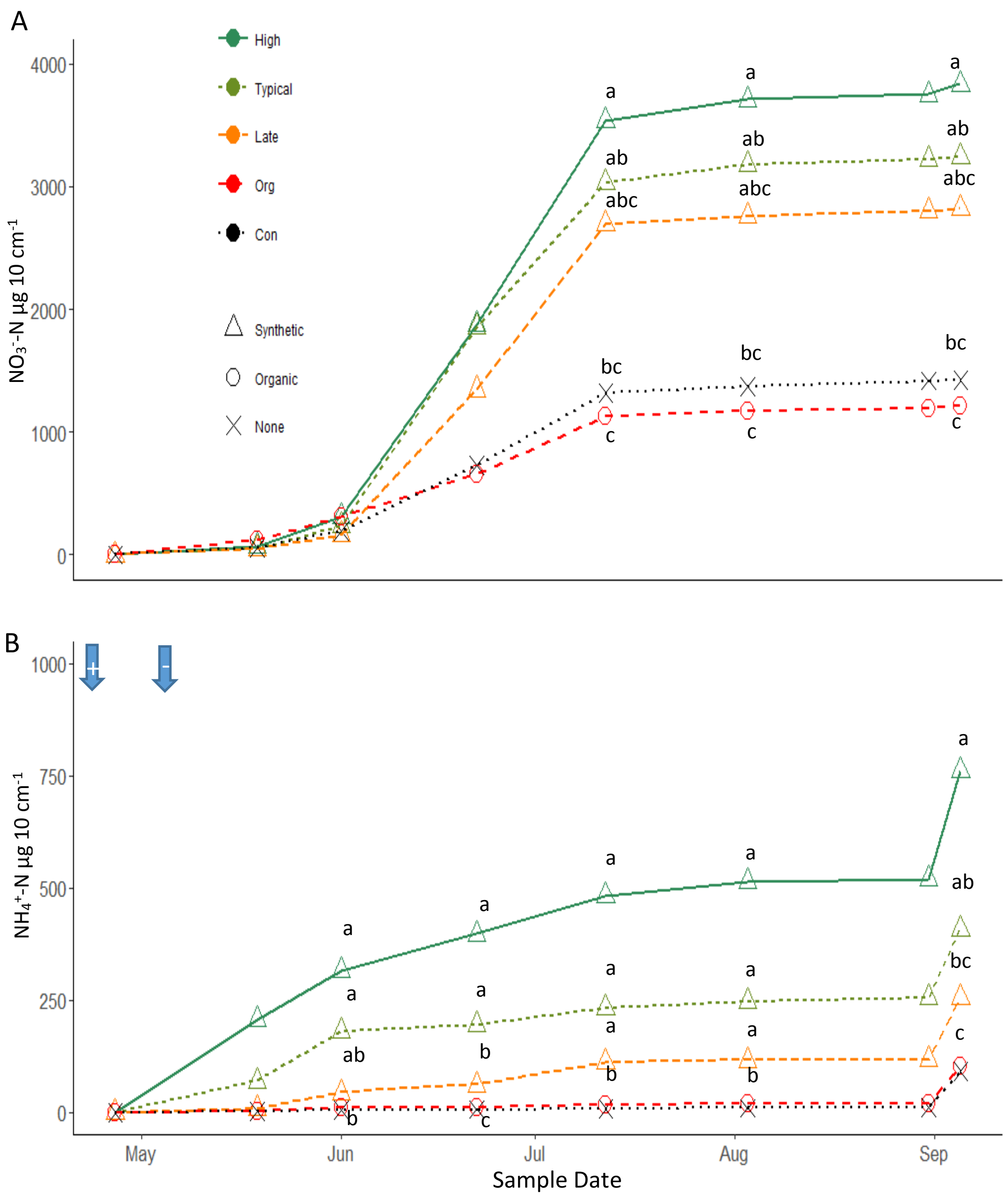

Figure 3.6: Cumulative nitrogen supply for High fertilizer(High), Typical fertilizer (Typical), Late incorporation (Late), Organic (Org) and Control (Con) treatments showing: cumulative nitrate supply (NO_3^--N) (A) and ammonium supply (NH_4^+-N) (B) over the growing season. Triangles symbols indicate synthetic fertilizer, open circles are organic fertilizers and X symbol no amendments. Incorporation of the grassland set-asides and fertilizer application is indicated with arrows where “+” for all treatments except for Li which is indicated with a “- “. Results are means of four replicates and different letters indicate significant differences ($p<0.05$). Note that Y axes scale differs between figure (A) and (B).

3.3.4 Potentially mineralizable nitrogen

Potentially mineralizable nitrogen was dominated by NO_3^--N as it is likely after 2 weeks all NH_4^+-N was nitrified. Mineralizable NO_3^--N displayed no significant differences from the first 2-week incubations. (Fig 3.7.A). In the second incubation the High treatment mineralized on average 4.3 kg ha^{-1} day^{-1} of NO_3^--N significantly ($p<0.05$) more than all other treatments (Fig 3.7.B) except for the Typical treatment. At the fourth and final incubation (Fig 3.7.D) the High treatment on average mineralized 2.7 kg ha^{-1} day^{-1} of NO_3^--N, significantly ($p<0.05$) more than the Org and Con treatments but was not different than the Typical or Late treatments.

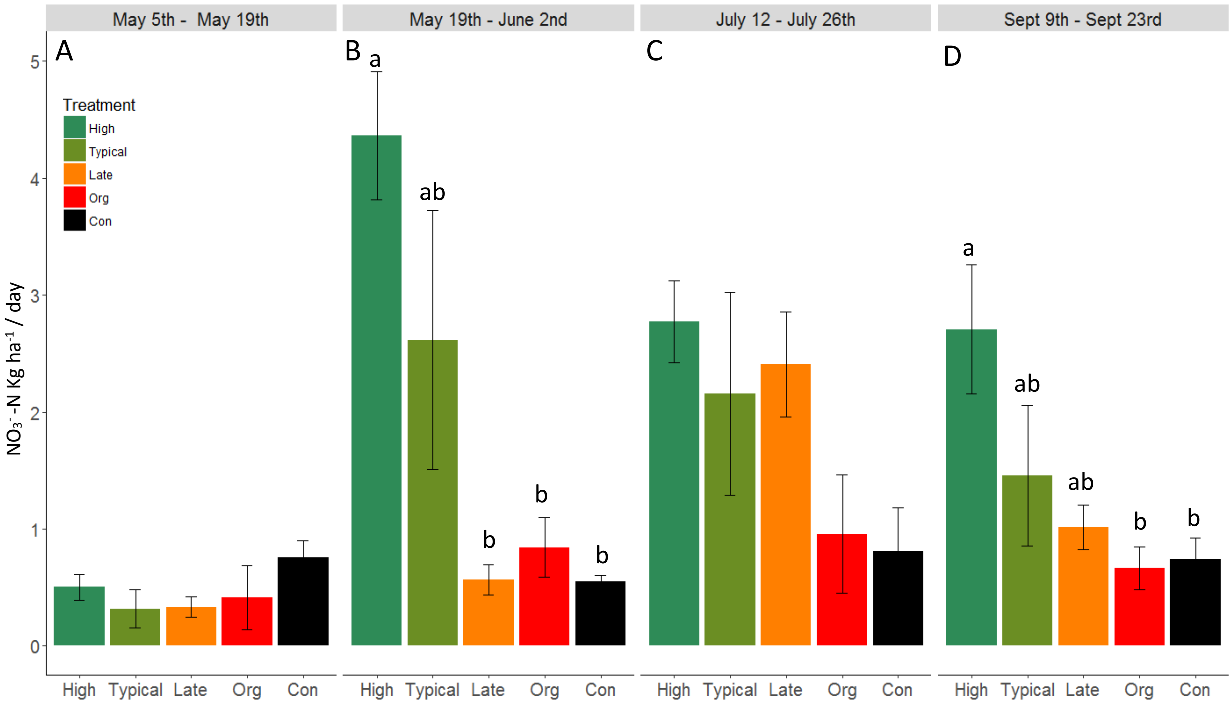

Figure 3.7: Potentially mineralizable nitrogen for High fertilizer (High), Typical fertilizer (Typical), Late incorporation (Late), Organic (Org) and Control (Con) treatments showing mineralized (NO_3^--N) over 2-week incubations from May 5th -9th (A) May 19th to June 2nd(B) and from July 12th – July 26th(C) and from September 9th – 23rd (D) Different letters indicate significant differences ($p<0.05$).

3. 4 Discussion of Controlled Field- Level Experiment

3.4.1 Timing and Quantity of Plant Available Nitrogen

The findings of this controlled field experiment indicate that fertilizer type, application rate and the timing of incorporation all had a significant effect on the timing and quantity of PAN over the growing season. PAN in NH_4^+-N form peaked in the soil for the first time 21 DAI in the High and Typical treatments. Our observations of PMN supported these results and showed no significant differences between any treatments in the first one to three weeks after GLSA incorporation. The cumulative NH_4^+-N supply did not reflect the patterns observed in the soil NH_4^+-N samples, showing a steady increase from incorporation until the end of the season, rather than any discernable peaks and overall showed much lower rates of adsorption compared to NO_3^- -N, although soils showed the opposite trend. This could be due to the fine textured nature of our soils which have a high surface area and high charge densities (Balard et al., 1997) and could potentially fix NH_4^+ (Bot and Benites, 2005) if they are 2:1 clay minerals (Scherer et al., 2014), leaving it less abundant for probes to adsorb.

Concentrations dropped rapidly following this initial NH_4^+-N peak, likely due to nitrification by microbial communities, as directly following this drop the greatest NO_3^--N peak for the season occurred on June 22nd, 56 DAI. At this peak, High and Typical applications supplied similar amounts, but significantly more NO_3^--N than all other treatments. Cumulative NO_3^--N supply displayed similar trends to soil NO_3^--N, with no noticeable differences before the beginning of June. However, from June 1st until July 11th large amounts of NO_3^--N were adsorbed, supporting the middle of June date as the most favorable time for NO_3^--N supply. For example, Davies et al. (2001) found slightly earlier timing of PAN after the incorporation of grazed grass-clover mix GLSA in Scotland where the NH_4^+-N availability peaked within two weeks and NO_3^--N within three weeks attributed to lower C:N ratios of incorporated biomass.

The initial NH_4^+-N peak observed in our study can likely be attributed the synthetic fertilizer application, which would have provided enough PAN for microbial growth while also maintaining an adequate level of N in the soil solution. A second NH_4^+-N peak occurred on June 22nd, 56 DAI in all treatments with synthetic fertilizer applications. The secondary peak could be explained by delayed N turnover from the incorporated grass biomass with a high C:N ratio, which would have spurred the growth of the microbial population and would have decomposed N from AGB.

By July 12th, 76 DAI, the only significant differences in soil NO_3^--N were found between High, Typical, and Late treatments, which supplied significantly more NO_3^--N than Org and Con treatments. Similar to soil NO_3^--N patterns, cumulative NO_3^--N values plateaued after this peak and did not increase at all for the rest of the sampling time, supporting the hypotheses of either N loss through leaching or nitrification, or continued immobilization by microbial bodies until after the end of the sampling season.

Throughout sampling we observed spikes and drops in PAN that tracked with changes in soil moisture. Significant ($p<0.05$) negative correlations were found between soil moisture, and NO_3^--N and NH_4^+-N with r values of -0.47 and -0.44 respectively. There was also a significant and positive correlation ($p<0.05$; $r = 0.45$) between average air temperature and NO_3^--N (data in appendix Fig A2). This is commonly observed in nitrogen studies as decomposition, mineralization and microbial biomass are often tightly coupled to favorable soil conditions like soil moisture and temperature (Wells et al., 2013). Given that there was no plant interaction involved in this experiment as no crops were planted, the observed PAN declines could not be due to plant uptake, the decline in NO_3^--N could be explained by: (1.) leaching below the soil profile; (2.) denitrification losses to the atmosphere or (3.) microbial immobilization. There were, however, no observed increases in NO_3^--N concentrations from samples taken from the 15-30 cm depth (data not shown) hence, leaching would have had to have been below this depth which is unlikely given that these plots were not irrigated and rainfall was minimal during the sampling period.

Cumulative NO_3^--N and NH_4^+-N results at the end of the season, 131 DAI showed that doubling the fertilizer application rate did not increase the total cumulative release of PAN. This was supported by results of seasonal average NO_3^--N and NH_4^+-N down to 30 cm depth but was not supported by the results of seasonal average PAN, which showed the High treatment to release significantly more PAN than all other treatments and that Typical and Late treatments released similar amounts.

These results also indicated that doubling the application rate of fertilizer did not reduce the duration of immobilization or supply more PAN early in the season in either NO_3^--N or NH_4^+-N forms. However, delayed incorporation did appear to supply less PAN in both forms early in the season and appeared to delay the initial peak in NH_4^+-N from 21 DAI to 42 DAI. Late incorporation plots also never appeared to peak in NO_3^--N over the whole sampling season, unlike other treatments with synthetic fertilizer applications. PMN data supported this observation, showing that not until the third incubation period did the Late treatment at 62 DAI begin mineralizing similar amounts of NO_3^--N to that of the High and Typical treatments. Results show that delaying incorporation by even 14 days could delay N mineralization processes and leave fields with inadequate time for N to be fully mineralized and released by microbial bodies into the soil solution as NO_3^--N.

The High and Typical treatments in the controlled experiment were most comparable to the management of the on-farm regional GLSA fields. These two treatments applied similar fertilizer rates and were incorporated within 2 weeks of the regional GLSA fields. These treatments appeared to release PAN at a similar magnitude to the regional GLSA fields in NH_4^+-N, which peaked at 21 DAI and 56 DAI and NO_3^--N at 56 DAI. At both NH_4^+-N peaks, the High treatment supplied 95 and the Typical 45 kg ha^{-1} compared to the regional GLSA fields which supplied 55 kg ha^{-1} and 30 kg ha $^{-1}$respectively, at their own peaks. Soil NO_3^--N showed similar patterns with High treatments supplying 65 and Typical 40 kg ha^{-1} at 56 DAI compared to regional GLSA fields at 38 kg ha^{-1}. Comparing the end of season cumulative PAN showed that High and Typical treatments supplied substantially more PAN at the end of season compared to regional GLSA estimates, the High treatment supplying eight times more cumulative NO_3^--N and 3.7 times more cumulative NH_4^+-N while the Typical treatment supplied three times more NO_3^--N and four times more NH_4^+-N by the end of the season.

The higher supply of PAN in both soil and probe data from the plot experiment compared to the field scale was not unexpected given the lack of crop N uptake in the plot experiment and also given that no roots were present to compete for ion adsorption with probes like they were at the on-farm experiment. It is also possible that given the lack of root interaction in the plots and given the higher sand and lower clay composition of the plot experiment field that leaching occurred below the 30 cm depth. Also given that sampling in the plot experiment began at incorporation while in the on-farm experiment sampling began at crop planting it could be that earlier spikes in PAN were missed in our sampling, contributing to the observed higher supply from the plot treatments.

These results also indicate that an important factor determining PAN following GLSA is the type of fertilizer used (i.e., organic or conventional). In this experiment, treatments with synthetic N inputs maintained PAN levels throughout much of the season, while the Org treatments did not mineralize much nitrogen at all and performed most similarly to the Con treatment. The Org treatment performed extremely poorly relative to all synthetic fertilizer treatments releasing two to three times less seasonal average PAN. The PMN data also show that the Org and Con treatments did not release much NO_3^--N in any incubation periods. These results are supported by observations found in both soil and probe samples, where plots treated in synthetic fertilizers appeared to supply significantly more PAN than Org treatments. Although not explored in this study, different configurations of synthetic N (i.e., ammonium phosphate vs ammonium nitrate) would likely also have an effect on the N dynamics following incorporation and should be considered in observations of timing of N availability in the growing season.

Other studies have also found fertilizer type to play an important role in N dynamics and N availability. For example, Doltra et al. (2011) investigated the effect of fertilizer type and quantity on subsequent N availability, yield and quality in a 3-year crop rotation in Denmark and found fertilizer type to be the most important factor in growing spring barley and winter wheat. The study also found that mineral N fertilizers paired with pesticides resulted in the highest yields when compared to an organically managed pair. A four-year study by (Tu et al., 2006) on a loamy sand in North Carolina observed the impact of transitional strategies, moving from conventional to organic management on crop yield, microbial biomass and soil nitrogen availability. The study found microbial biomass C and N were enhanced by organic management, and responded quicker than other soil indicators such as TN or SOC. They also found that N mineralization was greater in organically managed soils; however, these differences were not followed by similar impacts on crop yield in the first two years of the study, actually finding reduced yields by 15-20 % in the first two years compared to conventionally cropped pairs. A study by (Parfitt et al., 2005) investigated the effect of long term conventional and organic pasture management on the microbial and nutrient pools and N availability in New Zealand and found no evidence that N mineralization was enhanced or depressed under organic vs conventional management, ascribing the soil N status in soils to be mediated primarily by the soil phosphorous status and to past legume crop performance.

In my study, Org treatments were amended with composted chicken manure with 1% TN and a calculated mineralization rate of 15%. Mineralization rates from organic amendments can be quite variable (Cabrera et al., 2005) and are known to delay N release compared to readily available synthetic fertilizers (Herencia et al., 2011) depending on a range of properties of both the organic input and the soils that they are being applied to (e.g., temperature, moisture, texture, C:N ratio) (Cabrera et al., 2005). It is possible that the calculated mineralization rate underestimated the amount required to reach 100 kg of PAN within the plot which could explain the drastic undersupply of PAN from this treatment.

3.4.2 Implications of Nitrogen Dynamics

These results illustrate some of the management decisions that likely affect how much PAN a GLSA will provide relative to continuously cropped fields. These results showed that farmers transitioning out of the GLSA stewardship program could expect a PAN benefit between 21 and 56 DAI depending mainly on when the incorporation happened. If managed correctly and crops were planted within this time frame, farmers have the opportunity to benefit from this additional N credit. This was also highlighted in chapter 2 where potato fields planted within 11-32 days between planting and GLSA incorporation (DBPI) likely benefited from the PAN through the earlier peak of NH_4^+-N and the more delayed peak of NO_3^--N. Chapter 2 also showed that GLSA fields appeared to peak in NO_3^--N later in the season than paired Control fields in 2015. Farmers may choose to initially apply less fertilizer in expectation of this N benefit or if planting an early crop may forego additional fertilizer banding in the season in expectation of this subsequent N peak. Either way, the N benefit from GLSA represent an opportunity to reduce production costs from additional fertilizer inputs but the farmer selection of planting times will largely determine how much of a benefit this will actually be.

The results of this experiment also highlight the variability in GLSA performance based on fertilizer type. The results of this chapter clearly support the difference in performance of the organic and conventional fields observed in chapter 2. Given that this experiment was conducted at one site, without crops and without irrigation, it should be noted that some of the other factors observed in chapter 2 that influenced GLSA performance could also interact with these management options (e.g., the level of degradation in the field and the amount of time left in between incorporation and crop planting). Any assessment on GLSA PAN benefits must be done in the context of these factors and farmers managing cropped fields transitioning out of the GLSA program will need to be conscious of the impacts these have on any calculated N credit.

Chapter 4: Conclusions

4.1 General Summary and Conclusions

In the regional on-farm experiment, I examined how effectively GLSA remediated soil chemical properties after 3 years and found no evidence to suggest that GLSA fields contained higher SOC and TN compared to cropped Control fields. A major question remains as to the level of degradation of the paired Control fields when entering into this study and how this affects the conclusions of a GLSA N benefit. A more thorough understanding of the cropping history or more detailed characterization of the status of degradation across the region could help to clarify this. It is possible that the observations of similar SOC and TN between Control and GLSA fields are indicative either of adequate remediation from GLSA or merely similar degradation levels between treatments, as there is no baseline in this study from which to compare. This could lead to a false conclusion that GLSA have adequately improved SOC and TN.

The on-farm experiment examined the effect of GLSA on supplying additional PAN in the first growing season following incorporation. I found that a substantial amount of residue nitrogen was added to GLSA fields through incorporation of AGB ranging from 86 -101 kg ha^{-1} over both seasons, a meaningful amount of additional N which could allow farmers to reduce fertilizer application rates; however, this would only be likely if the timing of mineralized PAN was early enough in the production season for the crop to utilize it. Although my experiments showed high amounts of residue nitrogen incorporated, I found variable results in N benefits in each growing season. In 2015, I found that GLSA contributed an additional 18 kg ha^{-1} relative to Control fields but found the opposite in 2016 with Control fields, actually supplying 20 kg N ha^{-1} more compared to GLSA in the 0-30 cm depth.

GLSA utilized by farmers in Delta appear to provide less additional N compared to GLSA employed elsewhere in the first year after incorporation. Studies which show higher N benefits often had GLSA with higher percentages of clover in their AGB composition and involved grazing, which increased N inputs through manure and urine. There is also the possibility that in my study I missed earlier flushes of N, which could have reduced my calculations of N benefits, as I began tracking N availability only once crops were planted. The additional N provided by the GLSA, which was uncounted for in this study could also potentially continue to be mineralized after the harvest during the fall and winter if soil temperatures are warm enough which could result in losses due to leaching or to a nitrogen pathway not tracked in my study. It is also possible the organic N may in fact not mineralize until the second year after incorporation and may still be beneficial for future crop production.

The on-farm experiment also investigated the impact of the C:N ratio in the incorporated AGB on nitrogen dynamics. I found the GLSA AGB comprised primarily of grasses, and had high C:N ratios, on average between 25-31, suggesting a high likelihood of N immobilization and a delay in N availability. The soil PAN data corroborated this and showed that NO_3^--N in GLSA fields in both seasons did not peak in until several weeks after their paired Control fields. Other studies which found rapid N mineralization often incorporated lower C:N residues comprised of clover, and those which observed immobilization of N incorporated residues such as grass with C:N ratios above 25 similar to my study. Results from the controlled experiment further support the hypothesis of initial N immobilization as the first NH_4^+-N peak did not occur until 21 DAI in plots amended with synthetic fertilizer and the NO_3^--N peak did not occur until 56 days after incorporation. There was also a secondary NH_4^+-N peak, which occurred 56 days after incorporation in synthetic fertilizer treatments, which could represent N being released after initial immobilization from incorporated AGB. Although no secondary NO_3^--N peak was observed an upward trend in all treatments towards at the final sampling point, 131 DAI could signal it would continue after sampling ceased to potentially be lost through N leaching. It is likely that the RSN would be much lower if crops had been grown and taken up some of the N.

The result from the on-farm study did not support the hypotheses that GLSA sites would leave higher rates of RSN resulting in a higher risk of NO_3^--N leaching at the end of the season. Other studies on GLSA often find high rates of NO_3^--N leaching potential in the first year following AGB incorporation. Increased RSN at the end of the production season may be a clear environmental tradeoff in GLSA rotations that increase PAN during the season as additional N benefits to farmers, if not utilized by the crop during the growing season, could result in NO_3^- leaching and lead to negative environmental impacts.

The controlled experiment investigated the impact of fertilizer type, rates and delayed incorporation on PAN dynamics. The findings from this experiment suggest that doubling of fertilizer applications from Typical to High did not reduce the immobilization of N or supply more PAN earlier in the season and suggest farmers would be able to apply typical rates and reduce inputs without the worry of additional early season immobilization. Delaying incorporation of GLSA, however, did reduce the early season PAN and as with findings of the regional experiment that highlighted farmers must be aware of the timing left between incorporation and planting in order to get maximum benefits from the additional N supplied by the AGB of GLSA.

The controlled experiment also very clearly demonstrated the impact of fertilizer type on N dynamics illustrating important differences in N supply following synthetic and organic amendments. Synthetic fertiliser supplied significantly more PAN earlier in the season and overall in the seasonal average compared to Organic, which mineralized similar amount of PAN to the Con treatment which removed AGB and added no additional N.

The evidence collected from this thesis provides insight into the importance of farmer management and the variation of soil properties on the benefits of GLSA in terms of PAN to subsequent production crops. Of critical importance appear to be the level of degradation in the field, the timing of GLSA incorporation and subsequent crop planting, the C:N ratio of the AGB residue and the fertilizer type selected by farmers in the first year after returning to crop rotation. The role of the remediation of physical properties following GLSA, which were not followed in this experiment, need to be further investigated. Finer textured soils like clay were shown to have higher PAN but are also more susceptible to compaction, and it remains to be seen what the adequate amount of time in set aside is for the remediation of both physical and chemical properties together particularly in the context of soil texture.

4.2 Strengths and Challenges of Research

My research design incorporated both a field and plot scale experiment, each presenting unique benefits, challenges and limitations. Working on-farm in operational fields enabled the observations of GLSA performance under the most realistic conditions. By studying fields with variable management, soil types, and locations the sample population adequately represented the range of GLSA fields around Delta. The on-farm study also enabled the monitoring of farmer management practices and their complex interactions with various soil types across the study region, making the results realistic and relevant for Delta farmers. The field scale study also presented many challenges, as sampling was often delayed due to staggered pesticide spraying times and variable management practices. Fields used in the study had different cropping histories and so, not surprisingly varying levels of degradation. The study was also limited by the number of fields coming out of a 3-year GLSA, giving little choice in crop and fertilizer type to include. All of these factors likely confounded treatment effects and made the interpretation of results more difficult due to high variability of observed data and limited replication. The plot scale experiment was opposite to that of the field trial in many ways, allowing me to maintain much more control over inputs, treatments and sampling times and ensuring the results were less masked by other factors. The plot study will surely better reflect the underlying mechanisms at play after GLSA cessation, although it did not effectively replicate crop production (e.g., there were no plant grown in the plots) and it was less representative of the population of GLSA fields in Delta therefor it will be less relevant to Delta farmers.

4.3 Directions for Future Research

It is important for future research to maintain relevancy to the Delta farmer, while attempting to better understand the underlying mechanisms in the GLSA system. To do so, future research should aim to, as much as possible, control field conditions, whilst also minimizing the confounding factors found in the on-farm experiment. I would recommend adopting a similar plot scale design from this plot study and increasing the number of replicates, if possible, by utilizing multiple sites of the same aged GLSAs as well as incorporating crops into the system to better mimic crop nitrogen dynamics. Incorporating multiple application rates of nitrogen as well as incorporating biomass without any nitrogen would be helpful to follow mineralization of just the incorporated AGB, this could be supported by a decomposition study done in the lab with ideal moisture and temperature conditions. Further, by controlling the type of crop used in the system, nitrogen uptake and dynamics will be more comparable across treatments as will the effect of nitrogen availability on crop yield and quality. By decreasing the spatial variability on a plot scale, having more control over all inputs and better control of sampling times, I believe future research could more adequately answer the question of GLSA effect on subsequent crop yield as well as identifying which management factors are most important for farmers to consider.

4.4 Implications to Delta Farmland and Wildlife Trust and Farmers

This study aimed to provide the DF&WT as well as Delta farmers with a better understanding of the impact of 3-year-old GLSA on soil quality and nitrogen dynamics following incorporation. My research has shown that GLSA have the potential to remediate SOC and TN or at least appear comparable to that of the paired Control fields selected. The study clearly illustrated the potential for AGB in GLSA to contribute a N benefit to the system and began to unravel the complexity of nitrogen mineralization and availability for subsequent crop production. The study also showed how GLSA performance is highly dependent on the fertilizer type used by farmers, the rate of application, the timing left between incorporation and planting of crops and the texture of the soil. These results showed that the GLSA in Delta certainly do not provide as much nitrogen to subsequent crops as has been found in other studies which utilize high amounts of clover in their mix, fix more nitrogen and mineralize N more quickly. Further study is required to better predict when nitrogen is most available following incorporation. This study found initial peaks of NH_4^+-N by 21 days after incorporation and NO_3^--N peaks were delayed until 56 days after planting, and that NO_3^--N peaks may occur later than in continuously cropped systems. Additional analysis should also include the GLSA's effect on other factors that impact subsequent crop production and quality including phosphorus availability, water holding capacity and infiltration, and pest prevalence.

GLSAs should continue to be used as a conservation practice in Delta to remediate soil quality over short time periods, while concurrently providing critical wildlife habitat in the region. However, any recommendations of changes to field management (i.e., fertilizer reduction, cover crop participation) to farmers who participate in the GLSA programs will require more clarity on the nitrogen dynamics in order to maximize both production and environmental benefits.

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Appendices

Table A1. Study sites with details of each paired field's management including fertilizer, irrigation, field size and incorporation information from on farm regional assessment Chapter 2.

2015														
Site	**Field**	**Treatment**	**Area (ha)**	**Days between incorporation and planting**	**Soil Series (++)**	**Field Preparation**	**Crop**	**Fertilizer type**	**NPK or Compost type**	**Rate (kg/ha) or (yds/acre)**	**Irrigation**	**pH**	**pH(CaCl2)**	**ECw (dS/m)**
I	1	GLSA	9.3	17 days	Delta, Ladner, Delta-Ladner complex	Cut, ploughed, pulvi-mulched two times, planted with barley nurse crop	Mixed potato	Synthetic	8-18-22	1233 kg/ha	Gun 3-4 times	5.82	5.34	2.121
	2	Control	6.5	-	Crescent, Delta	Winter cover cropped in oats planted September 16 at 150 lbs./ac undisturbed until March 31 2015	Goldust potato	Synthetic	12.9-16-19.8	1233 kg/ha	Gun 3-4 times	5.82	5.34	1.14
II	3	GLSA	13.8	19 days	Guichon	Cut, ploughed, pulvi-mulched two times, planted with barley nurse crop	Chieftain potato	Synthetic	18-18-22	1120 kg/ha	Gun 3-4 times	5.86	5.52	4.29
	4	Control	8	-	Spetifore, Delta	No winter cover crop planted in previous winter season	Imola potato	Synthetic	18-18-22	1120 kg/ha	Gun 3-4 times	5.96	5.62	7.85
III	5	GLSA	4	32 days	Westham	Mowed, disked 2-3 times, cultivated to dry and shake out sods. subsoiled and pulvi-mulched	Kendo green bean	Organic	spread with composted poultry manure	20 yds/acre	None	5.72	5.24	2.66
	6	Control	2.9	-	Westham,	No winter cover crop planted, field prep included subsoiling, brought to seed bed with cultivator and pulvi-mulcher	Cadillac green bean	Organic	spread with composted poultry manure	20 yds/acre	None	5.75	5.02	1.21
IV	7	GLSA	4	30 days	Blundell, Westham , Crescent	Mowed, disked 2-3 times, cultivated to dry and shake out sods. Subsoiled and pulvi-mulched	Kendo green bean	Organic	spread with composted poultry manure	20 yds./acre	None	5.89	5.24	1.75
	8	Control	3.3	-	Westham, Blundell	Planted in cover crop mix at 29 lbs./acre, field prep included, subsoiling, brought to seed bed with cultivator and pulvi-mulcher	Impact wax bean	Organic	spread with half composted poultry manure half aged horse bedding	20 yds/acre	None	5.88	5.11	1.19
2016														
V	9	GLSA	2.5	19 days	Westham, Delta	No mowing, rototilled, subsoiled to 3 ½ feet, disked, mounded	Yukon Gold	Synthetic	10-20-20	784 kg/ha	None	4.72	4.19	1.37
	10	Control	2.6	-	Westham, Delta	Winter cover cropped in oats plant in Fall of 2015 at 100 lbs./ acre, field prep included rototilling and mounding.	Yukon Gold	Synthetic	10-20-20	784 kg/ha	None	5.45	4.84	0.98
VI	11	GLSA	0.8	19 days	Westham, Delta	No mowing, rototilled, subsoiled to 3 ½ feet, disked, mounded	Yukon Gold	Synthetic	10-20-20	784 kg/ha	None	4.99	4.34	1.25
	12	Control	1.1	-	Westham, Delta	Winter cover cropped in oats plant in Fall of 2015 at 100 lbs./ acre, field prep included rototilling and mounding.	Yukon Gold	Synthetic	10-20-20	784 kg/ha	None	5.18	4.63	0.88
VII	13	GLSA	5.2	59 days	Westham, Blundell	Mowed, disked 2-3 times, moldboard plowed before final prep	Cadillac green bean	Organic	composted poultry manure	15 yds./acre	None	5.19	4.82	0.69
	14	Control	2	-	Westham	No winter cover crop planted in previous winter season	Cadillac green bean	Organic	composted poultry manure	15 yds./acre	None	5.77	5.67	2.09
VIII	15	GLSA	2.6	30 days	Ladner, Guichon-Ladner complex	Mowed, disked 2-3 times, used a single offset disc and a heavy chisel, and cuts down deeper.	Broccoli	Organic	70 % composted dairy manure, 30% composted broiler chicken	15 yds/acre	Gun 1 time in July	6.27	5.62	0.811
	16	Control	0.8	-	Guichon	No winter cover crop planted in previous winter season	Broccoli	Organic	70 % composted dairy manure, 30% composted broiler chicken	15 yds/acre	Gun 1 time in July.	5.93	5.44	0.84

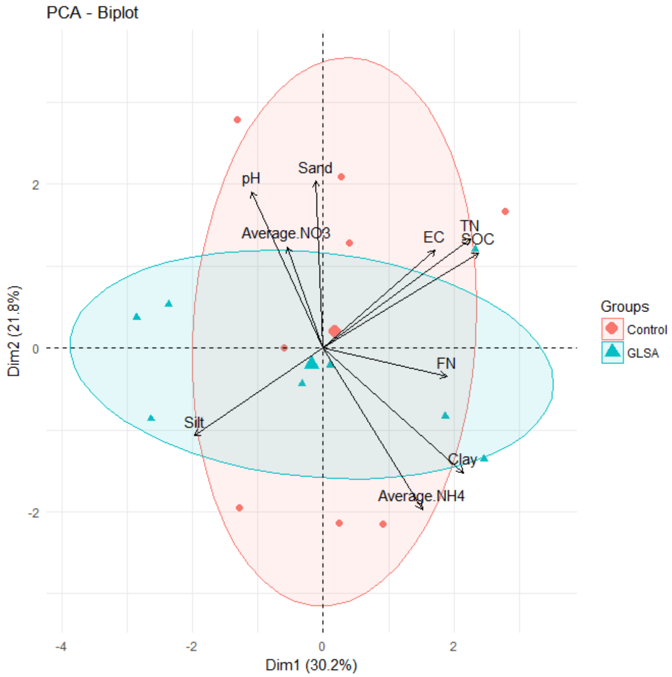
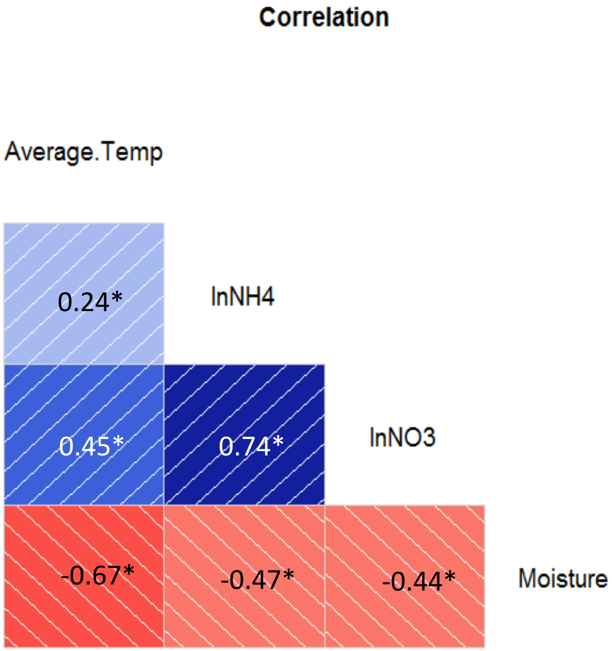


Figure A1. Principal components analysis (PCA): biplot from regional study with variables (SOC: soil organic carbon, EC: electrical conductivity, pH: soil pH, Fertilizer nitrogen: FN, Sand, Silt, Clay, Average NO3: nitrate (NO$_3^-$-N), Average NH4: ammonium (NH$_4^+$-N)) for fields treated in GLSA and Control grouped by treatment.



	Average.Temp	lnNH4	lnNO3
lnNH4	0.24*		
lnNO3	0.45*	0.74*	
Moisture	-0.67*	-0.47*	-0.44*

Figure A2. Pearson's correlation matrix between measured PAN and climatic variables. All variables were transformed with a log base 10. Variables included were average temperature (Average.Temp), soil moisture (Soil.fracwet), nitrate (lnNO3), and ammonium (lnNH4). Values represent positive (blue) or negative (red) correlation coefficients (r) with darker shading representing stronger correlations and values with stars represent significant correlations (p<0.05).