Soil dynamics driven by controlled traffic farming in the Canadian Prairies

by

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Abstract

Growth of the human population within the next half century is projected to reach a staggering quantity. Maintaining our food security for future generations without causing further environmental degradation in an ever dynamic landscape is a complex challenge, which may be partially remedied through the application of practices that promote sustainability in the agricultural industry. The implementation of controlled traffic farming (CTF), a management system which reduces spatially applied compaction, is a doorway to reach sustainability as it can reduce soil degradation and facilitate soil amelioration. As soil degradation from conventional agricultural practices may greatly hinder our food production ability, any means of mitigating the risk in achieving future food security must be rigorously studied. Thus, it was the goal of this study to analyze how the implementation of CTF impacts soil and its respective quality in the Canadian Prairies. This was achieved through: (i) a regional analysis of how CTF affects soil physical quality in annual croplands throughout Alberta, Canada, (ii) investigating how simulated CTF field conditions impact the water use of faba beans (*Vicia faba* L.) and (iii) assessing how CTF influences the spatial heterogeneity of soil quality at the field scale in Alberta, Canada. The findings of this study revealed how the implementation of CTF can have variable effects on different soils throughout Alberta, Canada due to intrinsic and extrinsic influencing factors (i.e., the landscape under examination, the duration of CTF usage and the management practices previously employed). However, despite site specific variability influencing CTF responses, soil physical quality was found to greatly benefit the un-trafficked areas of CTF, which can potentially represent a maximum of 80% of the field area from CTF implementation. Further investigation into the interaction of faba beans with soil conditions experienced in CTF fields throughout Alberta showed that high levels of compaction, observed uniformly or as a plow plan, largely inhibited faba bean productivity. Furthermore, conditions of high water availability were able to partially mask the detrimental effects of high compaction, while a relatively lower water availability representing field moist conditions displayed great disparity in faba bean productivity among varying levels of compaction. Additionally, improvements to un-trafficked soil quality and its corresponding spatial structure were quantified at the field scale through standard and hybrid geostatistical methods. Extrinsic factors from the CTF management system predominantly influenced the spatial structure of soil physical and hydraulic quality parameters, which were best predicted through regression and regression kriging methods. Moreover, intrinsic variations due to landscape features and water movement were shown to highly contribute to the spatial structure of soil nutrient quality parameters. Furthermore, topographic influence on the spatial structure of soil nutrient properties were highlighted, as terrain-derived covariates (e.g., elevation and topographic position index) paired with the covariate kriging method yielding the best model.

Dedication

I dedicate this study to my friend, Christopher Mark Rogers. Your passion for academia and continuous pursuit of knowledge has kept me inspired.

Table of Contents

List of Table Captions

List of Figure Captions

exhibits the highest stomatal conductance and evapotranspiration, with the relatively lower water availability (-100 KPa) showing the lowest stomatal conductance and evapotranspiration.

Fig. 3.1a: Cyclic soil sampling design with distance dimensions in meters. Sampling locations represent locations of undisturbed soil core sample, with composite samples taken within 2 cm of each sampling location (n=96). Plot orientation at Dapp encompassed tramline orientation from east to west, with tramlines oriented north to south at Lacombe.

Fig. 3.1b: Nest sampling design within cyclic sampling design with dimensions in meters. Both undisturbed soil core samples and push probe samples taken within the nest (samples #73-84) were taken at two depths, 5-10 cm and 15-20 cm (n=24).

Fig 3.2 Comparison of (i) macro pore volume fraction (PVF) and (ii) bulk density across traffic types (sprayer tramline, CTF tramline and un-trafficked zones) that are commonly displayed in a CTF landscape.

Fig. 3.3: The Lacombe site soil organic carbon (SOC) standard error (SE) spatial distribution shown through the ordinary kriging method (i) and the covariate kriging method (ii). The ordinary kriging method (i) has larger error variation when compared to the covariate kriging method (ii). Not the different z-scales across both SE predictions for each method.

Fig. 3.4: Soil calcium (i) and boron (ii) concentrations as a function of pH for two field sites in Alberta using controlled traffic farming.

Fig. 3.5: Lacombe site LiDAR elevation (i), soil pH (ii) and soil organic carbon (iii) spatial distributions. The elevation (i) spatial distribution is derived from the LiDAR bare earth data in meters above sea level (masl). The soil pH (ii) spatial distribution in the 5-10 cm depth is derived from the covariate kriging method with LiDAR elevation as a covariate. The soil organic carbon (iii) spatial distribution in the 5-10 cm depth is also derived from the covariate kriging method with LiDAR elevation as a covariate.

Introduction

The human population of Earth is projected to grow more than 50% to reach a median value of 11.2 billion souls by 2100, with a possibility of reaching a maximum of 13.3 billion people (United Nations, 2015). The projected increase in population will most likely add strain on current resources, as higher efficiencies and greater levels of production across all sectors will need to be achieved to sustain current consumption rates across an ever-increasing pool of consumers. Additionally, the increased demand for food production may be further intensified by projected global temperatures increases, thus driving the need to have an accurate means of forecasting future production requirements (Nelson et al. 2014). According to the Goddard Institute for Space Studies, the global temperature for 2015 was greater than any measured in the 1951-1980 period, with the 2015 mean temperature being 1.13°C higher than the 1880-1920 mean (Hansen et al. 2016). Temperature increases per decade are expected to continuously rise by 0.2°C, with the possibility of global temperatures increasing between 1.3 to 3.4 degrees by 2100 (Smith et al. 2015).

The use of climate change models to analyze and predict the effects of global temperature increases has yielded high variability in the outcomes due to varying assumptions and model influences; however, global reductions in crop production due to limitations of water availability and soil degradation are certain (Rosenzweig et al. 2014). Integration of various forecasting models has displayed a decline to global crop yield of 17%, without taking into account enhanced fertilization due to increases in atmospheric CO_2, by 2050 (Nelson et al. 2014). Furthermore, climate change models have recently shown that the use of current production practices may not be possible as the global temperature increases within some production areas (Rosenzweig et al. 2014). The potential prevalence of severe weather conditions due to climate change has greatly increased the risk in agriculture and given rise for agricultural systems to achieve the goal of sustainability (Doran 2002).

The ability to intensify quantity and quality of production while reducing external inputs and land degradation may be achieved through sustainable agricultural practices (Hurni et al. 2015). Sustainable agriculture can in part be conceptualized as maintaining the demand of food production for the growing population while employing environmentally sound management practices. Thus, there is a need to analyze current practices as well as develop new techniques to achieve the projected production rates while mitigating environmental effects to avoid exacerbating global temperature increases. Achieving sustainability in agricultural systems requires reformation of many of the existing methodologies used for achieving production. In intensive agricultural systems, excessive tillage and compaction associated with conventional management has had profound degradation effects on soil quality (Alakukku 1996b; McPhee et al. 2015; Strudley et al. 2008). Despite the adoption of soil erosion limiting management practices in the Canadian Prairies, such as organic production and zero tillage methods (Derpsch & Friedrich 2009; Shirtliffe & Johnson 2012), other management techniques may be needed to further limit soil degradation (Arshad et al. 1999; Azooz & Arshad 1996; Miller et al. 1998). A potential means of reducing soil damage and moving towards the goal of sustainability may be realized through the use of controlled traffic farming (CTF) as the dominant in-field management system.

The in-field management system of CTF can be described as restriction of production vehicle movement to predefined longitudinal and parallel features known as tramlines. Tramlines are considered as unchanging permanent roadways that the equipment transverse throughout the field. The layout of the tramlines within each field is site specific and often based upon a predetermined optimal layout (Bochtis et al. 2010). However, the frequency in which tramlines occur within the field is determined by a chosen uniform implement width, where the uniform width or multiples of said width can be used for implement sizing. The direct benefit of CTF systems and their rigid traffic regime is a reduction of 40-70% of trafficked areas when compared to conventional farming techniques, as a random traffic regime covers 20-35% of the field area with traffic per farming operation (Tullberg 2000). Furthermore, the use of CTF has been shown to improve soil structure (McHugh et al. 2009; McPhee et al. 2015), reduce greenhouse gas emissions (Antille et al. 2015; Gasso et al. 2013; Gasso et al. 2014), and improve water use efficiencies (Blanco-Canqui et al. 2010; Li et al. 2007), as it has become a common management practice in Australia and Europe. Although, the lack of manufacturer equipment standardization (Kingwell & Fuchsbichler 2011; McPhee & Aird 2013) and the incorporation of custom operations into management activities can lead to difficulties in adhering to the tramline structure (CTFA 2016). There is a need to explore the applicability of CTF and other means of agricultural improvement within the Canadian Prairies to ensure the goal of sustainability is met and exceeded.

Integration of management systems that reduce the environmental impact can be further enhanced through the incorporation of diverse crop rotations (Congreves et al. 2015; Dias et al. 2015). The amalgamation of pulse crops into crop rotations is beneficial to soil quality through the nitrogen fixation properties of pulses as well as the diversification to soil biota (Dias et al. 2015). Adoption of pulse crops, specifically faba beans (*Vicia faba* L.) within the Canadian Prairies, has been slowly increasing due to overall limitations (e.g., poor market prices) being overcome. Faba beans have been shown to directly benefit the yield of successive crops (Jensen et al. 2010). Furthermore, the advent of intensified production systems to meet the needs of food production coupled with the resulting soil degradation gives rise to the need of achieving a better understanding and optimization of the use of pulses in varying agroecosystems. Access to water resources for crop production via dryland farming has been shown to be a major limiting factor (Kröbel et al. 2014; Medrano et al. 2015; Xu & Hsiao 2004) when combined with poor soil quality caused by conventional management techniques, indicating that the potential benefits of pulse crops may not be reaching their full potential (Buttery et al. 1998; Hamza

& Anderson 2005). Thus, a knowledge gap exists in both the physiological and water use interactions of faba beans compared between conventional traffic and controlled traffic environments, in particular within the Canadian Prairies.

The necessary shift in agriculture towards sustainable practices, such as CTF, is possible with the incorporation of global positioning systems (GPS) into new techniques, which has been coined in the agricultural industry as precision agriculture (PA). With the use of PA, there is a need to create accurate and precise models that stem from the ability to understand and adequately predict soil dynamics and their driving forces at the field, regional and global scales (Rosenzweig et al. 2014). Soil dynamics and its corresponding variability may be understood and represented through the use of geostatistical methods, which encompass the quantification and explanation of spatial heterogeneity on multiple scales (Baveye & Laba 2015). However, many forms of geostatistical interpolation exist, with comparisons between both standard and hybrid methods of geo-statistics over regional scale models not yielding definitive results (Hengl et al. 2004; Mirzaee et al. 2016; Wang et al. 2013; Watt & Palmer 2012). Discrepancies across geospatial methods may also be applicable for field scale models, thus leading to the need for the examination and determination of optimal small scale interpolation methods (Mirzaee et al. 2016; Simbahan et al. 2006). Comparisons between standard and hybrid geostatistical analyses of the spatial variability of soil properties are not available for annual croplands in the Canadian Prairies, let alone within a CTF environment. Collectively, this indicates that a quantification of the optimal small scale interpolation method is necessary for both CTF management systems as well as the development of field scale models within the Canadian Prairies.

The purpose of this thesis is to explore and quantify differences and variability in soil properties within commercial farming landscapes that employ CTF throughout the Canadian Prairies at both regional and field scales. This thesis comprises of three chapters which addresses the overarching goal through: (i) determining how soil quality parameters differ between conventional traffic and controlled traffic management across the regional scale of the Canadian Prairies, (ii) quantify how the confinement of compactive effort affects the soil-plant-atmosphere continuum from CTF usage in soils common to Alberta and (iii) evaluate geostatistical interpolation methods to identify the best performing spatial models and to decipher the dynamics of field scale variability within the Canadian Prairie and CTF environments. The comparison of soil physical and hydraulic properties between trafficked and un-trafficked areas across various climatic conditions and soil types used for agricultural production in Alberta should reveal potential areas for beneficial usage of CTF. Furthermore, the incorporation of a controlled experiment with applied treatments of varying compactive effort and water availability should reveal the resiliency of CTF through sensor-based measurements of crop water use efficiency. Finally, the integration of fine spatial resolution digital elevation data derived from remote sensing with advanced geostatistical interpolation methods should divulge optimal spatial pairings for measurements of soil quality heterogeneity at the field scale.

Chapter 1. Soil Quality Dynamics in Annual Croplands under Controlled Traffic Management within the Canadian Prairies: A Regional Study

1.1 Abstract

Land management systems that help reduce soil degradation can contribute to achieving a state of sustainable agriculture. Controlled traffic farming (CTF) is the practice of confining all equipment traffic within tramlines and can facilitate the amelioration of soil within the un-trafficked areas. However, widespread regional analysis of CTF and its potential effects in the Canadian Prairies on soil quality have been largely unexplored. This study analyzes soil physical and hydraulic properties in several commercial agriculture sites across Alberta, Canada and compares conventional (imposed) traffic and controlled traffic regimes. Soil characteristics, such as bulk density, pore volume fractions (PVF) and unsaturated hydraulic conductivity (UHC) were compared with soil physical quality parameters, such as S-Index and mass fractal aggregation between trafficked and un-trafficked field areas. The results of this study showed that most of the observed soil characteristics displayed substantial improvements in the absence of traffic. Soil porosity in the un-trafficked areas improved up to 15% in more than half the study sites. Additionally, soil pore diameters associated with water transmission displayed prominent increases in volume from 40-180% due to the spatial reduction of wheel compaction. These improvements in soil characteristics correlated well with improvements in soil physical quality metrics, as shown by enhancements to the S-Index (slope of inflection point on water retention curve) coupled with evidence of hierarchical aggregation occurring within the un-trafficked zones. Irrespective of the trend of soil physical quality enhancements due to reductions of trafficked areas, significant increases in crop yield were rarely observed in favor of CTF. Our results suggest that the employment of CTF in the Canadian Prairies as the dominant management system may take several years to result in improvements of soil quality which translates into observable benefits in the form of crop yield.

1.2 Introduction

Sustaining and increasing food production for a population that is expected to surpass 11 billion by 2100 (United Nations, 2015) creates a complex challenge for existing production techniques; however, long term food security may be achieved through the implementation of sustainable agricultural practices (Hurni et al. 2015). Sustainable agriculture can be described as maintaining the demand of food production for the growing population while employing environmentally sound management practices to mitigate the environmental footprint. Innovative management techniques, such as controlled traffic farming (CTF), may be a tool for the producer to maintain sustainability (Tullberg 2010). Despite the shift towards the adoption of best management practices, with 1.8% of producers practicing organic production, 56% practicing zero tillage and 25% practicing reduced tillage (Statistics Canada, 2011), and the benefits to soil that are experienced with their subsequent adoption (Dyck et al. 2015; Helgason et al. 2010; Shirtliffe & Johnson 2012; Smith et al. 2016), existing land management systems have deteriorated soil quality within the Canadian Prairies (Arshad et al. 1999; Azooz & Arshad 1996; Miller et al. 1998). In intensive agricultural systems, continuous compaction events (Alakukku 1996a; Alakukku 1996b) coupled with conventional tillage (Li et al. 2007; McPhee et al. 2015) as well as zero tillage (Dyck et al. 2015) has had a profound degrading effect on soil structure (Strudley et al. 2008). Therefore, the use of modern management techniques, such as CTF, may potentially aid in the recovery of soil quality (Chamen et al. 2015; McHugh et al. 2009) and reduce the harmful effects of soil degradation due to recurrent equipment traffic (Qingjie et al. 2009).

The management system of CTF is described as the confinement of in-field production vehicle movement to a predefined area known as a tramline (Tullberg et al. 2007). Tramlines are permanent tracks inside the field boundary that are travelled on by the production equipment for every farming operation. The tramline frequency within a field boundary is based upon a uniform implement width, where the uniform width or multiples of said width can be used for implement sizing. Conventional traffic techniques utilize uncontrolled production vehicle movement within the field, with every unsystematic traffic regime typically covering 20-35% of the field area with equipment compaction in each farming operation (Tullberg 2000). Considering a minimum of three farming operations occurring throughout a growing season, conventional traffic systems cause 40 to 70% more spatial compaction compared to a CTF system. Decreases in spatially applied compaction through CTF results in a concentration of the mechanical compactive effort within the tramlines, which can also lead to reductions in fuel and fertilizer usage (Kingwell & Fuchsbichler 2011), greenhouse gas emissions (Antille et al. 2015; Gasso et al. 2013; Gasso et al. 2014; Vermeulen & Mosquera 2009), soil degradation (Li et al. 2009) as well as improvements to crop yields (Chen et al. 2008; Li et al. 2007; Smith et al. 2014). However, continual usage of tramlines can lead to complications with residue management as well as degradation of the tramlines in wet spots or during events of high precipitation, facilitating the need for tramline renovation (Tullberg et al. 2007; Tullberg 2010).

The basic postulate of confining the compactive effort to tramlines through CTF implementation is advantageous as the reduction of trafficked areas can facilitate potential benefits in soil quality parameters to be experienced more prominently, as larger portions of the field become permanent un-trafficked areas. The alterations in soil quality experienced between conventional and controlled traffic systems are largely based upon changes to soil structure due to the contrasting traffic regimes (McHugh et al. 2009). Measurement of soil quality parameters through both physical and hydraulic characteristics of the soil structure, such as pore volume and unsaturated hydraulic conductivity at varying diameters, have been shown to illuminate differences across management types (Lipiec et al. 2006). Further evaluation of soil structure is described by Hirmas et al. (2013), as the soil's ability to support hierarchical aggregation may provide insights into the organization of soil structure. Revealing the suitability of CTF within the Canadian Prairies requires an understanding of the dynamics of soil structure between conventional and controlled traffic systems on a regional scale, as this knowledge is essential to developing a comprehensive understanding and quantification of soil quality (Congreves et al. 2015).

Implementation of CTF has been shown to improve soil structure in Australia (McHugh et al. 2009; Radford et al. 2007), China (Qingjie et al. 2009), the United Kingdom (Chamen et al. 2015) and the United States (Blanco-Canqui et al. 2010; Unger 1996). Thus, CTF systems may also promote the recovery and improvement of soil quality through the enhancement of soil structure within the Canadian Prairies. Increasing our understanding of management systems that improve soil quality within the Canadian Prairies is a required step in selecting and achieving sustainable practices. Addressing this knowledge gap could help mitigate the production risks associated with uncontrollable factors when trying to achieve future food security. Thus, the objectives of this study were: (i) evaluate the dynamics of soil characteristics across contrasting traffic systems in annual croplands, and (ii) determine how controlled traffic management systems impact soil quality in the Canadian prairies.

1.3 Materials and Methods

1.3.1 Study Sites

The study was carried out on eight commercial field sites within Alberta, Canada (Table 1.1), which encompass the dominant soil subgroups throughout the agricultural regions of the province. The use of CTF as the dominant management practice varies temporally for each field site, with a maximum time period of five years and a minimum of one year, at the time of field sample collection. The sites have traditionally been managed through conventional techniques, with most sites being converted to reduced or zero tillage practices in the last two decades. Tillage practices used by the producers who employ CTF consisted of either reduced or zero tillage, with zero tillage being the most common. Each field site was managed by different producers and could be classified as dryland management, with the exception of Rolling Hills which utilizes irrigation. Each site employs different crop rotations and was classified as either a legacy site (CTF implementation from 2 to 5 years) or a new site (CTF implementation less than 2 years).

Each site, which consists of a quarter section of land equating to approximately 64 ha, was fully managed by CTF. The underlying principles of CTF were consistent across all sites; tramline spacing typically occurred at roughly 9 m with a wheel gauge width of either 3.05 m or 3.40 m. The imposed traffic (IT) treatment consisted of a randomly chosen swath within the CTF managed field that was exposed to additional traffic in the spring and fall. Three to four replications of the IT treatments were distributed throughout each of the sites. The IT treatments and respective replicates were used to simulate additional traffic experienced in random traffic patterns that conventional traffic systems employ. The IT treatment was applied via driving a tractor and grain cart combination on either side of the tramlines within the swath. The CTF treatment constituted of a nominal CTF swath with tramlines and un-trafficked areas, which was adjacent to the IT treatment.

1.3.2 Sampling Design

Sample collection at the sites (Fig. 1.1) was executed in either 2014 or 2015. The sampling design carried out in each individual field site consisted of randomly chosen soil sampling locations within the treatment replicates, where samples were taken from beneath the trafficked portions of the IT treatment and un-trafficked areas of the adjacent CTF swath. Eight soil core samples were taken from each replicate, with four samples taken within the trafficked area of the IT swath and four samples taken in the un-trafficked area of the adjacent CTF swath (Fig. 1.2). Two sampling depths of 5-10 cm and 15-20 cm were taken for each soil core sample from a position one-third of the inter-row to capture any potential variation with depth. Depending if the field site had either three of four replicates, a total of 24 or 32 soil core samples were collected for each site, respectively. Additionally, at four of the field sites

(Cleardale, Dapp, Neerlandia and New Norway), undisturbed soil clod samples were randomly taken from the trafficked portion of the IT treatment and un-trafficked areas of the adjacent CTF swath a depth of 5-15 cm in the same manner as the soil core samples. The time of collection from each site ranged from late June to early July to minimize any changes within the soil due to biological or physiological processes and to capture conditions experienced during the growing season.

Undisturbed soil core samples were used to determine soil physical and hydraulic properties and were collected in stainless steel cores of 5 cm in height with a diameter of 8 cm, resulting in ~250 cm^3 of soil volume. Collection of the samples was accomplished through the use of a handheld sampler and rubber hammer. Removal of the soil core from the sampling location involved the placement of a shovel beneath the soil core to preserve the integrity of the sample. After the field sampling campaign was completed, the soil cores were sealed, packaged in protective wrapping, transported back to the laboratory and stored at 5 °C until testing. The additional soil clod samples were used to determine the mass fractal dimension and consisted of a large intact piece of soil removed from the field (~300 cm^3), which were packaged and stored at 5 °C until analysis.

1.3.3 Procedures and Calculations

The water retention and unsaturated hydraulic conductivity curves are a measure of the soils ability to hold and interact with the water present. Obtaining these curves was achieved through the simple evaporation method by using a HYPROP® system (UMS GmbH, Munich, Germany). This technique consisted of saturating an undisturbed soil core sample, which was then placed on to a de-gassed HYPROP® unit and left to evaporate under room temperature conditions. The HYPROP® is a laboratory instrument that uses porous ceramic cup tensiometers attached to transducers within the HYRPOP® unit to measure the matric potential via water tension within the soil core sample at heights of 1.75 cm and 3.75 cm during the evaporation process (Peters & Durner 2008; Schelle et al. 2013). The tensiometers are capable of measuring the matric potential within the sample to ranges of pF 0.0 to 3.0, which is a logarithmic derivation of the matric potential in hPa and translates to a range of 0 to -100 KPa (Schindler & Müller 2006; Schindler et al. 2010). The HYPROP® units were interfaced to a computer which automatically recorded changes in tension within the sample every 10 minutes. The samples were weighted two to four times daily for the duration of the experiment. At the end of the tensiometer measurement range, cavitation occurred and the experiment was completed. The samples were then removed from the HYPROP® units and placed in an oven at 105 °C for a minimum of 24 hours to obtain their respective constant dry weights. The bulk density (ρ_B, g cm^{-3}) and total porosity of each sample was calculated based on the volume of the soil core with its respective dry mass and an assumed particle density of 2.65 g cm^{-3}.

Data gathered from the evaporation experiment, which described changes in water content versus the average value of the pressure gradient between the tensiometers, was analyzed by using HYPROP® FIT software (Pertassek et al. 2015). The software calculated the water retention and unsaturated hydraulic conductivity curves from the measured data points and fit the curves to the van Genuchten model (van Genuchten 1980), as follow:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{(1+(\alpha h)^n)^m} \qquad [1.1]$$

where, θ is the calculated water content (cm^3 cm^{-3}), θ_r is the residual water content (cm^3 cm^{-3}), θ_s is the saturated water content (cm^3 cm^{-3}), α is the inverse of the air entry potential (KPa^{-1}), h is the matric potential (KPa), and n & m ($m=1-n^{-1}$) are shape parameters.

The pore volume fractions (PVF) of a soil are used to explain the volumetric (cm^3 cm^{-3}) quantity of space within the soil that is allocated to a specific pore diameter. Using the raw water retention curve, the PVF were calculated through the relationship between the tension values and its corresponding pore diameter (Hernandez-Ramirez et al. 2014). In this study, the PVF were quantified as macro (0 to -5 KPa), meso (- 5 to -33 KPa), micro (-33 to -50 KPa) and residual (< -50 KPa). The resulting macro, meso, micro and residual pore diameters translate to >60, 60 to 9, 9 to 6 and <6 µm, respectively. The division of PVF was quantified upon the raw measurement range of the tensiometers, as the dry portion of the water retention curve was not calculated and thus not analyzed. The unsaturated hydraulic conductivity (UHC, cm d^{-1}) of the soil was analyzed by subsets separated as large (-1 to -10 KPa), medium (-10 to -20 KPa) and small (-20 to -33 KPa) classes. The saturated water content and field capacity of the soil was determined at a tension of pF 0 (0 KPa) and 2.52 (-33 KPa), respectively, from each sampled water retention curve. Water contents corresponding to the soils saturated and field capacity states can be different for each soil (Cassel & Nielsen 1986); however, the values stated above were applied to the soil samples at all sites to provide a frame of reference that could be comparable among sites.

The S-Index, a general indicator of soil physical quality postulated by Dexter (2004), was calculated based on the slope of the inflection point from the van Genuchten modeled water retention curve and is as follows:

$$S = -n(\theta_s - \theta_r)\left(\frac{2n-1}{n-1}\right)^{\left(1/n-2\right)} \qquad [1.2]$$

The resulting S-index or calculated value of the slope at the inflection point is a representation of the physical quality of the soil, where values greater than 0.035 indicate good soil physical quality and values less than 0.035 indicate poor soil physical quality (Dexter 2004).

The fractal dimension of a soil is a means of describing the soil's ability to aggregate in a hierarchical manner. Determination of the aggregate size was completed by the laser scanning technique (3D Scanner Ultra HD, NextEngine, California). The 3-dimensional scans of the clods revealed the size of the aggregate by determination of the sample volume. Where micro-aggregates have a higher density and thus are easily combined to form macro-aggregates, which have a lower density

(Hirmas et al. 2013). The undisturbed soil clod samples were separated into five separate diameter ranges (4-8, 2-4, 1-2, 0.5-1, and 0.25-0.5 cm) and analyzed for volume and mass. The fractal dimension was quantified from two aggregate samples within each diameter range for a total of at least ten aggregates from every soil clod, and was determined by the following:

$$M(v) = k_m v^{D_m} \quad [1.3]$$

Where M(v) is the mass of the aggregate (g), k_m is a constant, v is the aggregate volume (cm^3), and D_m is the fractal dimension. Smaller estimated values of fractal dimension indicate greater evidence of hierarchal aggregation within the sampled soil due to a greater distribution of both macro and micro aggregates reducing the mass per volume ratio.

1.3.4 Statistics

Water retention and unsaturated hydraulic conductivity curves fit with the van Genuchten model were chosen based on the lowest root mean square values. Data was derived from the tensiometer measurement range (0 to -100 KPa) of the fitted van Genuchten curves to ensure accuracy. Prior to analyzing the data, assumptions of normality and homogeneity of variance were checked through the Shapiro-Wilk and Bartlett tests, respectively. The statistical analysis was carried out on the original data that met the assumptions, with the exception of the pore volume fractions and unsaturated hydraulic conductivity, which were log (base 10) transformed to fulfill statistical assumptions. Original and transformed data was analyzed with two types of software, R ver. 3.3.1 (RDCT 2015) and SigmaPlot ver. 11.1 (SYSTAT 2008).

Two separate data analyses were conducted, where the first analysis was run with treatment, depth and site used as fixed effects and replicate used as a random effect. However, significant interactions involving the fixed effect of site (Table 1.2) led to an additional data analysis, where the first analysis was considered as preliminary. A second analysis was conducted on each individual site, with treatment and depth considered fixed effects and replicate considered as a random effect. The test method used to differentiate changes across both traffic treatments and depth was an analysis of variance (ANOVA). When the ANOVA yielded significant differences between traffic treatments (α = 0.05), a Tukey HSD post-hoc test was carried out (Table 1.2). A Kruskal-Wallis rank sum test was carried out on variables that did not meet the assumptions of normality and homogeneity of variance using the transformed data, as continuity between pre and post transformed results were sought.

Analysis of the mass fractal dimension used a range of diameters, and thus to addresses any scaling effects between mass and diameter, a linear regression was applied. Larger diameter clods may have introduced experimental bias when being compared to their smaller counterparts. Thus, the data was log (base 10) transformed to mitigate such bias. To analyze any statistical relationships among soil parameters (ρ_B, S-Index, field capacity, saturated water content, PVF and UHC), Spearman rank correlations (ρ) were carried out on original and transformed data.

1.4 Results

1.4.1 Bulk Density

Analysis of each individual study site revealed inconsistent trends in soil bulk density (ρ_B) between the trafficked areas of the conventional traffic system and the un-trafficked areas of the controlled traffic system. However, the average ρ_B decreased by 6% in the un-trafficked areas (Table 1.3) and increased by 6% in the 15-20 cm depth (Table 1.4). Several of the sites (Cleardale, Dapp, Lacombe, Neerlandia and Trochu) displayed statistically significant (α = 0.05) overall decreases of ρ_B within the un-trafficked areas of 4-17% (Table 1.3). The remainder of the sites (Morrin, New Norway and Rolling Hills) did not show significant differences between traffic treatments. These aforementioned sites showed changes in un-trafficked ρ_B of -1%, 2% and 0.5%, respectively (Table 1.3). Morrin was the only site that displayed an increase in un-trafficked ρ_B. Furthermore, the trafficked ρ_B at Morrin was the lowest of all the sites at 1.10 ± 0.156 g cm^{-3}, with the mean and standard deviation substantially lower than the total un-trafficked average of 1.22 ± 0.21 g cm^{-3}.

1.4.2 Porosity and Pore Volume Fractions

As anticipated, changes in the total porosity mirrored the bulk density results due to high correlation ($\rho = -0.966$, $P < 0.001$) between the parameters. On average, a increase of total porosity by 6% in the un-trafficked CTF area was observed (Table 1.3), followed by a decrease by 4% in the 15-10 cm depth (Table 1.4). Significant increases of total porosity by 4-15% were observed in the un-trafficked CTF areas at Cleardale, Dapp, Lacombe, Neerlandia and Trochu (Table 1.3). Morrin and New Norway showed no significant differences in total porosity, with the largest increase in total porosity of the un-trafficked samples observed at the Neerlandia (15%) and Cleardale (12%) sites. Thus, two of the three sites sampled within their first year of CTF establishment (Neerlandia and Cleardale) registered the largest differential boost in total porosity in the un-trafficked zones. Furthermore, analysis of pore volume fractions (PVF) provided insights as to how improvements in soil porosity were occurring.

Pore volumes were broken into fractions according to differing ranges of diameters and were, therefore, classified as macro (>60 µm), meso (60 to 9 µm), micro (9 to 6 µm) and residual (<6 µm). Comparing the macro PVF among sites, only Cleardale, Dapp, Lacombe and Trochu displayed significant improvements within the un-trafficked CTF regions between 39% and 163% (Table 1.3). Meanwhile, our Neerlandia and New Norway sites exhibited non-significant increases of 5% and 22% within the un-trafficked macro PVF range, respectively. By contrast, non-significant decreases in macro PVF of 3% at Morrin and 15% at Rolling Hills were witnessed. However, it is noteworthy to mention that the Morrin site displayed the lowest trafficked bulk density with a macro PVF a striking 1.5 times higher in the un-trafficked CTF soils when compared with the overall mean across all of our sites (0.093 versus 0.058 cm^3 cm^{-3}, respectively).

Differences in the soil meso PVF between the trafficked IT treatments and un-trafficked CTF zones were of a lesser extent than the macro PVF. The meso PVF were significantly larger in the un-trafficked soils by 36% in Cleardale, 29% in Dapp and 47% in Trochu, with non-significant increases of 12% in Lacombe and 19% in Neerlandia (Table 1.3). Following the similar pattern as the macro PVF results, Morrin, New Norway and Rolling Hills did not show statistically significant differences between the traffic treatments. Generally speaking, a larger portion of the total pore volume was typically allocated to the meso pore diameter range, as it comprised of nearly 20% of the total pore volume within the averaged soil matrix.

The changes in macro and meso PVF were generally shown to be inversely related to alterations in micro and residual PVF, which may be due to changes in the pore diameter distribution. Un-trafficked soils at Dapp and Trochu displayed a significant increase of 14% and 25% in micro PVF, while concurrently exhibiting reductions in residual PVF of 10% and 21%, respectively (Table 1.3). However, the Neerlandia site showed significant increases in both the micro (26%) and residual (10%) PVF for the un-trafficked CTF soils, which followed the opposite trend of the majority of the sites (Table 1.3). The remainder of the sites (Cleardale, Lacombe, Morrin, New Norway and Rolling Hills) displayed minimal non-significant differences between traffic treatments for the both the micro and residual PVF. Although, significant differences between soil depths were observed at Morrin, Neerlandia, New Norway and Rolling Hills, with a higher micro PVF exhibited in the 15-20 cm depth and a greater residual PVF occurring in the 5-10 cm depth (Table 1.4).

1.4.3 Saturated Water Content and Field Capacity

The ability of the soil to retain water was measured through an analysis of the saturated water content (θ at 0 KPa) and field capacity (θ at -33 KPa). Comparison of the average saturated water content between traffic treatments and depth revealed an increase of 5% in the both un-trafficked CTF soils (Table 1.3) and the 5-10 cm depth (Table 1.4). Changes in saturated water content attributed from the cessation of traffic led to soils at Cleardale and Neerlandia showing significant increases within the un-trafficked zones of 10% and 15%, respectively (Table 1.3). With the exception of Rolling Hills, non-significant increases of 5% and under were displayed in the un-trafficked saturated water contents at the remainder of the sites, while the Rolling Hills site showed a 1% reduction in the un-trafficked areas. Water content at field capacity showed a mixed trend among the sites, with Cleardale displaying the highest field capacity and New Norway yielding the lowest (Table 1.4). A significant increase in the un-trafficked soils field capacity water content of 11% was observed at Neerlandia, which was contrasted by a significant reduction in un-trafficked field capacity of 13% at Trochu (Table 1.4). Additionally, significant differences between the 5-10 cm and 15-20 cm depth occurred at Neerlandia, New Norway and Rolling Hills (Table 1.3), with the 5-10 cm depth displaying consistently higher field capacity water contents.

1.4.4 Unsaturated Hydraulic Conductivity

The unsaturated hydraulic conductivity (UHC) was separated into three classes of large (-1 to -10 KPa), medium (-10 to -20 KPa) and small (-20 to -33 KPa). Analysis of the UHC beyond -33 KPa was not carried out due limited data availability. A quantification of the conductivity beyond the measurement range would have been based upon extrapolated models with high RMSE and low R^2 values, thus resulting in low precision. Due to the high variability of UHC data, significant differences were only observed between depths and not traffic treatments. Increases in the large UHC occurred in the 15-20 cm depth, with significant increases witnessed from 47% to 354% at Morrin, Neerlandia, New Norway, Rolling Hills and Trochu (Table 1.4). Similarly, the 15-20 cm depth also displayed significant increases in the medium and small UHC at the same sites, with increases ranging from 40% to 251% (Table 1.4).

1.4.5 Soil Quality Parameters

Analysis of the slope at the inflection point of the water retention curve showed that Neerlandia was the only site that displayed an S-Index value beyond the good soil quality threshold (Table 1.3). Independent of the low S-Index values, the average un-trafficked CTF S-Index increased by 14% (Table 1.4), with significant increases in the un-trafficked CTF areas occurring between 12 and 39% at Cleardale, Dapp, Neerlandia and Trochu (Table 1.3). Furthermore, non-significant increases in soil S-Index were also witnessed in the un-trafficked CTF soils at the Lacombe and Rolling Hills sites, with the remainder of the sites displaying minimal differentiation between the traffic treatments. Additionally, a general trend of higher S-Index in the 5-10 cm depth occurred throughout the sites, with significantly higher values displayed at Morrin, Neerlandia, and Trochu (Table 1.4).

In general agreement with the relationships observed in the S-Index, analysis of the fractal dimension displayed similar trends. The fractal dimension (D_m) was observed to significantly decrease in the un-trafficked CTF areas at Cleardale, Dapp and Neerlandia (Table 1.6). Reductions in un-trafficked D_m throughout 75% of the measured sites displayed that hierarchical aggregation was occurring with the absence of traffic. Meanwhile, the New Norway site exhibited an increase in the un-trafficked D_m parameter, indicating a greater formation of micro aggregates with the recent removal of traffic. The similar trends witnessed between the fractal dimension and soil physical and hydraulic properties also correspond to the observation that the average fractal dimension indicated an improvement to soil structure by formation of macro aggregates witnessed through the reduction of overall D_m from 0.997 to 0.988 when comparing trafficked areas to un-trafficked areas, respectively (data not shown).

1.5 Discussion

1.5.1 Soil Physical Improvements from Controlled Traffic Implementation

Bulk density, porosity and the corresponding pore volume fractions are indicators that have commonly been used to quantify compaction in contrasting tillage regimes (Alakukku 1996a; Alakukku 1996b) and CTF environments (Chan et al. 2006; McHugh et al. 2009). The reduction of traffic had substantial effects on more than half of our study sites (Cleardale, Dapp, Lacombe, Neerlandia and Trochu), as they displayed significant improvements in key soil physical attributes when comparing the trafficked IT treatments with the un-trafficked CTF areas. Alterations between traffic treatments at Morrin were inconsistent with other sites; however, it should be noted that both the trafficked and un-trafficked bulk densities were relatively low for a clay textured soil (Table 1.1). This may imply that both the relatively low degree of compaction within the soil beneath the trafficked areas and the ameliorative effect within the un-trafficked areas at Morrin caused minimal differentiating effects (i.e., IT ≈ CTF). Soil samples in the 15-20 cm depth consistently displayed higher soil bulk densities then the 5-10 cm depth; however, the only significant interaction between depth and traffic treatment occurred at Neerlandia (Table 1.2). The significant interaction at Neerlandia showed no significant difference between traffic treatments in the 5-10 depth, but a significant increase in ρ_B in the IT treatment within the 15-20 cm depth (Table 1.5).

An increasing ρ_B within the deeper layers was expected as preexisting random traffic patterns in the field sites would have propagated compaction below the plow layer, which may still exist as legacy subsurface compaction (Alakukku 1996a; Strudley et al. 2008). Diminutions in the soil bulk density beneath the un-trafficked areas were evident across our study sites; however, ρ_B may not be the best indicator of soil quality between traffic treatments as soil texture and organic matter can also influence ρ_B values (Strudley et al. 2008). The rootability of soil, and by proxy the soils porosity, may be a better indicator of ameliorative effects; plant roots require pore space and connectivity for growth coupled with some form of modest compaction to facilitate root and soil matrix contact (Hernandez-Ramirez et al. 2014). Improvements to soil porosity and associated rootability facilitate greater access to water and nutrients within the soil (Taylor & Brar 1991), indicating the usefulness of porosity as a soil quality attribute.

Samples collected from field replicates in each of the study sites were taken from within the same soil subgroup map unit, with the exception of the Lacombe and Tochu sites. The first and second field replications at Lacombe were taken from a low relief Eluviated to Orthic Black Chernozem underlain by medium to fine textured till, while the third and fourth replications were collected in a medium relief Orthic Black Chernozem underlain with moderately course textured sediments. Furthermore, these different soil classifications and properties occur in conjunction with clear differences in landscape forms and positions, which may allow for each of these two sets of field replicates to be assessed separately. Significant increases in porosity (7%) in the un-trafficked CTF soils was found in the uniform landscape positions (i.e., first and second replications) with null differences between traffic treatments occurring in the replicates within the undulating portion (i.e., third and fourth replications) (data not shown). This may suggest that implementation of CTF systems could lead to spatially heterogeneous responses as an interaction with terrain attributes. Furthermore, three of the field replications at Trochu were located in an Orthic Black Chernozem underlain by fine sediments, while the outlier field replicate was underlain by medium textured sediments. While the entire data set for the Trochu site resulted in null statistical effects, exclusion of the field replicate with different parent material as informed by soil classification (AGRASID) yielded a significant increase of 8% in total porosity for the un-trafficked CTF soils (data not shown). Thus, when considering samples collected within their respective soil subgroup map units, this confounding factor can be removed to potentially display inherit differences between traffic types. This may also allude to the observation that CTF implementation within a field may have a large degree of variability in a non-uniform landscape.

The general increases in soil porosity witnessed following the removal of traffic were further quantified by determining which diameters of pore volume were altered. The most consistent trend of pore volume differences occurred in the macro and meso PVF, as these pore diameters are the most susceptible to degradation due to compaction (Blanco-Canqui et al. 2010; Li et al. 2009). From both the statistically and biologically significant perspectives, increases in the macro and meso PVF indicate that adoption of CTF had a profound effect beneath the un-trafficked areas in terms of water transmission pores. Transmission or macro pores are largely responsible infiltration rates at the soil surface and available water storage capacity of the soil (Lipiec et al. 2006), and thus play an important role in the capture of surface runoff. If the un-trafficked areas within CTF are capable of supporting higher infiltration rates and water storage capacities, then it can be hypothesized that the overall water capture and availability would beneficially increase in a CTF system when compared to conventional traffic systems. This hypothesis can be further reinforced as CTF managed fields receive 40-70% less spatial compaction than their counterparts with conventional traffic systems (Tullberg 2000). Confinement of the spatially applied compactive effort can lead to a greater area of soil within a CTF environment having an increased ability to transmit water. The increases in macro pore volume may be a good indicator of improvements in soil physical quality, as there can be direct correlations of intake, redistribution and storage of water in soils with plant productivity (Whalley et al. 1995).

The majority of our un-trafficked porosity enhancements occurred in the macro and meso pore volume diameter range (Table 1.3), with the 5-10 cm depth showing higher values and more frequent improvements (Table 1.4). Although the enhancements to the soil in the 5-10 cm depth were rarely significantly better than the 15-20 cm depth, the improvements may have been marginally influenced by the occurrence of wet-dry and freeze-thaw cycles along with root growth. In contrast to our findings, Hakansson et al. (1988) describes that the compaction alleviation potential of these cycles were shown to considerably decrease with depth and to have variable effects with differing soil textures. Furthermore, reductions in equipment applied compactive effort have showed a much greater influence with soil compaction alleviation when compared to natural soil state changes (Alakukku 1996b; Radford et al. 2001; Radford et al. 2007), indicating that our soil improvements were mainly attributed to the CTF traffic regime. As our study sites employing CTF were either managed with zero or reduced tillage, improvements to the macro and meso pore volume in the 5-10 cm depth cannot be attributed to some perceived short term effect of tillage. Conversely, positive changes in the 15-20 cm depth of the un-trafficked areas were observed less frequently, as amelioration of the soil at greater depths may take longer periods of time to accrue (Radford et al. 2007).

Most of our legacy sites (Dapp, Lacombe and Trochu), with greater than two years of CTF implementation, displayed clear increases in un-trafficked pore volume (Table 1.2). More specifically, the legacy sites were observed to have more noticeable improvements in the un-trafficked macro and meso PVF. However, the Morrin site exhibited no significant changes between treatments in any of the measured soil physical properties despite employing CTF for 5 years. Although, this site had one of the lowest un-trafficked bulk densities and highest trafficked porosity (59%), which may collectively indicate that an overall good status of soil quality had already existed prior to CTF establishment. As described by McHugh et al. (2009), the majority of the soil improvements attributed to the reduction of trafficked areas were observed within the 22 months following CTF implementation. This observation may suggest that the use of CTF at a site that already displays indicators of good soil physical quality could lead to incremental or minimal changes experienced by the soil. On the contrary, the Rolling Hills site showed no indication of soil structure improvements (Table 1.2) irrespective of nearly the same duration of CTF application as Morrin. Rolling Hills displayed the lowest overall porosity of 41% in our study, indicating that unaccounted intrinsic management variables and the soil texture coupled with the application of continuous irrigation (Table 1.1) may be limiting any potential benefits perceived from CTF implementation.

Among the recently initiated CTF sites (Cleardale, Neerlandia and New Norway), no continuous trend of changes was observed between traffic treatments in the soils physical characteristics (Table 1.2 & 1.3). However, the Cleardale site exhibited larger soil pore volume in the un-trafficked CTF areas, which can in part be attributed to a deep vertical tillage (30 cm) operation conducted prior to CTF tramline establishment. This deep tillage treatment at Cleardale before CTF implementation could have alleviated pre-existing soil compaction (Chamen et al. 2015; Chan et al. 2006), facilitating the soil amelioration process faster than other new sites (Hebb 2015) and therefore, may explain why the Cleardale site behaved similar to the legacy sites. The significant differences in pore volume between traffic treatments observed at Neerlandia mainly occurred in the micro and residual range within the 15-20 cm depth (Table 1.5). Furthermore, a lack of observable differences between traffic treatments at New Norway were likely due to application of the IT treatment consisting of only one additional equipment pass, which would have been an inadequate representation of a conventional traffic system. These differences between traffic types among the sites may allude to CTF enhancing micro pore volume in the early phase of implementation, while improvements to the macro pore volume may require a lengthier usage of CTF. Collectively, these results suggest that the outcome of CTF implementation can be site specific and may occur at varying temporal stages (McHugh et al. 2009; McPhee et al. 2015). Additionally, our data analysis showed that the spatial distribution of soil properties was not only affected by the management system, but also the soil type and landscape (Guenette 2017, Chapter 3). The spatial variation entailed by both the management system and the underlying landscape should be further studied to understand any spatial interactions or concurrences that may be taking place beyond the sole contrast of conventional versus controlled traffic systems.

1.5.2 Alterations to Soil Water Dynamics

Examination of the hydraulic properties of a soil can help to inform how alterations to the soil structure influence the dynamics of water movement (Blanco-Canqui et al. 2010; Lipiec et al. 2006), indicating that the soil physical enhancements found in the un-trafficked areas should also extend to improvements in water storage and movement. Linking the improvements to soil structure found in the un-trafficked soils, significantly larger saturated water contents at the recently established CTF sites could be attributed to large initial increases in total porosity (Table 1.3). The water content at field capacity differed across each soil order and texture, as this property refers to the water content at a specific matric potential at which the evapo-transpirational flux does not exceed the re-distributional flux within the profile (Cassel & Nielsen 1986). Thus, the assumption of field capacity existing at a water potential of -33 KPa allows for direct comparisons among the sites and between traffic treatments. The significant increase of the un-trafficked field capacity at Neerlandia could be a result of the initial increase in total porosity; moreover, the observed reductions in soil field capacity with longer durations of CTF (i.e., legacy sites) may be attributed to visual shifts in the pore size distribution as shown by the average water retention curves (Fig. 1.3). As our measurement of field capacity is based upon a specific matric potential and thus pore diameter, increases in the un-trafficked water transmission pores derived from enhanced soil structure were found to be inversely proportional to corresponding decreases in residual pore volume when comparing the trafficked and un-trafficked soils (Fig. 1.3).

Movement of water throughout the soil profile can be measured by means of the hydraulic conductivity (Schindler & Müller 2006). The unsaturated hydraulic conductivity (UHC) was used instead of the saturated hydraulic conductivity because it provided a means of quantifying the pore connectivity attributed to water flux within the soil at varying matric potentials. The high variability of our UHC data between traffic treatments can be common (Strudley et al. 2008) and is shown as the UHC standard deviations were more than 200% of their respective mean values (data not shown). Thus, the highly variable data leads to inconclusive findings when comparing contrasting traffic management regimes over multiple temporal scales. However, it is noteworthy that the un-trafficked soils generally exhibited non-significant improvements for the large and medium UHC class (Table 1.3) with significantly higher conductivity in the 15-20 cm depth (Table 1.4). Nonetheless, nearly every site displayed enhancements in the un-trafficked large UHC range irrespective of corresponding increases in macro PVF. This lack of an interrelationship between UHC and PVF is further shown by a nonsignificant correlation between these two variables ($\rho = -0.335$, $P > 0.05$). This leads to the conclusion that the conductivity of the soil relies upon more than just its respective soil structure and that UHC data is highly dynamic (Strudley et al. 2008).

1.5.3 Soil Quality Recovery in CTF Systems

Soil quality may be defined as the ability of the soil to produce and sustain biological function and growth (Congreves et al. 2015). The quality of a soil can be measured by biological, chemical and physical indicators; however, focusing on the physical dimension, Dexter (2004) postulated a metric of soil physical quality (S-Index) derived from the slope of the water retention curve which correlates to the amount of structural and textural pores within the soil. Thus, for S-index values greater than 0.035, there exists an abundance of structural pores and hence a well-developed soil structure, which can be attributed to good soil quality (Dexter 2004). In our study, S-Index values lower than 0.035 were predominately observed and expected under both traffic systems (Table 1.3), as agricultural soils do not generally exhibit good S-Index values. Irrespective of this threshold of good soil quality not being met, the reduction of traffic significantly improved the S-Index soil quality metric within the un-trafficked areas at Cleardale, Dapp, Neerlandia and Trochu (Table 1.2). This is important, as relatively larger portions of un-trafficked areas with corresponding higher S-index values exist under controlled traffic systems when compared to conventional traffic systems. The trend of increasing S-Index values may be caused by their dependency on the shape of the water retention curve, which integrates a variety of factors besides the soil structural state. Thus, the un-trafficked S-index increases may be a function of multiple parameters, as shown by Fig. 1.4 and the significant correlations of S-Index with total porosity (ρ = 0.607, $P < 0.001$), meso pore volume (ρ = 0.903, $P < 0.001$), micro pore volume (ρ = 0.920, $P < 0.001$) and the Large UHC class (ρ = 0.836, $P < 0.001$). Furthermore, field sites that displayed statistically significant improvements of the S-Index also displayed improvements in the aforementioned soil properties (Fig. 1.4).

The fractal dimension (D_m) of aggregates was quantified at half of our study sites (Cleardale, Dapp, Neerlandia and New Norway) to examine if the existence of hierarchical aggregation and soil structural developments were a function of CTF implementation (Table 1.6). The lower the D_m values obtained from the fractal dimension calculation (Equation [1.3]), the greater the likelihood of the existence of a hierarchical structure (Hirmas et al. 2013). Notably, the measured D_m values (Table 1.6) for the un-trafficked areas agree with our observations of significant S-index increases (Table 1.3). Cleardale, Neerlandia and Dapp displayed evidence of hierarchical aggregation under un-trafficked CTF areas, indicating the existence of improved soil structure due to the formation of macro-aggregates. However, evidence of improved hierarchical aggregation in the un-trafficked soils was not witnessed at New Norway and was likely due to limited application of equipment traffic in the IT treatment. Furthermore, increases in un-trafficked D_m (Table 1.6) at New Norway were consistent with the respective non-significant reduction in un-trafficked S-Index values (Table 1.3), as these results displayed the opposite trend of the other sites. These observations may indicate that alterations to soil physical quality attributes directly coincide with changes in fractal dimension. The sites that displayed increases in un-trafficked S-Index values along with indications of hierarchical aggregation indicate coherent improvements in soil quality in the un-trafficked areas, and hence, further support the independent results of ρ_b, PVF ranges, and UHC classes.

From a regional perspective, the implementation of CTF with zero tillage methods, such as those in Australia (McHugh et al. 2009; Tullberg et al. 2007; Tullberg 2010), at sites that were comprised of a Dark Grey Luvisol or Black Chernozem generally displayed positive responses in the un-trafficked soils towards soil quality improvements. However, at the Morrin (Humic Vertisol) and Rolling Hills (Brown Chernozem) sites, non-significant and marginal differences were observed for soil physical and hydraulic indicators between the traffic types. This may be explained by natural variability within the commercial fields and may also reflect instances where the CTF traffic regime was not fully followed. As farming operations need to be dynamic and flexible, strict compliance to the CTF system may not always be feasible. Although the quantification of the spatio-temporal variability of soil properties and adherence to a prescribed traffic regime are beyond the scope of our study, these factors could have heavily influenced the observed variability within our field samples.

1.5.4 Controlled Traffic Farming Contributions and Limitations in the Canadian Prairies

Controlling where the traffic is applied within a commercial agriculture field is anticipated to contribute in reducing overall soil compaction, as a single farming operation can facilitate spatial coverage of 20-35% of the field in equipment traffic (Tullberg 2000). Management techniques that limit the environmental footprint, such as reducing spatially applied compaction, should theoretically aid in the attainment of agricultural sustainability (Hurni et al. 2015). Despite the motivation for producers to utilize sustainable practices, the adoption and acceptance of CTF has been met with hurdles and skepticism (Kingwell & Fuchsbichler 2011). The benefits of CTF implementation towards soil physical quality within the un-trafficked zones in the Canadian Prairies is shown in over half of our study sites (Cleardale, Dapp, Lacombe, Neerlandia and Trochu) as well as others in Australia (McHugh et al. 2009; Radford et al. 2007), China (Qingjie et al. 2009), the United Kingdom (Chamen et al. 2015) and the United States (Blanco-Canqui et al. 2010; Unger 1996). However, improvements may only be realized if conversions from conventional traffic regimes to controlled traffic regimes take place without any prior use of current best management practices (i.e., equipment size matching or use of auto guidance). Field sites that had been previously been managed through minimum tillage practices with various forms of auto guidance may have already contributed to improvements in traffic efficiencies. The use of these best management practices is common in the Canadian Prairies, indicating that the conversion of our commercial field sites to CTF would likely see reductions in spatial compaction toward the minimum value (i.e., ~40%).

In practical terms, CTF should be used within large fields that are well drained and allow for long linear distances to be exploited through the use of tramlines (Bochtis et al. 2010). Commercial field conditions in semi-arid dryland farming environments that are common to the Canadian Prairies are usually not representative of the ideal scenario, as controlling water movement over large areas can be costly and difficult. Additionally, equipment needed in CTF management systems require matching implement sizes and a standardized wheel gauge to be employed (Kingwell & Fuchsbichler 2011). Furthermore, tramline rutting from continual usage, reductions in production efficiency due to fixed tramline positions (Bochtis et al. 2010), complications in crop residue management due to uneven harvest residue distribution as well as lack of standardized equipment for CTF systems (McPhee & Aird 2013) can hinder the appeal of CTF**.** Irrespective of the benefits of CTF, complications in equipment matching and tramline establishment can occur in the adoption of CTF due to the costly endeavor of changing existing equipment. Furthermore, the confinement of the compactive effort to the tramlines had certain negative consequences, as the tramlines became less suitable for crop production and more suitable for equipment traffic. The inherit design of CTF, with our field geometry of 9 m swaths at 3 m tramline centers and 0.75 m tramline track widths, permits tramlines to comprise roughly 17% of the field area. Producers employing unseeded tramlines are challenged with leaving less area cropped per field in the CTF system, thus driving the need to experience yield gains to offset the reduced cropping area.

Reductions in trafficked areas due to pre-existing utilization of best management practices yielded very few significant differences in crop yields across our study sites (CTFA 2016). Likewise, crop yield improved under CTF management when compared to the conventional system for field pea crops in 2013 at Dapp (16%) and Trochu (2%) as well as at Neerlandia (13%) in 2015. Furthermore, significant increases ($P < 0.10$) in CTF barley yield were achieved at Trochu in 2012 (12%) and 2015 (3%) when compared to the IT treatment. The remainder of the sites displayed similar upturns in crop yield for both the controlled traffic and conventional traffic systems, with a similar amount significant crop yield increases occurring in the conventional traffic system (CTFA 2016). Despite inconsistent and marginal gains in CTF crop yield, the observed growing season precipitation for the sites sampled in 2014 showed nominal to higher than average rainfall, with sites sampled in 2015 showing much lower than average (Table 1.1). Thus, the adequate to surplus volumes of water experienced for the sites sampled in 2014 (legacy sites) may have masked benefits observed in CTF systems (Guenette 2017, Chapter 2), indicating the requirement of a longer temporal period needed for proper analysis of yield changes experienced in CTF systems throughout the Canadian Prairies. Yield benefits obtained from CTF implementation were observed in Australia (Li et al. 2007), China (Chen et al. 2008; Qingjie et al. 2009) and the United Kingdom (Smith et al. 2014); however, the same yield improvements may not directly apply to North America, as the climate and soils are inherently different (Kingwell & Fuchsbichler 2011). The size of farming operations and commercial fields in areas other than the Canadian Prairies (by proxy the North American Great Plains) are much smaller, inciting variability in the expected outcome of yield improvements within the Canadian Prairies.

1.6 Conclusion

The implementation of new management systems can often be accompanied by obstacles and limitations; however, the amelioration of soil quality attributed to controlling equipment traffic is a step towards achieving sustainable agricultural practices. The goals of this study were to evaluate across the regional scale of Alberta, Canada how soil characteristics changed in response to the presence of compaction and to determine how CTF affected soil quality. The removal of compaction within the un-trafficked soils caused a profound increase in water transmission storage and movement potential determined by significant increases in pore volume and non-significant increases in unsaturated hydraulic conductivity, respectively. Furthermore, indications of hierarchical aggregation occurring within the un-trafficked soils paired with enhancements to the un-trafficked soil S-Index allude to improvements of soil structure and quality due to CTF implementation in most sub-regions of Alberta. However, the trend of increases to the un-trafficked water transmission pore storage potential and movement ability were not always consistent in the smaller pore diameters. Thus, the highly variable nature of soil water dynamics was not solely influenced through soil structure and conductivity, despite being a function of the traffic management system.

Analysis of soil quality after varying temporal periods of CTF implementation suggested that substantial improvements to soil attributes occurred within the first two years after CTF employment. However, continual but lesser improvements to soil quality parameters were observed in most of the legacy sites. Thus, our findings suggest that soil quality improvements from CTF implementation are site specific and dependent on time from initiation, with higher amounts of variability experienced in non-uniform landscapes. Furthermore, regions that were comprised of Black Chernozemic and Dark Grey Luvisolic soils yielded the greatest response to traffic controlling. If a controlled traffic system is to be considered by producers, conversion from current best management practices, such as zero tillage, with increased traffic efficiencies to a CTF system may limit the positive impacts observed. This was shown across the regional areas of Alberta, as existing management techniques coupled with high amounts of precipitation at most of our sites in their respective sampling years contributed to minimal differences between controlled traffic and conventional traffic crop yields. However, it is imperative to recognize the substantial improvements to soil structure and quality that the implementation of CTF had on soil within the Canadian Prairies. As the quest for sustainable agriculture is pursued, CTF has shown to be tool that can aid in the achievement of this goal.

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1.9 List of Figure Captions

Fig. 1.1: Geographic locations (red dots) of the study sites across various soil groups throughout Alberta. Soil map courtesy of Alberta Ariculture and Forestry: http://www1.agric.gov.ab.ca/soils/soils.nsf/soilgroupmap?readform.

Fig. 1.2: Sampling design of a replicate, which consists of an imposed traffic treatment swath and a controlled traffic swath, within each field site across Alberta, Canada. Each sampling point has soil core samples taken from 5-10 cm and 15-20 cm depths (8 samples per replicate) and soil clod samples taken from a depth of 5-15 cm (4 samples per replicate).

Fig. 1.3: Water retention curve of the sites compared between trafficked (IT) and un-trafficked (CTF) treatments. The curves display van Genuchten modeled values based upon the data range of the measured values (n= 200).

Fig. 1.4: The soil physical quality as described by (i) S-Index (ii) Meso pore volume fraction (PVF) and (ii) Large unsaturated hydraulic conductivity (UHC) class in trafficked (IT) and un-trafficked (CTF) treatments for each site (NN: New Norway; RH: Rolling Hills). The soil physical quality metric S-Index is well correlated with the soil characteristics of meso PVF and large UHC. The mean values of each soil parameter is shown with their repective standard error values.

1.10 Tables and Figures

Table 1.1 Study site descriptions.

Type	Site	Texture	Soil Subgroup^	ATP^^ (mm)	GSPR^^^ (mm)	Sampling (year)	MP (years)	Tillage (type)	Crop (type)	Replicates (#)	Samples (#)
New	Cleardale	Clay	Gleyed Solonetzic Grey Chernozem	450-500	100	2015	1	Reduced	Wheat	4	32
	Neerlandia	Silty Loam	Orthic Dark Grey Chernozem	500-550	135	2015	1	Zero	Peas	4	32
	New Norway	Silty Loam	Eluviated Black Chernozem	450-500	170	2015	1	Reduced	Peas	4	32
Legacy	Dapp	Sandy Clay Loam	Dark Grey Luvisol	500-550	295	2014	5	Zero	Canola	3	24
	Lacombe	Sandy Loam	Eluviated/Orthic Black Chernozem	500-550	275	2014	5	Zero	Canola	4	32
	Morrin	Clay	Orthic Humic Vertisol	350-400	350	2014	5	Reduced	Canola	3	24
	Rolling Hills*	Fine Sandy Loam	Orthic Brown Chernozem	< 350	225	2014	4	Zero	Corn	3	24
	Trochu	Clay	Orthic Black Chernozem	400-450	258	2014	5	Reduced	Canola	4	32

New: CTF implementation less than 2 years; Legacy: CTF implementation from 2 to 5 years; ATP: average total precipitation from 1971-2000; GSPR: growing season precipitation received in year of sampling; MP: length of years the site has employed the management practice of CTF at the time of sampling. ^ soil subgroup data taken from agricultural region of Alberta soil inventory database (AGRASID) https://soil.agric.gov.ab.ca/agrasidviewer/; ^^ values obtained from agroclimatic atlas of Alberta 1971-2000 http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex10303; ^^^ values obtained from the Alberta climate information service (ACIS) http://agriculture.alberta.ca/acis/township-data-viewer.jsp

Table 1.2 Soil properties significance for ANOVA statistical analysis separated by factors of treatment (IT versus CTF), depth (5-10 versus 15-20 cm) and site. For soil properties that have the treatment x depth interaction not displayed, there were no significant interactions found.

Type	Site	Factor	Saturated (%)	BD (g cm^{-3})	Porosity (cm^3 cm^{-3})	FC (%)	S-Index (unitless)	Macro (cm^3 cm^{-3})	Meso (cm^3 cm^{-3})	Micro (cm^3 cm^{-3})	Residual (cm^3 cm^{-3})	Large (cm d^{-1})	Medium (cm d^{-1})	Small (cm d^{-1})
All Sites		Treatment	**	***	***	NS	***	***	***	*	NS	NS	NS	NS
		Depth	**	***	***	*	NS	NS	NS	NS	**	***	***	**
		Site	***	***	***	***	***	***	***	***	***	***	***	***
		T x D	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
		T x S	NS	*	NS	NS	*	*	*	**	***	NS	NS	NS
		D x S	*	NS	NS	NS	***	NS	NS	***	NS	**	*	NS
		T x D x S	NS	*	*	NS	*	NS	NS	**	NS	NS	NS	NS
New	Cleardale	Treatment	**	**	***	NS	*	**	***	NS	NS	NS	NS	NS
		Depth	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Neerlandia	Treatment	***	***	***	***	***	NS	NS	***	**	NS	NS	NS
		Depth	***	***	***	***	*	NS	NS	*	***	*	***	**
		T x D	***	***	***	**	**	NS	*	**	**	NS	NS	*
	New Norway	Treatment	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		Depth	NS	NS	NS	***	**	NS	***	***	***	***	**	*
Legacy	Dapp	Treatment	NS	**	**	NS	*	***	***	**	NS	NS	NS	NS
		Depth	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Lacombe	Treatment	NS	*	*	NS	NS	*	NS	NS	NS	NS	NS	NS
		Depth	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Morrin	Treatment	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		Depth	NS	**	**	NS	**	*	NS	NS	NS	***	***	NS
		T x D	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
	Rolling Hills	Treatment	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		Depth	*	NS	NS	*	NS	NS	NS	NS	*	**	*	NS
	Trochu	Treatment	NS	*	*	*	***	**	***	**	**	NS	NS	*
		Depth	NS	NS	NS	NS	*	NS	NS	NS	NS	***	***	***

* denotes $P < 0.05$; ** denotes $P < 0.01$; *** denotes $P < 0.001$; NS: no significant interaction occurring where $P > 0.05$; N/A: analysis did not involve interaction; Treatment (T): traffic fixed effect factor of IT versus CTF; Depth (D): fixed effect factor of 5-10 cm versus 15-20 cm; Site (S): fixed effect factor of different sites; Saturated: saturated water content at 0 KPa; BD: dry bulk density; Porosity: total porosity; FC: field capacity water content at -33 KPa; S-Index: soil physical quality metric; Macro: pore volume diameters >60 µm; Meso: pore volume diameters between 9-60 µm; Micro: pore volume diameters between 6-9 µm; Residual: pore volume diameters <6 µm; Large: unsaturated hydraulic conductivity between -5 and -10 KPa; Medium: unsaturated hydraulic conductivity between -10 and -20 KPa; Small: unsaturated hydraulic conductivity between -20 and -33 KPa; Fractal: mass fractal dimension

Table 1.3 Soil properties mean values across each study site contrasting trafficked (IT) versus un-trafficked (CTF) areas. The values displayed are composited by depth (5-10 and 15-20 cm) and by replicate. Volumetric saturated water content, field capacity, S-Index, macro, meso, micro and residual PVF, large, medium and small UHC were derived from the van Genuchten modeled curves, which are based upon raw data. Bulk density and total porosity are measured directly from dry weights.

Type	Site	Traffic	Saturated (%)	BD (g cm^{-3})	Porosity (cm^3 cm^{-3})	FC (%)	S-Index (unitless)	Macro (cm^3 cm^{-3})	Meso (cm^3 cm^{-3})	Micro (cm^3 cm^{-3})	Residual (cm^3 cm^{-3})	Large (cm d^{-1})	Medium (cm d^{-1})	Small (cm d^{-1})
Average		IT	50.13	1.31	0.505	35.04	0.022	0.044	0.079	0.035	0.344	0.0406	0.0099	0.0034
		CTF	52.39	1.24	0.534	34.59	0.025	0.058	0.091	0.039	0.335	0.0499	0.0108	0.0034
New	Cleardale	IT	48.96a	1.45b	0.454a	39.58	0.019a	0.022a	0.056a	0.023	0.384	0.0025	0.001	0.0006
		CTF	53.67b	1.30a	0.508b	38.64	0.021b	0.057b	0.077b	0.023	0.377	0.0026	0.0009	0.0005
	Neerlandia	IT	52.01a	1.24b	0.533a	32.64a	0.037a	0.034	0.111	0.063a	0.312a	0.1516	0.0277	0.0064
		CTF	59.57b	1.03a	0.612b	36.17b	0.045b	0.041	0.133	0.079b	0.343b	0.1658	0.0241	0.0052
	New Norway	IT	49.12	1.32	0.503	31.09	0.029	0.043	0.101	0.052	0.296	0.0687	0.0131	0.0035
		CTF	49.34	1.29	0.514	30.79	0.028	0.045	0.102	0.051	0.296	0.0897	0.0192	0.0051
Legacy	Dapp	IT	50.13	1.39b	0.477a	36.93	0.020a	0.035a	0.070a	0.034a	0.362	0.0143	0.0046	0.0022
		CTF	51.72	1.29a	0.513b	33.79	0.023b	0.060b	0.091b	0.039b	0.327	0.016	0.0048	0.0022
	Lacombe	IT	50.65	1.23b	0.538a	36.51	0.020	0.041a	0.076	0.029	0.360	0.0472	0.0181	0.0072
		CTF	53.23	1.17a	0.558b	36.53	0.021	0.057b	0.085	0.032	0.358	0.0687	0.0176	0.006
	Morrin	IT	52.36	1.10	0.586	30.35	0.025	0.096	0.103	0.033	0.292	0.008	0.0014	0.0006
		CTF	53.24	1.11	0.583	32.53	0.023	0.094	0.093	0.029	0.320	0.0065	0.0013	0.0005
	Rolling Hills	IT	45.07	1.56	0.412	34.57	0.014	0.039	0.048	0.021	0.344	0.0242	0.0117	0.0060
		CTF	44.64	1.55	0.414	34.72	0.016	0.033	0.047	0.024	0.346	0.0414	0.0169	0.0076
	Trochu	IT	52.71	1.21b	0.542a	38.65b	0.017a	0.044a	0.069a	0.028a	0.400b	0.0081	0.0019	0.0009b
		CTF	53.71	1.15a	0.567b	33.57a	0.024b	0.075b	0.102b	0.035b	0.317a	0.0089	0.0017	0.0006a

ab: letters indicate significant differences between treatment mean groupings within each site at a critical level of 0.05; IT: imposed traffic treatment; CTF: un-trafficked treatment; Saturated: saturated water content at 0 KPa; BD: dry bulk density; Porosity: total porosity; FC: field capacity water content at -33 KPa; S-Index: soil physical quality metric; Macro: pore volume diameters >60 µm; Meso: pore volume diameters between 9-60 µm; Micro: pore volume diameters between 6-9 µm; Residual: pore volume diameters <6 µm; Large: unsaturated hydraulic conductivity between -5 and -10 KPa; Medium: unsaturated hydraulic conductivity between -10 and -20 KPa; Small: unsaturated hydraulic conductivity between -20 and -33 KPa.

Table 1.4 Soil properties mean values across each study site contrasting surface (5-10 cm) versus subsurface (15-20 cm) layers. The values displayed are composited by treatment (IT and CTF) and by replicate. Volumetric saturated water content, field capacity, S-Index, macro, meso, micro and residual PVF, large, medium and small UHC were derived from the van Genuchten modeled curves, which are based upon raw data. Bulk density and total porosity are measured directly from dry weights.

Type	Site	Depth (cm)	Saturated (%)	BD (g cm^{-3})	Porosity (cm^{3} cm^{-3})	FC (%)	S-Index (unitless)	Macro (cm^{3} cm^{-3})	Meso (cm^{3} cm^{-3})	Micro (cm^{3} cm^{-3})	Residual (cm^{3} cm^{-3})	Large (cm d^{-1})	Medium (cm d^{-1})	Small (cm d^{-1})
Average		5-10	52.40	1.24	0.532	35.58	0.025	0.054	0.086	0.036	0.350	0.0324	0.0069	0.0026
		15-20	50.12	1.31	0.507	34.00	0.023	0.048	0.084	0.038	0.329	0.0581	0.0139	0.0043
New	Cleardale	5-10	51.02	1.35	0.491	38.48	0.020	0.045	0.066	0.026	0.379	0.0026	0.0009	0.0004
		15-20	51.61	1.40	0.471	39.74	0.019	0.035	0.067	0.021	0.381	0.0026	0.0010	0.0007
	Neerlandia	5-10	59.27	1.04a	0.608b	37.03b	0.044b	0.039	0.128b	0.076b	0.350b	0.1287a	0.0192a	0.0045a
		15-20	52.31	1.23b	0.537a	31.50a	0.038a	0.036	0.117a	0.066a	0.305a	0.1886b	0.0327b	0.0071b
	New Norway	5-10	49.55	1.31	0.508	32.48b	0.025a	0.047	0.090a	0.044a	0.314b	0.0337a	0.0074a	0.0029a
		15-20	48.91	1.30	0.509	29.30a	0.032b	0.040	0.113b	0.059b	0.278a	0.1246b	0.0248b	0.0057b
Legacy	Dapp	5-10	53.53	1.31	0.506	37.12	0.023	0.053	0.084	0.037	0.362	0.0133	0.0045	0.0021
		15-20	48.32	1.37	0.484	33.60	0.020	0.043	0.077	0.036	0.327	0.0170	0.0049	0.0022
	Lacombe	5-10	52.18	1.19	0.551	37.09	0.020	0.049	0.079	0.029	0.365	0.0611	0.0148	0.0060
		15-20	51.70	1.21	0.544	35.95	0.020	0.049	0.082	0.033	0.353	0.0548	0.0209	0.0071
	Morrin	5-10	54.91	1.03a	0.611b	31.81	0.027b	0.110b	0.104	0.026a	0.312	0.0026a	0.0007a	0.0004a
		15-20	50.69	1.18b	0.558a	31.07	0.021a	0.080a	0.092	0.035b	0.300	0.0119b	0.0020b	0.0006b
	Rolling Hills	5-10	46.24b	1.52	0.425	35.75b	0.014	0.038	0.047	0.022	0.355b	0.0127a	0.0063a	0.0038
		15-20	43.47a	1.59	0.401	33.54a	0.015	0.035	0.048	0.023	0.335a	0.0529b	0.0222b	0.0098
	Trochu	5-10	52.47	1.18	0.557	34.90	0.023b	0.052	0.092	0.031	0.364	0.0049a	0.0011a	0.0005a
		15-20	53.96	1.19	0.551	37.32	0.018a	0.066	0.077	0.032	0.355	0.0124b	0.0025b	0.0009b

ab: letters indicate significant differences between treatment mean groupings within each site at a critical level of 0.05; Saturated: saturated water content at 0 KPa; BD: dry bulk density; Porosity: total porosity; FC: field capacity water content at -33 KPa; S-Index: soil physical quality metric; Macro: pore volume diameters >60 µm; Meso: pore volume diameters between 9-60 µm; Micro: pore volume diameters between 6-9 µm; Residual: pore volume diameters <6 µm; Large: unsaturated hydraulic conductivity between -5 and -10 KPa; Medium: unsaturated hydraulic conductivity between -10 and -20 KPa; Small: unsaturated hydraulic conductivity between -20 and -33 KPa.

Table 1.5 Soil properties mean values across the Neerlandia site contrasting trafficked (IT) versus un-trafficked (CTF) areas at surface (5-10 cm) versus subsurface (15-20 cm) layers. The values displayed are composited by replicate. Volumetric saturated water content, field capacity, S-Index, macro, meso, micro and residual PVF, large, medium and small UHC were derived from the van Genuchten modeled curves, which are based upon raw data. Bulk density and total porosity are measured directly from dry weights.

Depth (cm)	Traffic	Saturated (%)	BD (g cm^{-3})	Porosity (cm^3 cm^{-3})	FC (%)	S-Index (unitless)	Macro (cm^3 cm^{-3})	Meso (cm^3 cm^{-3})	Micro (cm^3 cm^{-3})	Residual (cm^3 cm^{-3})	Large (cm d^{-1})	Medium (cm d^{-1})	Small (cm d^{-1})
5-10	IT	58.85	1.05	0.608	36.75	0.043	0.036	0.129	0.076	0.348	0.1265	0.0189	0.0043
	CTF	59.68	1.04	0.608	37.30	0.045	0.043	0.126	0.076	0.352	0.1310	0.0194	0.0047
15-20	IT	45.16a	1.44b	0.458a	28.5a	0.031a	0.032	0.093a	0.050a	0.277a	0.1767	0.0366	0.0085b
	CTF	59.45b	1.02a	0.616b	34.89b	0.046b	0.039	0.140b	0.081b	0.334b	0.2006	0.0288	0.0057a

ab: letters indicate significant differences between treatment mean groupings within each site at a critical level of 0.05; Saturated: saturated water content at 0 KPa; BD: dry bulk density; Porosity: total porosity; FC: field capacity water content at -33 KPa; S-Index: soil physical quality metric; Macro: pore volume diameters >60 µm; Meso: pore volume diameters between 9-60 µm; Micro: pore volume diameters between 6-9 µm; Residual: pore volume diameters <6 µm; Large: unsaturated hydraulic conductivity between -5 and -10 KPa; Medium: unsaturated hydraulic conductivity between -10 and -20 KPa; Small: unsaturated hydraulic conductivity between -20 and -33 KPa.

Table 1.6 Fractal dimension of soil aggregation. Lower D_m values indicate the existence of a hierarchical structure within the soil and thus correlates to improved soil quality.

Site	Treatment	*P* Value	D_m (unitless)	Standard Error	n
Cleardale	IT	***	1.0007b	0.0094	43
	CTF		0.9635a	0.0121	43
Dapp	IT	***	0.9900b	0.0133	65
	CTF		0.9870a	0.0065	53
Neerlandia	IT	***	1.0090b	0.0078	44
	CTF		1.0030a	0.0054	44
New Norway	IT	***	0.9880a	0.0056	44
	CTF		0.9970b	0.0096	42

ab: letters indicate significant differences between treatment mean groupings within each site at a critical level of 0.05; *** denotes $P < 0.001$; IT: imposed traffic treatment; CTF: un-trafficked treatment; n: sample size

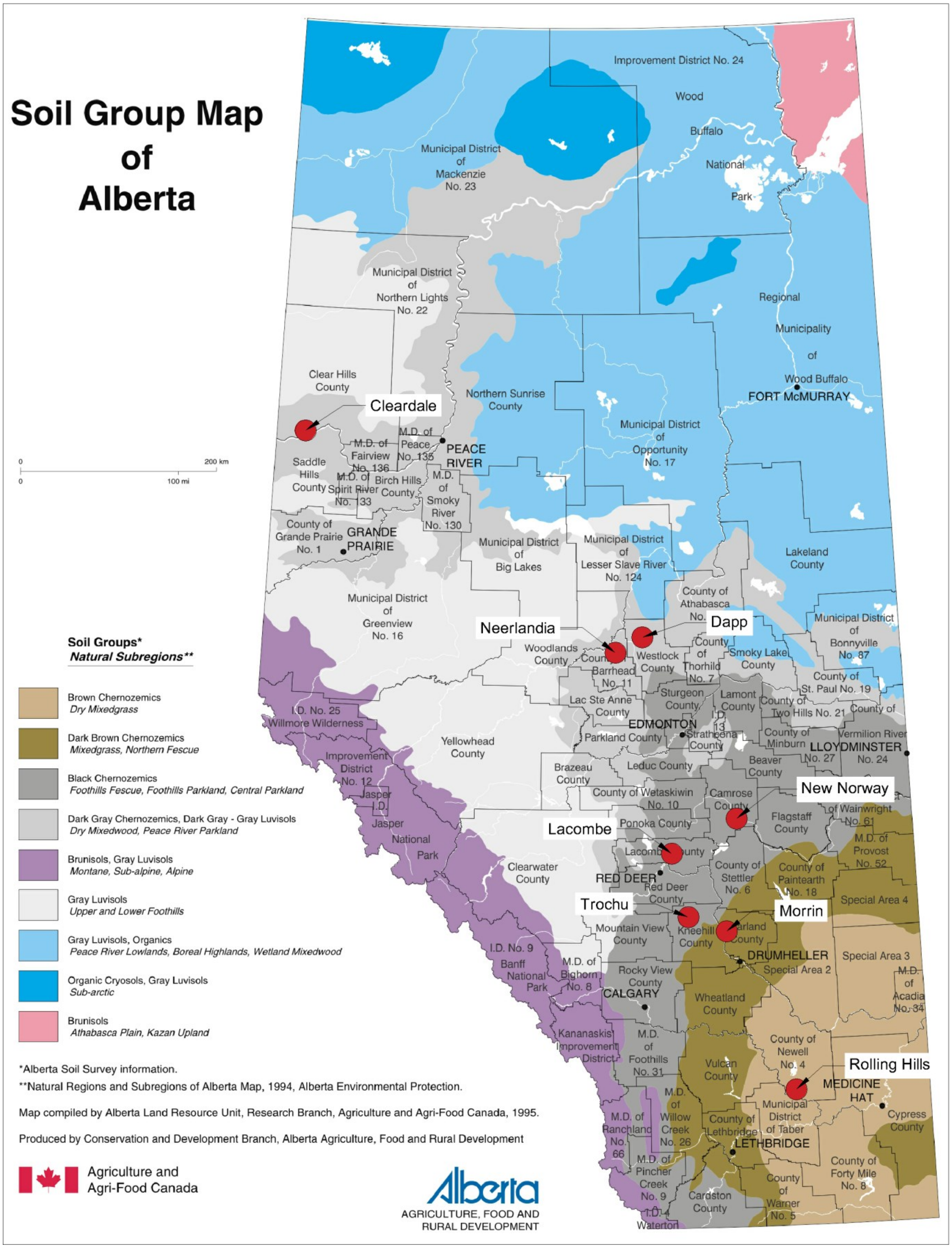

Fig. 1.1 Geographic locations (red dots) of the study sites across various soil groups throughout Alberta. Soil map courtesy of Alberta Ariculture and Forestry: http://www1.agric.gov.ab.ca/soils/soils.nsf/soilgroupmap?readform.

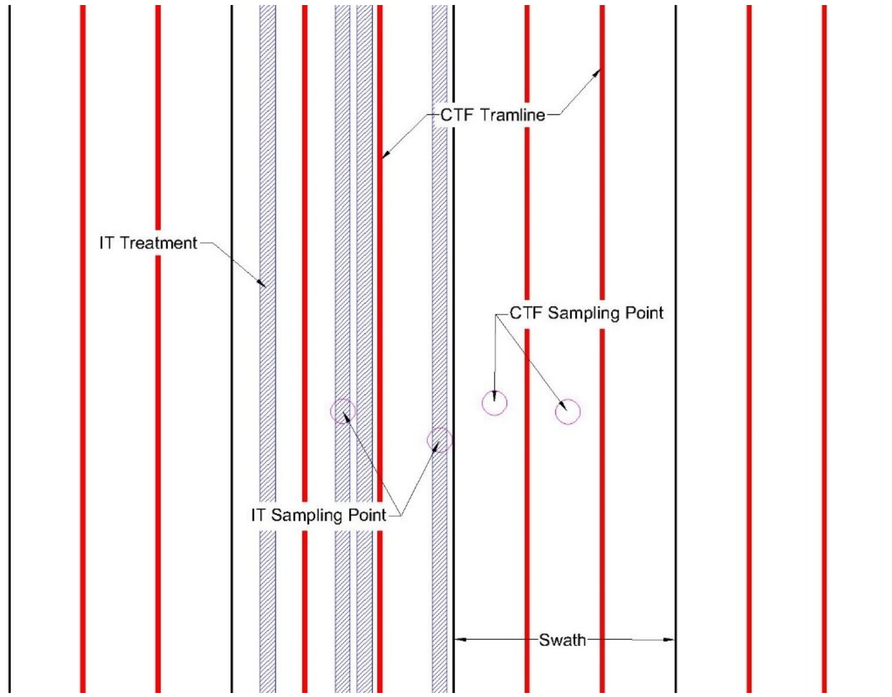

Fig. 1.2 Sampling design of a replicate, which consists of an imposed traffic treatment swath and a controlled traffic swath, within each field site across Alberta, Canada. Each sampling point has soil core samples taken from 5-10 cm and 15-20 cm depths (8 samples per replicate) and soil clod samples taken from a depth of 5-15 cm (4 samples per replicate).

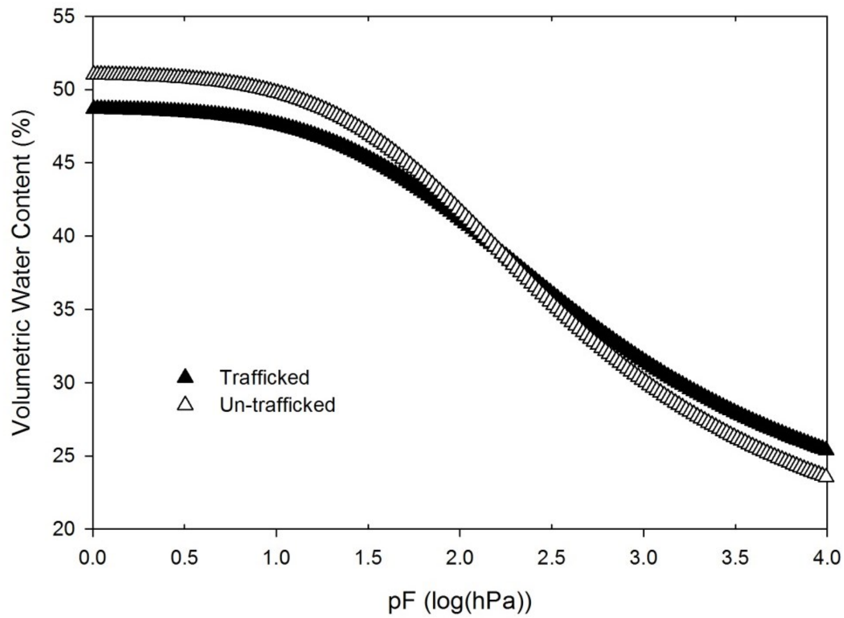

Fig. 1.3 Water retention curve of the sites compared between trafficked (IT) and un-trafficked (CTF) treatments. The curves display van Genuchten modeled values based upon the data range of the measured values (n= 200).

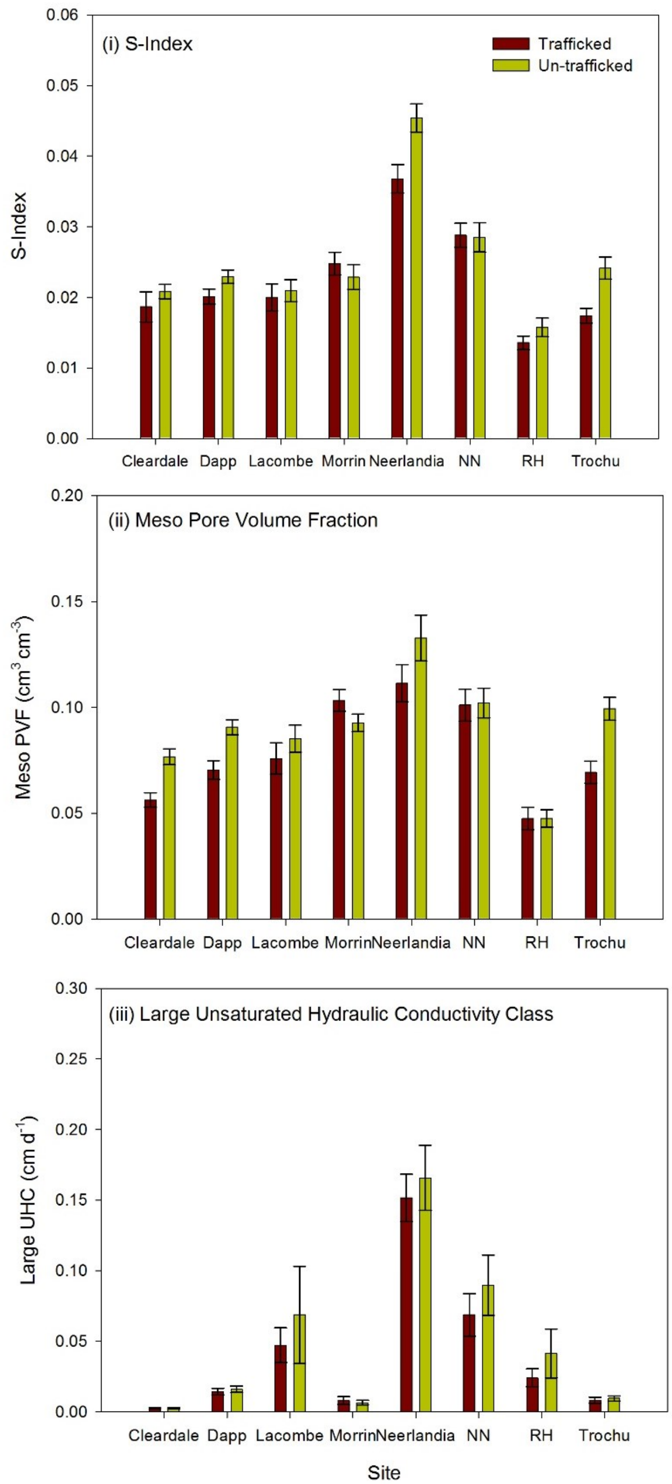

Fig. 1.4 The soil physical quality as described by (i) S-Index (ii) Meso pore volume fraction (PVF) and (ii) Large unsaturated hydraulic conductivity (UHC) class in trafficked (IT) and un-trafficked (CTF) treatments for each site (NN: New Norway; RH: Rolling Hills). The soil physical quality metric S-Index is well correlated with the soil characteristics of meso PVF and large UHC. The mean values of each soil parameter is shown with their repective standard error values.

Chapter 2. Water Use Responses of Faba Bean under Simulated Controlled Traffic Conditions

2.1 Abstract

Uncertainty in the severity of future weather systems poses a risk towards the production of future crops; however, contemporary managements systems, such as controlled traffic farming (CTF), may act as a buffer in improving the resiliency of arable soils. Achieving resiliency in agroecosystems can also be accomplished through the incorporation of pulse crops, such as faba beans (*Vicia faba* L.), into crop rotations. As these practices become more common in the Canadian Prairies, it is imperative to gain a comprehensive understanding of how faba beans interact with variations in the soil-plant-atmosphere continuum in a broad variety of management systems. A greenhouse study was carried out on faba beans with treatments of varying compactive effort and water availability in soil pots, which were chosen to emulate common field conditions found in CTF. Despite implicit dissimilarities between in-field and greenhouse settings, conclusive observations showed that increasing soil compaction restricted plant productivity. However, the presence of high water availability was shown to offset the negative results of increasing applications of compactive effort while displaying a lower water use efficiency (WUE) in the faba beans. The lower water availability, which represented field moist conditions, exacerbated differences in plant responses across compaction treatments. Furthermore, the compaction treatment with a bulk density of 1.2 g cm^{-3} coupled with a high water availability of -10 KPa yielded the best results for most measured parameters, with a contrasting detrimental compaction treatment of 1.4 g cm^{-3} bulk density at a lower water availability of -100 KPa. Handheld sensor-based measurements on faba bean canopies were closely associated with plant stress indicators. The normalized difference vegetation index (NDVI) exhibited a strong correlation with faba bean biomass production. Although the stomatal conductance (g_s) was able to determine plant water stress and capture WUE responses, g_s measurements were not linked to faba bean biomass production.

2.2 Introduction

The long term use of conventional agricultural systems coupled with the prevalence of changing climatic conditions has greatly increased the risk in agricultural practices as a function of food production (Hurni et al. 2015). Furthermore, changes within the climate may be further exacerbated by an expected global temperature increase from 1.3 to 3.4 °C by 2100 (Smith et al. 2015) with a mean increase of 2°C by 2100 in Alberta (Nixon et al. 2015). The severity of climatic deviations from normal conditions was shown by "the drought of 2012 in the United States [which] led to a reduction of maize yields of up to 25% (which is moderate compared with the impacts projected for some regions at higher levels of temperature increase)" (Rosenzweig et al. 2014). Therefore, it is important to develop and implement new management techniques that enable the mitigation of productivity risk and reduction of agriculture's environmental footprint, such as the use of more diverse crop rotations (Congreves et al. 2015). Specifically, the incorporation of legumes into current crop rotations has displayed positive effects on the soil biota, as legume amalgamation was shown to improve subsequent yields while simultaneously reducing fertilizer inputs (Dias et al. 2015). For instance, the inclusion of legumes into crop rotations has risen in Alberta, Canada from 623,200 planted hectares in 2014 to 734,500 planted hectares in 2015, with faba beans making up nearly 5% of total pulse cropped area (Alberta Agriculture and Forestry, 2015). Therefore, with current legume growth trends, faba bean cropped area should be poised to increase.

The integration of faba beans into crop rotations that are paired with management systems that improve soil quality may prove to be useful a tool to increase the resiliency of the soil in different conditions (Jensen et al. 2010). Conversely, changes in weather patterns may lead to reductions in the quantity of arable land and make the occurrence of drought conditions more common (Rosenzweig et al. 2014), forcing management systems to achieve a more efficient use of water resources. Thus, developing methods to improve the availability of water resources is important as water has been shown to be a major limiting factor in global agricultural crop production (Kröbel et al. 2014; Medrano et al. 2015; Xu & Hsiao 2004). Soil profile water storage is dependent on many factors within the soil-plant-atmosphere continuum (Federer 1979), which has led to the investigation of the factors that influence and control water use efficiencies in dryland environments on wheat (Kröbel et al. 2014; Liang et al. 2002; Sadras et al. 2005), faba beans (Husain et al. 1990; Loss & Siddique 1997) and the inclusion of both cereals and legumes with varying rotations (Campbell et al. 2007; Hatfield et al. 2001; Nielsen et al. 2005).

Despite the addition of water resources and any associated plant water stresses in dryland farming environments being dependent on uncontrollable sources, Li et al. (2007 & 2009) and McHugh et al. (2009) describe how management systems that control and reduce spatially-applied soil compaction, such as controlled traffic farming (CTF), can lessen plant stresses based on improvements to water storage capacity of the soils. Essentially, CTF is a management system where wheel traffic is confined to specific areas within the field (i.e., tramlines), which allows the majority of cropped areas to be grown in un-trafficked conditions (Tullberg et al. 2007). The contrasting effects of compacted and un-compacted soils on plant yield has been shown by Radford et al. (2001), as soils with a high bulk density can reduce the ability for plants to access and attain essential resources. Additionally, the detrimental effects of a combination of a high degree of soil compaction and depletion in soil water availability has been shown in wheat (Sadras et al. 2005), soybean (Buttery et al. 1994) and the common bean (Buttery et al. 1998). Conversely, there is a lack of existing literature on the dynamics and responses of faba beans exposed to varying levels of soil compaction and simultaneously different levels of water availability on common agricultural soils in the Canadian Prairies. Furthermore, a clear knowledge gap exists in both the physiological and water use interactions of plants when comparing between conventional and controlled traffic systems. This knowledge gap may be bridged through the quantification of plant canopy responses across contrasting management systems and varying soil conditions, which may be achieved through the use of hand held sensor based measurements (Holzapfel et al. 2009b) to potentially provide producers with the ability to un-intrusively measure plant stress.

If reductions in soil compaction can improve the water use efficiency, then management systems that support increases in water use efficiencies should be employed to help mitigate future productivity risks. It was the goal of this study to determine how different soil conditions typically experienced in a CTF managed landscape drive faba bean plant responses and if these responses are a function of either the compaction, water availability or both interacting simultaneously. This was pursued through experimentation and analysis of how simulated compaction and established water availability levels impact the soil-plant-atmosphere continuum under a controlled greenhouse setting. We also sought to determine if handheld sensor based measurements of faba bean canopies, such as normalized difference vegetation index and stomatal conductance, can be used to detect plant responses to varying soil compaction and contrasting water availabilities.

2.3 Materials and Methods

2.3.1 Experimental Design

The study was carried out in a greenhouse using soil pots (n=48) arranged in a randomized complete block (factorial) design with eight treatments and two soil types. Each pot (experimental unit in this study) consisted of a white 4.8 L rigid plastic bucket with dimensions of 20.5 cm in height, 19.5 cm in top inner diameter and 17.5 cm in bottom inner diameter that was packed with soil up to a height of 18 cm. The soils used in the experiment were collected from two commercial agriculture field sites within Alberta that were actively employing CTF. Soil collection took place in a Dark Grey Luvisol soil (Dapp, SW&SE-35-62-1-W5M) and a Black Chernozem soil (Lacombe, NE-34-40-26-W4M), as these soil orders are commonly found within agricultural regions across Alberta (Table 2.1). Within each site, soil was collected from a depth of 5-20 cm within the un-trafficked cropping zones, which was sealed in containers after collection at 5 °C until the experiment was performed. Soil taken from each of the sites was composited within each soil type and mixed prior to being packed into the pots.

Soil treatments (n=8) were applied to each individual pot as a combination of soil bulk density and water availability (Table 2.2) with two soil types. This greenhouse soil pot experiment followed three sequential phases: (i) a primary cropping phase with wheat (*Triticum aestivum* L.) grown as a soil conditioning period, (ii) a freeze/thaw period and (iii) a secondary cropping phase with faba bean (*Vicia faba* L.) grown as the analysis period. The goal of the wheat phase was to induce soil conditioning (through natural consolidation and root growth) as similar as possible to field conditions so that the faba bean phase would be grown in conditions emulating spring field sowing. The first cropping phase consisted of wheat being established in four dry soil bulk density treatments ranging from 1.0-1.4 g cm^{-3} in both soil types, with a consistent water availability of -33 KPa (Table 2.2). The second cropping phase of the study consisted of faba beans grown in the established pots with eight treatment combinations of four soil dry bulk densities (1.1-1.4 g cm^{-3}) and two contrasting water availabilities (10 and -100 KPa) in both soil types (Table 2.2).

The dry bulk density values were chosen based upon field conditions encountered in both conventional and controlled traffic environments. The density treatments consisted of one control treatment and three treatments with varying levels of compactive effort applied (Table 2.2). The control density of 1.0 g cm^{-3} (treatment 1) represented a soil with ample pore space and marginal compaction, which was established by filling the pot with soil without applying any significant compression. Natural consolidation in the control treatment over the course of the wheat phase raised the dry soil bulk density from 1.0 g cm^{-3} to 1.1 g cm^{-3} for the faba bean phase. The lightly compacted soil density treatment of 1.2 g cm^{-3} (treatment 2) represented a soil environment achieved with un-trafficked zero till CTF management. Treatment 3 consisted of lightly compacted soil within the top half of the pot (1.2 g cm^{-3}) and a heavily compacted soil within the bottom half (1.4 g cm^{-3}). This treatment represented the existence of a plow pan that may be experienced in some conventional traffic operations with un-controlled traffic regimes. Heavily compacted soils that exist in the tramlines of CTF systems or areas of high traffic volume in conventional traffic were simulated by treatment 4 (1.4 g cm^{-3}). The soil density treatments were applied at the beginning of the first cropping phase (wheat) and used without additional alterations throughout the duration of the study. Packing of the soil occurred at field moist conditions (22% gravimetric water content). Creating the specified dry bulk density within the pot was achieved by filling the soil pot with an approximate volume of soil that was gradually packed in four separate layers of 4.5 cm thickness from a Proctor Hammer (4.5 kg with a 45 cm falling distance).

The water availability, or matric potential, describes the energy state of water within the soil and corresponds to a specific volumetric water content that can be derived from the water retention curve (Schelle et al. 2013). The water contents at two pre-selected water availabilities were attained from water retention curves measured by soil samples taken from our Dapp and Lacombe sites in both trafficked and un-trafficked areas at depths of 5-10 cm and 15-20 cm (data not shown). The wheat or conditioning phase of the study employed a uniform water availability across all treatments (-33 KPa), which was used to ensure the wheat plants had adequate water availability and initial conditions for the faba bean phase were consistent. During the faba bean or measurement phase of the experiment, two treatments of water availability were to simulate field conditions at field capacity (-10 KPa) and at field moist (-100 KPa).

2.3.2 Greenhouse Study

Throughout the duration of both cropping phases, all pots received a 16-hour light period per day in the greenhouse. The light period for the wheat phase of the study was supplemented with additional lighting provided by two sets of high output fluorescent T5 lights (4100 K) positioned 1 m above the top of the plants, as daylight hours experienced in the winter months were shorter than those experienced during the growing season. Supplementary lighting was not directly supplied to the faba bean phase, as daylight hours were consistent with those experienced in growing season conditions throughout the Canadian Prairies. As recorded by a HOBO® UX100-001 temperature datalogger (Oneset® Computer Corporation, Bourne, MA, USA), ambient temperatures within the greenhouse had diurnal fluctuations between 17°C and 31°C (data not shown). Pot locations in the greenhouse were randomized every week to reduce any possible effects of varying microclimatic conditions and positional variation.

The wheat planted in the first cropping phase of the study was a Canadian Western Red Spring cultivar called AC® Muchmore (FP Genetics, Regina, SK, Canada). The seeds were planted on 10 Feb 2016 and terminated after anthesis, or at Z69 (Zadoks et al. 1974), on 26 April 2016. A seeding rate of 250 plants per m^2 (McKenzie et al. 2011) was followed, with 12 seeds initially planted in each pot and then thinned to 8 plants per pot after emergence. A seeding depth of 4 cm below soil surface was applied, as recommended by Alberta Agriculture and Forestry (2008). After sowing had taken place, the pots were exposed once a week to a fertilizer solution of 1 g L^{-1} of 20-8-20 (200 ppm N, 80 ppm P, 200 ppm K) and 0.05 g L^{-1} of stock tank mix (0.39 ppm B, 0.03 ppm Cu, 2.1 ppm Fe, 0.9 ppm Mg, 0.6 ppm Mn, 0.018 ppm Mo, 0.9 ppm S, 0.12 ppm Zn) with the corresponding water used to maintain the nominal water content. After harvesting of the wheat took place, wheat stubble was left standing at 2 cm above the soil surface in each pot. Upon completion of the first cropping phase of the study, 5 g of wheat straw biomass was applied to the soil surface to simulate crop residue addition. The pots were then placed in a freezer at -20°C from 6 May 2016 to 20 May 2016, as this was done to simulate winter conditions that take place between growing seasons in the Canadian Prairies.

Sowing of the faba beans in the second cropping phase of the study utilized a zero tannin faba bean cultivar called Snowbird (Innoseeds B.V., Vlijmen, Netherlands). Seeding of the faba beans took place on 2 June 2016 with termination of the plants occurring after anthesis, or at BBCH 69 (Lancashire et al. 1991), on 25 July 2016. Seeds were planted at a rate of 43 plants per m^2 (Alberta Agriculture and Forestry 2007; Douglas et al. 2013), with an initial seeding rate of 3 plants per pot that were thinned to 1 plant per pot shortly after emergence. Seeds were placed in each pot with 6.2 kg ha^{-1} of granular Tagteam inoculant to a depth of 6 cm below the soil surface (Douglas et al. 2013). Fertilization was administered in the same technique and interval as the first cropping phase, with weekly applications of 1 g L^{-1} of 10-52-10 (100 ppm N, 520 ppm P, 100 ppm K) and 0.05 g L^{-1} of stock tank mix (0.39 ppm B, 0.03 ppm Cu, 2.1 ppm Fe, 0.9 ppm Mg, 0.6 ppm Mn, 0.018 ppm Mo, 0.9 ppm S, 0.12 ppm Zn).

2.3.3 Measurements

Water availabilities were maintained for both cropping phases via measuring the mass of each pot through the use of a 30 ± 0.001 kg load cell (Sartorius AG, Goettingen, Germany), in which gravimetric water contents were calculated based up their respective dry bulk densities. Water contents were brought back to their nominal levels every two days based upon the difference between the measured and nominal weight, as drying periods were used to simulate natural growing conditions. During the addition of water in the wheat phase, the weight of the biomass was not accounted for. However, the weight of the aboveground biomass was accounted for in the faba bean phase through the use of a faba bean growth curve (Fig. 2.1) calculated prior to initiation.

Throughout the duration of the study, sensor and plant based measurements were taken on a weekly basis for both the wheat and faba bean plants. The sensor based readings were taken on a weekly basis and include the leaf stomatal conductance (g_s, mmol m^{-2} s^{-1}) and normalized difference vegetation index (NDVI, unitless). The g_s and NDVI readings were taken between 1100 and 1500 coordinated universal time (UTC), with care being taken to avoid direct sunlight during the measurement period. Stomatal conductance is a quantification of the water vapor efflux (and associated carbon dioxide influx) in leaf stomatal openings, and has been shown to be a good indicator of plant water stress (Fischer 1970). We measured g_s on the topmost fully developed leaf of each plant using a SC-1 steady state diffusion leaf porometer (Decagon Devices Inc., Pullman, WA, USA). Prior to taking g_s measurements, the porometer was calibrated to the relative humidity conditions experienced in the greenhouse each week. Analysis of the g_s data was normalized to 25°C to account for temperature fluctuations at the time of sampling.

Additionally, the NDVI of a plant has been shown to correlate to possible nutrient stresses (Raun et al. 2002; Tubaña et al. 2008) and was used as an indicator to quantify changes in plant nutrient status throughout the study. The NDVI was taken 60 cm directly above the plant canopy of each pot by using a handheld HCS-100 GreenSeeker® (Trimble® Inc., Sunnyvale, CA, USA) and ranged from a minimum reading of 0 to a maximum of 1. It is important to note that the measurement of NDVI is not a direct reading, but a measure of the reflectance of visible red and near infrared wavelengths from the plant surface (Rouse et al. 1974). The reflectance of the plant can also be correlated to the colour of the plant, which has been shown to have a direct correlation between the concentration of chlorophyll within the leaves and the nitrogen use of a given plant canopy (Filella et al. 1995) and is shown through the following:

$$NDVI = \frac{(NIR - red)}{(NIR + red)} \quad [2.1]$$

Where near infrared (NIR) and visible red (red) are measurements of light reflectance within those spectrums. Plant based measurements taken on a weekly temporal scale included the plant height (cm) and evapotranspiration rates (mm d^{-1}). Upon completion of each cropping phase, the final plant height and aboveground biomass for each pot was measured, where the aboveground biomass was collected and placed in an oven at 65°C for at least 24 hours to obtain the constant mass values. Root biomass was collected for the faba bean phase upon completion of harvesting, where six soil core samples (i.e., inner diameter of 3 cm and height of 15 cm) were taken from each pot in a circular pattern around the faba bean plant. The soil samples were composited by pot and wet-sieved to separate the root biomass from the soil. Wet sieving was accomplished with the application of room temperature water through a 2 mm sieve to catch larger roots and a 1 mm sieve to catch finer roots. The collected root biomass was then place in an oven at 65°C for 24 hours to determine the respective constant mass value.

The water use efficiency (WUE, mg dry biomass g^{-1} water) of each pot was calculated based upon the evapotranspiration rates and total aboveground dry plant biomass collected (De Jong & Rennie 1969), which was calculated through the following:

$$WUE = \frac{D_m}{\theta_i - \theta_f + \sum GSWI} \qquad [2.2]$$

Where D_m is the total aboveground collected or calculated dry biomass, θ_i is the initial water content of the soil at the start of each phase, θ_f is the final water content of the soil upon completion of each phase and GSWI is the growing season water input based upon the total amount of water added to each pot throughout the study.

2.3.4 Statistics

Multiple observations per soil pot of NDVI and g_s for each week were averaged to produce mean values and avoid pseudo-replication. Analysis of the WUE, final height, above and below ground biomass was done with the treatment combinations of soil bulk density and water availability and soil type used as the fixed effects and replicate used as the blocking factor. Additionally, the treatment combinations of soil bulk density and water availability, soil type and time (i.e., week) were used as the fixed effects, with replicate used as a blocking factor for the temporal analysis of the repeated measurements of ET, height, NDVI and g_s. To account for the lack of independence between repeated measurements, correlation and variance structures were introduced into the model and checked with an autocorrelation function (alpha = 0.05) to ensure the assumption of sphericity was met. Furthermore, each soil type was analyzed separately due to significant interactions between soil type and treatment, with soil bulk density and water availability as the fixed effects and replicate as the blocking factor. The analysis was carried out in both, R ver. 3.3.1 (RDCT 2015) and SigmaPlot ver. 11.1. (SYSTAT 2008).

Prior to analyzing the data, the assumptions of normality and homogeneity of variance were checked through the Kolmogorov-Smirnov and Bartlett Tests, respectively. The test method used to differentiate changes across treatments was an analysis of variance (ANOVA). When the ANOVA yielded significantly different results among treatments ($\alpha = 0.05$), a Tukey HSD post-hoc analysis was carried out (Table 2.3). Least square means were calculated to determine significant trends within treatments and the temporal scale. Spearman rank correlations (ρ) were carried out on both plant and sensor-based measurements.

2.4 Results

2.4.1 Evapotranspiration and Water Use Efficiency

The water use efficiency for the faba bean plants was based upon the total aboveground dry plant biomass (mg) and the total amount of water added to each pot (g) over the duration of the faba bean phase. The Black Chernozem (Lacombe) displayed a higher ability to sustain evapotranspiration rates on average and in the lower water availability treatment (-100 KPa) than the Dark Grey Luvisol (Dapp), which was also reflected by the water use efficiencies (Table 2.4). Evapotranspiration rates showed statistically significant ($\alpha = 0.05$) differences across treatments for both soil types, where the higher water availability (-10 KPa) showcased consistently higher evapotranspiration rates than the lower water availability (Table 2.4). Additionally, the compaction treatment of 1.2 g cm^{-3} coupled with the high water availability displayed the highest and a significantly better level of evapotranspiration across the treatments in both soils, with a 56% difference occurring between the lowest flux values witnessed in the 1.4 g cm^{-3} at the lower water availability. Furthermore, treatments with lower bulk densities generally displayed higher evapotranspirational flux than the higher bulk density treatments.

The faba bean WUE displayed no significant differences among treatments in the Dark Grey Luvisol, but displayed significant differences in the Black Chernozem (Table 2.3). In the Black Chernozem soil, the lowest WUE occurred in the in the control (1.1 g cm^{-3}) at the high water availability (-10 KPa) and was contrasted by a 28% and a 32% increase in the highest WUE treatments displayed at bulk densities of 1.2/1.4 g cm $^{-3}$ and 1.4 g cm^{-3} in the lower water availability (-100 KPa), respectively (Table 2.4). Additionally, the lower water availability treatments that continuously yielded lower evapotranspiration flux also showed higher WUE when compared to the high water availability. Conversely, this trend was not followed in the Dark Grey Luvisol, as non-significant differences between treatments displayed no clear trend. Generally, the lower soil bulk density treatments coupled with higher water availability yielded favorable growing conditions for the plants which contributed to an environment with a lower efficiency in water use.

2.4.2 Normalized Difference Vegetation Index

The NDVI readings of the plant canopy were used in our study to differentiate possible changes in plant nutrient status among the treatments, as it may be considered a proxy for the general nutrient status of a plant in respect to nutrient uptake (Holzapfel et al. 2009a; Mkhabela et al. 2011). The Black Chernozem soil displayed a higher average NDVI than the Dark Grey Luvisol; however, both soils displayed similar trends among treatments. Significant differences were observed among treatments in both soils, as the 1.4 g cm^{-3} at -100 KPa treatment yielded the lowest levels of leaf reflectance (Table 2.4). Conversely, the 1.2 g cm^{-3} at -10 KPa treatment produced the highest NDVI readings in the Black

Chernozem, with all compaction treatments at the high water availability in the Dark Grey Luvisol yielding the highest NDVI (Table 2.4). Treatments with the higher water availability (-10 KPa) generally displayed higher NDVI values than the treatments with lower water availability (-100 KPa), indicating that greater water availability may positively influence faba bean plant nutrient use. However, increasing the compactive effort showed noticeable decreases in NDVI under the lower water availability treatment representing field moist conditions in both soils (Table 2.4).

2.4.3 Stomatal Conductance

Stomatal conductance (g_s) was used to monitor the water vapor flux as an indicator of water stress in our study. A consistent trend among the measured variables with the Black Chernozem displaying marginally better values than the Dark Grey Luvisol was also observed in the g_s readings. The measured g_s in the faba bean treatments displayed significant differences and followed a similar pattern found throughout the majority of the parameters, where g_s values in the higher water availability were consistently higher in all compaction treatments (Table 2.4). However, an additional data structure between the compaction treatments was observed, with g_s values decreasing with increasing compactive effort for both soils. Both the control treatment (1.1 g cm^{-3}) and the treatment representing un-trafficked areas (1.2 g cm^{-3}) at the high water availability (-10 KPa) displayed the highest g_s values in both soils, with the 1.4 g cm^{-3} at -100 KPa treatment showing a reduction from 90-160% (Table 2.4). Highlighting the difference in g_s values between water availabilities, a variation in conductance of 20% in the Dark Grey Luvisol and 35% in the Black Chernozem was found in the control bulk density (1.1 g cm^{-3}).

2.4.4 Plant Biomass

Significant variations among treatments in the aboveground biomass production occurred in both soil types, with the Black Chernozem producing an average of 20% more aboveground biomass than the Dark Grey Luvisol (Table 2.4). The highest producing treatment was observed at a bulk density of 1.1 g cm^{-3} at -10 KPa in the Dark Grey Luvisol and 1.2 g cm^{-3} at -10 KPa in the Black Chernozem, while the lowest production of aboveground biomass occurred in 1.4 g cm^{-3} at -10 KPa treatment for both soils (Table 2.4). The treatment response structure in regards to the least amount of aboveground biomass created was expected to occur in the highest compaction treatment; however, the poor performance of the control in the Black Chernozem was contrary to our initial hypothesis that the lowest bulk density treatment would yield the most optimum plant production. Significant differences among treatments for the root biomass production were only shown in the Black Chernozem soil, with the 1.2 g cm^{-3} at -10 KPa treatment showcasing the highest mean value. Significant differences observed in the Black Chernozem were the result of different compaction treatments (Table 2.3); however, the significant interaction between the bulk density and water availability treatments illustrate how the degree of access to water can attribute to the expansion or hindrance of root biomass at varying levels of compactive effort. Contrary to the other plant parameters, the high compaction treatment (1.4 g cm^{-3}) produced nearly the largest quantity of root biomass in both soils. Greater amounts of root biomass in the high compaction treatment may be attributed to the increased mass of soil within the constant volume of the pot, as rising levels of compaction received a higher quantity of water to achieve the same water availability as the lower compaction levels.

Faba bean plant height was measured throughout the duration of the faba bean study; however, final faba bean heights were measured at the termination of the faba beans and were shown to generally resemble a similar statistical response (Table 2.3) as well as emulate the same numerical pattern as the aboveground biomass and NDVI (Table 2.4). These results further demonstrate the usefulness of NDVI as a measure of faba bean nutrient status. The plant height results revealed a direct response to increasing amounts of water within the soil, as high water availability (-10 KPa) treatments generally displayed the largest final faba bean height in both soils. Dissimilar significant differences between both soil types were shown, as the Dark Grey Luvisol yielded the highest final faba bean height in the 1.1 g cm^{-3} at -10 KPa, while the 1.2 g cm^{-3} at – 10 KPa and 1.4 g cm^{-3} at – 10 KPa treatments displayed the highest overall final faba bean height in the Black Chernozem (Table 2.4). However, both soil types showed that the high compaction treatment of 1.4 g cm^{-3} at -100 KPa produced the lowest significant final faba bean height (Table 2.4). As was consistent with the majority of the measured parameters, the Black Chernozem (Lacombe) displayed higher plant height values. The detrimental effect of the high compaction treatment (1.4 g cm^{-3}) representing the tramlines or high traffic areas on final faba bean height was illuminated in both soils, as it was generally the poorest performing treatment across all the measure parameters.

2.4.5 Temporal Variation of Plant Parameters

Temporal changes were observed on a weekly basis after emergence of the faba beans for NDVI, plant height, g_s and WUE. Measurements took place within the second week after sowing (week 2), as the week of sowing was labeled as week 1. Temporal variations for the measured NDVI and stomatal conductance (Fig. 2.2a & 2.2b) did not follow the same trend, indicating each sensor-based measurement may be quantifying different plant processes. Temporal patterns for faba bean height and NDVI readings displayed similar patterns of steady increases with time; although, faba bean NDVI readings plateaued for all treatments in the seventh week after sowing (Fig. 2.2a & 2.2b). The plant height measurements showed no indication of a maximum being reached, which may be attributed to termination of the faba bean plants prior to the physiological maximum being realized. Maximum g_s was witnessed in the third week, with a continuous downward trend observed until the seventh week (Fig. 2.2a & 2.2b). Beyond week seven, conductance values displayed a rising tendency in all treatments apart from the 1.4 g cm^{-3} at -10 KPa. Similarly, the WUE exhibited the same peak in the third week followed by the downward trend for the remainder of the study (data not shown).

2.5 Discussion

2.5.1 Plant Dynamics Impacted by Varying Compactive Effort

Using a greenhouse study to draw conclusive observations that are applicable to field conditions can be challenging due to inherit differences in controlled environments of the greenhouse versus highly variable field conditions. However, in our study, we utilized soil taken from active commercial sites and subjected each soil pot to conditions that would be experienced throughout pre and post growing seasons before the main cropping phase of the study (i.e., faba beans) took place. Therefore, observations made from this greenhouse study may be considerably linked to environments found in comparable field conditions. Increasing compaction levels caused a variety of detrimental effects on the measured parameters irrespective of water potentials; however, a lack of continuity in the compaction response structure alludes to the possibility that the high water availability near field capacity (-10 KPa) was masking the overall negative effects of compaction. Conversely, at the relatively lower water availability comparable to field moist conditions (-100 KPa), the compaction experienced within the soil became the driving factor.

The control treatment (1.1 g cm^{-3}) experienced consolidation over the duration of the wheat cropping phase of the study, as the natural settlement of the soil increased the dry bulk density by 10% from 1.0 to 1.1 g cm^{-3}. The natural state of the soil reached through consolidation in the control treatment during the wheat phase was hypothesized to yield optimum results for the faba bean phase; however, the control was usually outperformed by the compaction treatment representing un-trafficked areas (1.2 g cm^{-3}). The sub-optimal performance of the control may have occurred due to enhancements in soil porosity observed in low soil bulk density settings, such as environments with applications of annual tillage, dissipating over the growing season to pre-sowing conditions near harvest (Strudley et al. 2008). Moreover, an evaluation of the effects of compaction show that a minimum amount of soil contact is required to facilitate ideal plant growing conditions (Chen & Weil 2011; Hernandez-Ramirez et al. 2014). Thus, a lack of soil and root contact experienced in the control treatment (1.1 g cm^{-3}) may have also attributed to the to the 1.2 g cm $^{-3}$ treatment yielding better plant productivity.

The increasing application of compactive effort generally showed both an optimum and unfavorable density for all parameters (Table 2.4). The bulk density of 1.2 g cm^{-3} representing the un-trafficked areas in CTF was considered as the optimal treatment due to its near continuous peak performance in both plant (Fig. 2.3) and sensor based measurements (Fig. 2.2a), which may have been realized due to its adequate water holding capacity coupled with the appropriate soil structure formation needed to facilitate soil-root contact (Hernandez-Ramirez et al. 2014). Deficient performance observed by the bulk density treatment of 1.4 g cm^{-3} at the relatively lower water availability representing field moist conditions (-100 KPa) was to be expected, as high applications of compaction have been shown to reduce plant yield and hamper plant nutrient uptake (Hamza & Anderson 2005; Horn et al. 1995). Furthermore, excessive soil contact experienced in both the plow pan treatment (1.2/1.4 g cm^{-3}) and the heavy compaction treatment (1.4 g cm^{-3}) exhibited generally poor but different responses as the water availability treatment changed. Dissimilarities in the trends between the water availability treatments when comparing the bulk density treatments of 1.2/1.4 g cm^{-3} and 1.4 g cm^{-3} suggest that a soil with uniform heavy compaction throughout the vertical profile has a more profound detrimental effect at relatively lower water availabilities than a soil profile exhibiting heavy compaction in the just subsurface layer alone (Table 2.4).

The parameter that was solely influenced by variations in compactive effort was the faba bean root biomass, as significant differences among treatments were only witnessed due to variations in bulk density in the Black Chernozem (Table 2.3). Plant root biomass (i.e., root diameter and length) has been shown to be significantly affected by soil strength by Shein & Pachepsky (1995), and in our case, was driven by the intensity of applied compaction in each treatment. The large quantities of root biomass in the 1.4 g cm^{-3} treatment that was displayed in our study for both soil types is inconsistent with other studies (Muñoz-Romero et al. 2011; Smit & Groenwold 2005), as well as the majority of our measured parameters (Table 2.4). However, in highly compacted soil, the structure is largely massive, which reduces the ability for water and nutrients to be transmitted through soil via mass flow and diffusion mechanisms (Taylor & Brar 1991; Salama & Sinclair 1994). Furthermore, this may indicate that the high mean values of root biomass observed in the 1.4 g cm^{-3} bulk density treatment could allude to increased amounts of root growth being developed by the faba beans which could be used to acquire access and uptake of nutrient and water resources through root interception processes.

Compaction treatments applied to the soil pots were shown to be representative of field conditions experienced in un-trafficked and trafficked portions of both conventional and CTF traffic systems in the Canadian Prairies (Guenette 2017, Chapter 1). The control treatment of 1.1 g cm^{-3} was representative of un-trafficked areas that received minimum tillage, with the optimal compaction treatment of 1.2 g cm^{-3} mimicking the un-trafficked areas managed with zero till. These representations of un-trafficked field conditions display the exceptional performance that un-trafficked soils in CTF management systems can have, which further indicate that these areas could incur the formation of an optimal plant growth medium from superior soil quality (McHugh et al. 2009). Alternatively, the heavy compaction treatment with a bulk density of 1.4 g cm^{-3}, which was representative of soil conditions experienced in tramlines or areas with recurring equipment traffic, displayed both reduced soil quality (Guenette 2017, Chapter 3) and diminished plant productivity. The highly compacted nature of tramlines can lead to reduced infiltration and water storage capacity (Li et al. 2009; Lipiec et al. 2006), which points to the high likelihood of plant growth in tramlines occurring in conditions more similar to the treatment of 1.4 g cm^{-3} at -100 KPa and suggests large reductions in tramline faba bean biomass and potential yield.

2.5.2 Influences of Soil Water Potential

Treatment response variations between the two water availabilities displayed a clear and consistent trend, as anticipated by the majority of the parameters measured (aboveground biomass, evapotranspiration, final faba bean height, normalized difference vegetation index and stomatal conductance), which displayed the most favorable responses in the high water availability treatment (-10 KPa) for most compaction treatments (Table 2.4). Faba beans have been shown to be highly susceptible to water stress (De Costa et al. 1997), indicating that the amount of available water within the soil can be an active component when determining the physiological state of the faba beans. Additionally, when fluctuations in water contents are paired with spatial distributions of compaction throughout a production field, variable plant production may be witnessed (Sadras et al. 2005). Contrary to our initial hypothesis of high bulk density treatments performing poorly in both water availabilities, the masking effect of adequate available water was shown as the high compaction treatment (1.4 g cm^{-3}) coupled with the high water availability treatment (-10 KPa) usually yielded favorable outcomes (Table 2.4). This masking effect could be attributed to the greater volume of water applied to the high compaction treatments, as a greater mass of soil and water is needed to achieve a higher bulk density and respective water availability within the fixed volume of the pot. The capacity for high water availability to mask the effects of the compaction treatments may also be explained through the increased ability of the faba beans to readily adapt and thrive in higher water environments (Husain et al. 1990; Jensen et al. 2010). Furthermore, the soil pots that contained the faba beans acted as a closed system and retained the applied water; however, in a field setting, this water may move away from these highly compacted areas as runoff or towards areas of greater porosity (i.e., lower compaction or bulk density) within the soil profile.

Although a clear indication of symmetry between high and low water availability was observed in our experiment, some of our measured parameters showed inconsistent response structures for compaction treatments when comparing the high and low water availabilities. Suggesting that the aboveground biomass, evapotranspiration, final faba bean height, NDVI and g_s parameters were a simultaneous and interactive function of both water availability and compactive effort within the soil (Table 2.3). Conversely, the WUE displayed statistically significant differences only as a function of the water availability treatments in the Black Chernozem (Table 2.3), indicating that it may not be directly driven by the amount of compactive effort applied to the soil. In general terms, higher water availability coupled with lower bulk densities in the soil pots were observed to create an environment suitable for optimum growing conditions. However, observed reductions of the WUE in the assumed optimal conditions may have been caused by a lack of initial plant stress, as plant stress in wheat crops have been shown to increase the overall WUE (Campbell et al. 2007; Kröbel et al. 2014). Despite faba beans possessing the perceived functionality to offset the detrimental effects of water stress through various physiological responses (Husain et al. 1990; Munoz-Romero et al. 2011), the physiological response of improved WUE in the high compaction treatments in our study was not enough to offset the damaging effects of excessive compaction (Khan et al. 2010) experienced in the other measured parameters.

2.5.3 Sensor-Based Measurements in the Soil-Plant-Atmosphere Continuum

Although variations in faba bean productivity were observed across treatments, inherit differences in some parameters were also experienced between soil types (Table 2.3). Despite very similar treatment response structures, the Black Chernozem taken from the Lacombe site generally displayed higher mean performance values for each treatment (Table 2.4). The enhanced productivity of the Black Chernozem soil may be explained by its lower pH, despite Jensen et al. (2010) indicating a threshold of pH higher than 6.5 for optimal growth of faba beans, as well as higher quantity of soil inorganic ammonium ion (NH_4^+) and a narrower C:N ratio due to smaller amounts of organic carbon when compared to the Dark Grey Luvisol taken from the Dapp site (Table 2.1). The movement of water throughout the soil-plant-atmosphere continuum (SPAC) in terms of treatments with high water availabilities and a dry bulk densities of 1.1 g cm^{-3} and 1.2 g cm^{-3} elicited the greatest response; however, at this matric potential (-10 KPa), the amount of available water was the main driving force (Table 2.3). Responses at the lower water availability (-100 KPa) were dependent on the compaction level, indicating that at field moist conditions, soil compaction can highly influence faba bean productivity (Table 2.4). Thus, the determination of how *insitu* field conditions could potentially effect SPAC-induced stress or predict faba bean biomass production during the early growth stages may prove useful via portable sensors as plant destructive testing can be avoided.

As a conceptual framework, SPAC can be used to describe the movement of water from the soil and through the plant into the atmosphere (Federer 1979). The sensor-based measurements captured in our study (NDVI and g_s) may be used as indicators of the dynamics of the SPAC, as they both revealed and quantified crucial factors causing plant stress. The normalized difference vegetation index has been previously demonstrated to model plant nitrogen use and accurately determine yield projections in multiple crop types (Holzapel et al. 2009b; Raun et al. 2002; Tubana et al. 2008). Moreover, our study is consistent with these existing reports as is evident by a high correlation (ρ=0.940, $P < 0.0001$) of our NDVI results with faba bean biomass production. Experimental conditions in our study which were more conducive to increased stress potential (i.e., high compaction and low water availability) caused decreased faba bean biomass and final faba bean height and support the clear association of NDVI with aboveground faba bean biomass production (Fig. 2.3). Despite the capacity of NDVI to reflect potentially confounding effects of plant nutrient uptake (Holzapfel et al. 2009a; Mkhabela et al. 2011), weekly fertilizer additions during the wheat and faba bean phases of our study aimed at limiting nutrient deficiency experienced by the plants. Thus, significant differences in our NDVI results across compaction and water availability treatments implied NDVI results were fundamentally caused by stress induced from fluctuations in both compaction level and water availability.

Differences across applied treatments support NDVI as a useful indicator of plant stress as driven by SPAC dynamics; however, correlating canopy NDVI readings with biomass production or plant height should be used with caution. Depending on the cultivar, indeterminate faba beans have been shown to display continuous growth and potential maturity delays under optimal growing conditions (De Costa et al. 1997). Therefore, the assumption that high NDVI readings and adequate faba bean nutrient uptake will produce optimal yields may not always hold, due to the potential of late maturity. This was shown in our study, as NDVI reading plateaued in the sixth week after sowing for varying bulk density (Fig. 2.2a) and water availability treatments (Fig. 2.2b) despite continual faba bean growth. Furthermore, faba bean nutrient deficiencies may not be captured from handheld NDVI readings as the NDVI indirectly measures the greenness of the plant from nitrogen uptake due to leaf reflectance from chlorophyll concentration (Filella et al. 1995), which may be inflated due to faba bean nitrogen fixation (Jensen et al. 2010). Further research is needed to address any possible disparities between the use of NDVI as a measure of the nutrient status in legumes due to their nitrogen fixation properties. Furthermore, additional rigorous analysis of sensor-based data should be completed for multiple crop types under a wider range of edaphic and climatic conditions before incorporation of sensor-based measurements, such as NDVI, into crop modeling, yield prediction or management zone delineation can confidently be undertaken.

The flux of water vapor and carbon dioxide through the leaf stomata is largely driven by changes in plant turgor, which can be correlated to the ability of the plant to obtain water through the SPAC (Fischer 1970) and be measured through the corresponding stomatal conductance (g_s) (Fischer et al. 1970a; Khan et al. 2010; Liang et al. 2002; Xia 1997). In our study, g_s responses to the treatments only partially parallel aboveground faba bean biomass production (ρ=0.424, *P*=0.003), but instead followed similar observations made by Liang et al. (2002) and inversely correlate with the total WUE in the Black Chernozem (ρ=-0.610, *P*=0.002). High values of g_s in the Black Chernozem were witnessed in treatments that displayed the lowest efficiency in water usage (1.1 g cm^{-3} and 1.2 g cm^{-3} at -10 KPa), indicating that g_s was able to adequately represent the evapotranspiration (ρ=0.623, P<0.001) and inversely represent the WUE of faba beans (Fig. 2.4). Additionally, the pod setting and filling stages of faba beans has been shown to be highly sensitive to the availability of water resources for faba beans (Jensen et al. 2010; Khan et al. 2010; Mwanamwenge et al. 1999; Xia 1994); however, in our study, large stomatal conductance within the corresponding second lowest week of WUE was observed in third week after faba bean sowing (Fig. 2.2b). This suggests that within the third week after sowing, there may be a threshold for responses of the Snowbird variety of faba bean, with subsequent weeks revealing divergent physiological responses due to compaction and water availability treatments. Regardless of both the NDVI and g_s measurements displaying similar treatment response symmetry, each parameter was able to capture and display different drivers for plant stress as evident by high correlations with different measures of plant productivity (e.g., NDVI with aboveground biomass and g_s with evapotranspiration and WUE). Furthermore, the significant interactions in both treatment levels for both soil types suggests that the stomatal conductance could be used as an indicator of water stress or the water use efficiency influenced by both the compactive effort and water availability in faba beans.

2.6 Conclusion

Faba bean plants displayed superior responses to treatments encompassing high water availability and soils with relatively low levels of compaction, with the optimal treatment in our study for faba bean productivity determined as 1.2 g cm^{-3} at -10 KPa. This optimal condition represents potential field conditions encountered in un-trafficked areas within CTF management systems at the maximum attainable water availability, as these soils generally incur lower bulk densities with higher water storage capacity (Guenette 2017, Chapter 3). Un-trafficked areas represent 65-80% of the field area in controlled traffic systems (Tullberg et al. 2007), indicating that the implementation of CTF may increase the buffering capacity of soils to sustain peak growth conditions for faba beans. Furthermore, applications of large amounts of compaction (i.e., areas with plow pans, tramlines or heavy traffic) were shown to limit plant productivity in terms of biomass production and water use efficiency. However, the detrimental effects of high compactive effort to faba bean productivity were somewhat offset through high amounts of available water (i.e., near field capacity), as faba beans displayed the ability to increase and sustain their WUE in less than optimal growing conditions.

Slight variations in treatment responses were witnessed between the Dark Grey Luvisol and the Black Chernozem soils. The Black Chernozem soil showed slightly elevated values for the measured parameters, apart from root biomass, when contrasted against the Dark Grey Luvisol. However, both soil types consistently displayed the poorest plant productivity in the 1.4 g cm^{-3} at -100 KPa treatment, as the use of sensor based measurements was able to enumerate faba bean stress across our range of treatments and soil conditions. Leaf reflectance quantified as NDVI was highly correlated with faba bean aboveground biomass production and could be a good indicator of plant nutrient uptake; although, use of NDVI as a quantification of whole biomass production may be skewed from sources of uncertainty, such as nutrient deficits (other than nitrogen), nitrogen fixation mechanisms and plant diseases. Moreover, stomatal conductance was a good indicator of the general water movement and stress elicited by variations in both compaction and water availability treatments, as it reflected changes in evapotranspiration and inversely correlated with water use efficiency. This study highlighted the effects of plant stress on faba beans caused by two different factors and reiterates the recommendation of achieving optimal growing conditions which may be possible in the un-trafficked areas of controlled traffic systems.

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2.9 List of Figure Captions

Fig. 2.1: Allometric growth of faba beans. Shows the relationship between the average height of faba bean plants and dry aboveground biomass. Data obtained for > 60 cm heights were taken from the dry weight of the aboveground biomass of all pots after completion of the second phases. Faba bean plants were grown during the first cropping phase in separate pots within the same greenhouse and were used to provide heights and dry weights in < 60 cm heights. The trend line is modeled based upon the best R^2 value.

Fig. 2.2a: Temporal changes of (i) normalized difference vegetation index (NDVI) and (ii) stomatal conductance per bulk density treatments. Shows the changes on a weekly basis of the NDVI and stomatal conductance measurements for mean values of each treatment combination. In both panels, the bulk density of 1.2 g cm^{-3} is shown to represent the most productive results, while the bulk density of 1.4 g cm^{-3} displays the worst.

Fig. 2.2b: Temporal changes of (i) normalized difference vegetation index (NDVI) and (ii) stomatal conductance per water availability treatments. Shows the changes on a weekly basis of the NDVI and stomatal conductance measurements for mean values of each treatment combination. In both panels, the high water availability (-10 KPa) is shown to represent the most productive results, while the low water availability (-100 KPa) displays the worst.

Fig. 2.3 Faba bean aboveground dry biomass and average normalized difference vegetation index (NDVI) as a function of bulk density treatments. Shows the compaction treatment effects on dry aboveground biomass and NDVI. The bulk density that was representative of the best growing condition in our study was 1.2 g cm^{-3} and generally shows the highest biomass production.

Fig. 2.4 Faba bean average evapotranspiration rates and average stomatal conductance changes among water availability treatments. Shows the relationship between the evapotranspiration and stomatal conductance and total for both matric potentials. The high water availability treatments (-10 KPa) exhibits the highest stomatal conductance and evapotranspiration, with the relatively lower water availability (-100 KPa) showing the lowest stomatal conductance and evapotranspiration.

2.10 Tables and Figures

Table 2.1 Soil type and characteristics. Shows both soil types used in the study and their respective attributes.

Site	Texture	Soil Order	(θ_{10}) (%)	(θ_{1500}) (%)	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})	pH	STN (g kg^{-1})	SOC (g kg^{-1})	C:N Ratio
Dapp	Sandy Clay Loam	Dark Grey Luvisol	40.6	25.2	1.8	24.0	7.0	380.0	4980.0	13.4
Lacombe	Sandy Loam	Black Chernozem	41.3	26.8	3.1	24.0	6.2	370.0	4190.0	11.2

Θ_{10}: mean volumetric water content at water availability of -10 KPa; Θ_{1500}: mean volumetric water content at water availability of -1500 KPa; NH_4^+: mean ammonium ion concentration in soil; NO_3^-: mean nitrate ion concentration in soil; STN: mean soil total nitrogen in soil; SOC: mean soil organic carbon in soil

Table 2.2 Cropping phases and treatment list during the greenhouse pot experiment. Shows the treatment description for the soil pots (n=48) in the faba bean phase of the greenhouse study. Eight different fixed effect treatments of bulk density and matric potential (water availability) were applied in both soil types, with conditions representative of the entire pot (20.5 cm height, 17.5 cm inner bottom diameter, 19.5 cm top diameter with 18.0 cm soil column height).

Soil	Bulk Density (g cm^{-3})	Water Availability (KPa)	Replicate Quantity	Treatment
Dark Grey Luvisol (Dapp)	1.1	-100	3	1a
		-10	3	1b
	1.2	-100	3	2a
		-10	3	2b
	1.2/1.4	-100	3	3a
		-10	3	3b
	1.4	-100	3	4a
		-10	3	4b
Black Chernozem (Lacombe)	1.1	-100	3	1a
		-10	3	1b
	1.2	-100	3	2a
		-10	3	2b
	1.2/1.4	-100	3	3a
		-10	3	3b
	1.4	-100	3	4a
		-10	3	4b

Treatments 3a and 3b: dry bulk density of 1.2 g cm^{-3} for top 9 cm and 1.4 g cm^{-3} for bottom 9 cm of soil pot

Table 2.3 Faba bean measured parameter significance for repeated measure ANOVA statistical analysis, separated by fixed effects of treatment (eight treatments combinations of bulk density and water availability), soil (Dapp versus Lacombe) and week (repeated measure) with a blocking factor of replicate for the exploratory analysis. Significant interactions with the soil (Dapp versus Lacombe) fixed effect allowed each soil to be considered individually, with fixed effects of bulk density (1.1-1.4 g cm^{-3}) and water availability (-10 and -100 KPa) and a blocking factor of replicate.

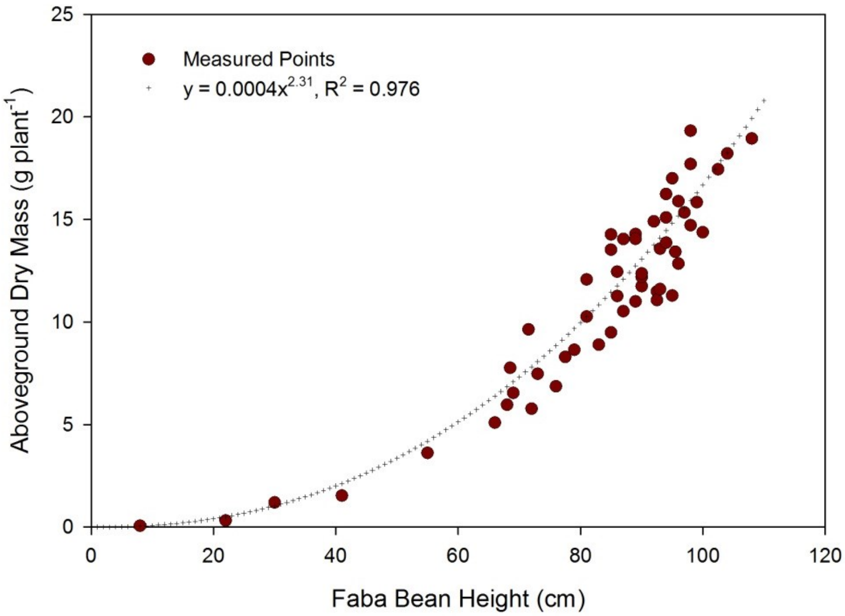
Model Type	Factor	AG Biomass (g)	R Biomass (g)	ET (mm d^{-1})	Height (cm)	NDVI (unitless)	g_s (mmol m^{-2} s^{-1})	WUE (mg g^{-1})
Composited Soil Type	Treatment	***	*	***	***	***	***	NS
	Soil	**	NS	**	***	**	NS	**
	Week	N/A	N/A	***	N/A	***	***	N/A
	T x S	**	*	***	*	***	*	*
	T x W	N/A	N/A	***	N/A	*	NS	N/A
	S x W	N/A	N/A	NS	N/A	**	NS	N/A
	T x S x W	N/A	N/A	NS	N/A	NS	NS	N/A
Dark Grey Luvisol (Dapp)	Bulk Density	**	NS	***	NS	**	***	NS
	Water Availability	***	NS	***	***	***	***	NS
	BD x WA	NS	NS	***	NS	NS	**	NS
Black Chernozem (Lacombe)	Bulk Density	NS	*	***	NS	*	***	NS
	Water Availability	NS	NS	***	NS	NS	***	**
	BD x WA	*	**	***	**	**	NS	NS

* denotes $P < 0.05$; ** denotes $P < 0.01$; *** denotes $P < 0.001$; NS: no significant interaction occurring where $P > 0.05$; N/A: analysis did not involve repeated measurements; T: treatment fixed effect factor of 8 different bulk density and water availability combinations; S: soil fixed effect factor of Dapp versus Lacombe; W: week fixed effect factor; AG Biomass: aboveground biomass; R Biomass: root biomass, ET: evapotranspiration; Height: faba bean final plant height; NDVI: normalized difference vegetative index; g_s: stomatal conductance; WUE: total water use efficiency

Table 2.4 Measured parameters during the faba bean cropping phase. Shows the mean values of each sensor and plant based measurement, with parameter groupings derived across the eight different treatment combinations of bulk density and water availability for each soil type. Mean values of evapotranspiration (ET), normalized difference vegetation index (NDVI) and stomatal conductance (g_s) are averaged across multiple weeks and multiple experimental units (soil pots) with use of correlation and variance structures. Mean values for water use efficiency (WUE), height, above and below ground biomass are averaged across multiple experimental units (n=48) at the end of the study. Treatment combinations are defined in Table 2.2.

Soil	BD ($g\ cm^{-3}$)	WA (KPa)	AG Biomass (g)	R Biomass (g)	ET ($mm\ d^{-1}$)	Height (cm)	NDVI (unitless)	g_s ($mmol\ m^{-2}\ s^{-1}$)	WUE ($mg\ g^{-1}$)
Dark Grey Luvisol (Dapp)	1.1	-100	9.2ab	0.125	3.9b	77.2ab	0.305ab	345.8bcd	2.02
		-10	15.3c	0.184	5.6de	94.7c	0.370c	413.6d	2.14
	1.2	-100	9.9abc	0.195	4.6bc	79.8abc	0.333bc	271.7b	2.09
		-10	14.2bc	0.240	6.5e	89.7bc	0.367c	388.1d	2.03
	1.2/1.4	-100	8.6ab	0.132	4.0b	79.8abc	0.302ab	289.8bc	2.12
		-10	13.9bc	0.162	5.3cd	93.0bc	0.352c	341.9bcd	2.15
	1.4	-100	5.8a	0.266	2.7a	69.0a	0.287a	158.7a	1.98
		-10	12.9bc	0.121	5.7de	93.0bc	0.352c	367.8cd	2.01
Average			11.2	0.178	4.8	84.5	0.334	322.2	2.07
Black Chernozem (Lacombe)	1.1	-100	13.5abc	0.236ab	4.5b	90.5ab	0.366bc	304.0abc	2.34ab
		-10	11.1ab	0.105a	5.2bc	85.3ab	0.345ab	410.9d	1.89a
	1.2	-100	14.2abc	0.103a	5.3bc	92.8ab	0.365abc	302.9abc	2.21ab
		-10	18.2c	0.329b	6.8d	99.5b	0.403c	433.4d	2.16ab
	1.2/1.4	-100	13.7abc	0.114a	4.6b	95.8bc	0.362abc	237.9ab	2.41b
		-10	11.4ab	0.068a	4.8bc	91.3ab	0.330ab	382.8cd	2.04ab
	1.4	-100	10.2a	0.101a	3.1a	78.3a	0.323a	215.8a	2.50b
		-10	16.05bc	0.247ab	5.6c	100.3b	0.375bc	314.4bc	2.21ab
Average			13.5	0.163	5.0	91.8	0.359	325.3	2.22

Abcde: letters indicate significant differences across soil or treatment mean groupings at a critical level of 0.05; BD: bulk density treatment; WA: water availability treatment; AG Biomass: aboveground biomass; R Biomass: root biomass, ET: evapotranspiration; Height: faba bean final plant height; NDVI: normalized difference vegetative index; g_s: stomatal conductance; WUE: total water use efficiency



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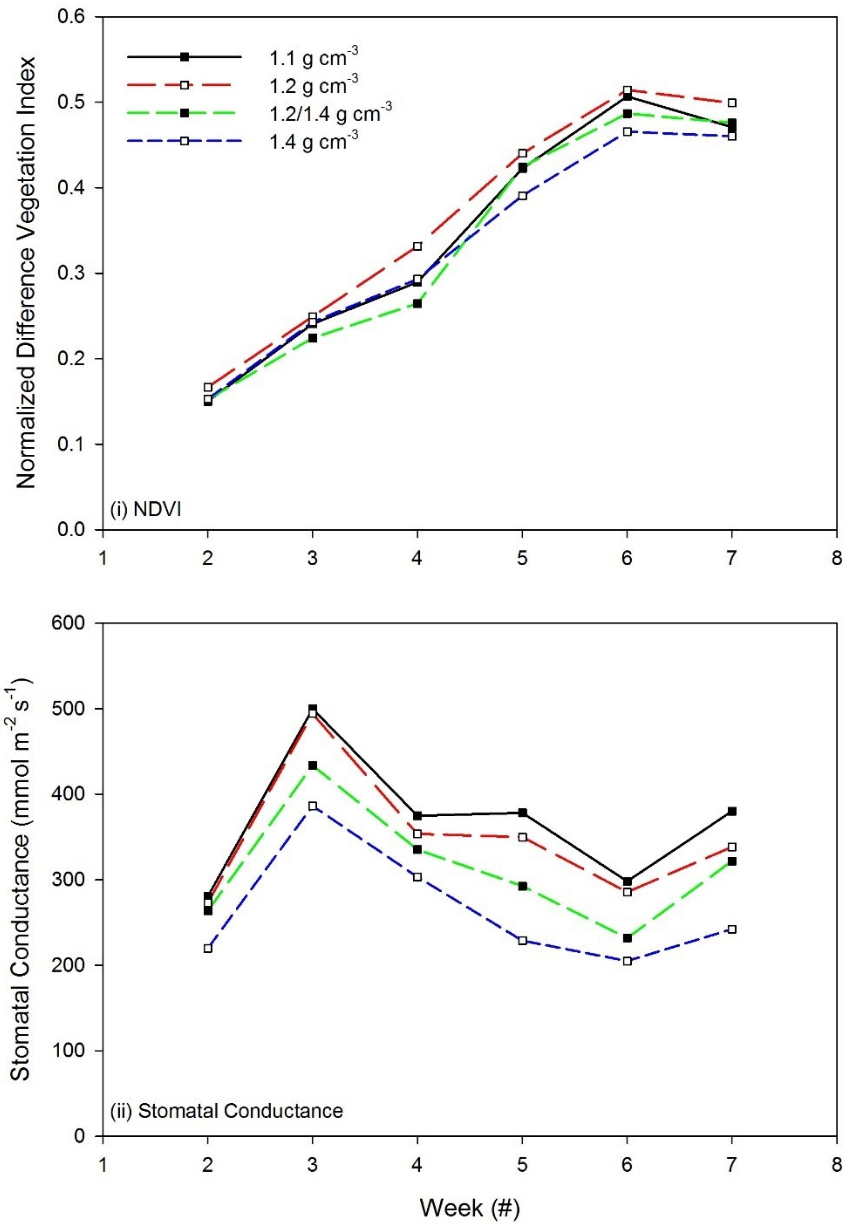

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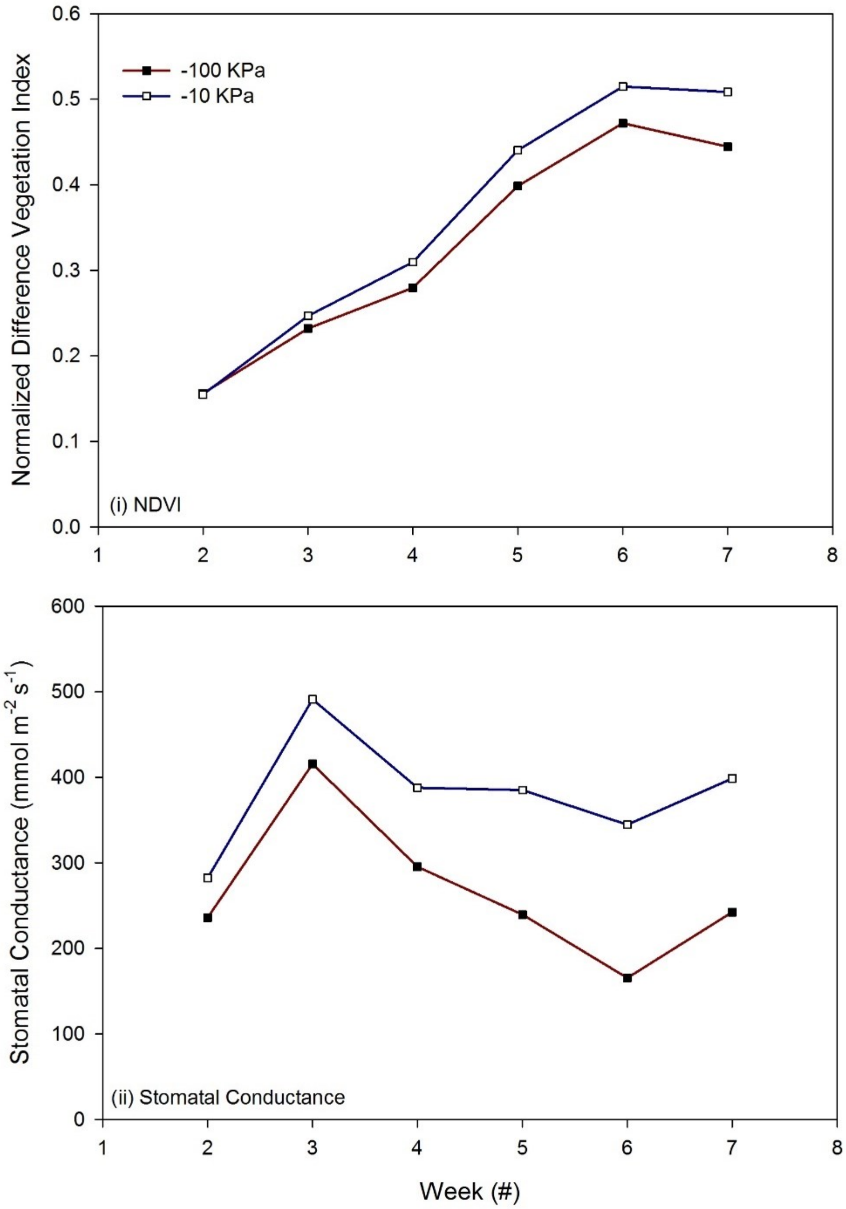

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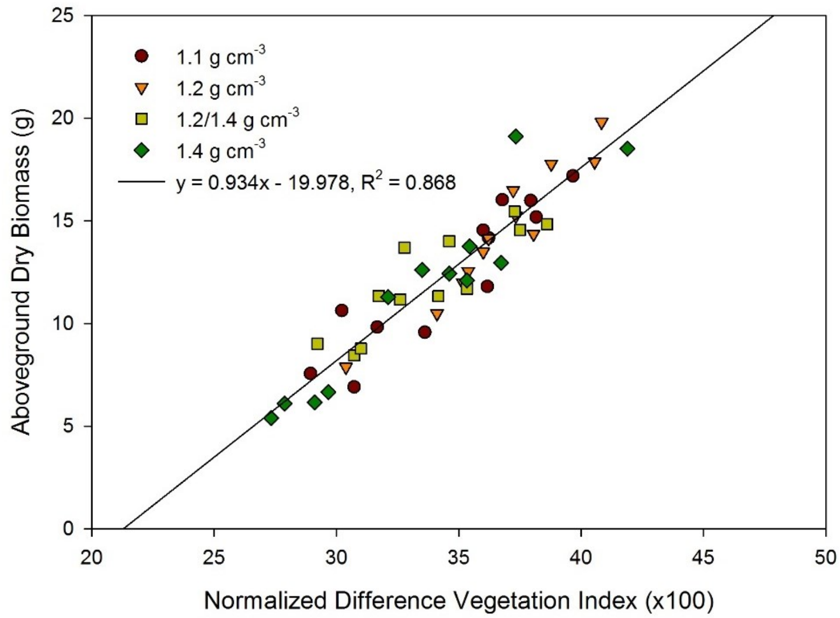

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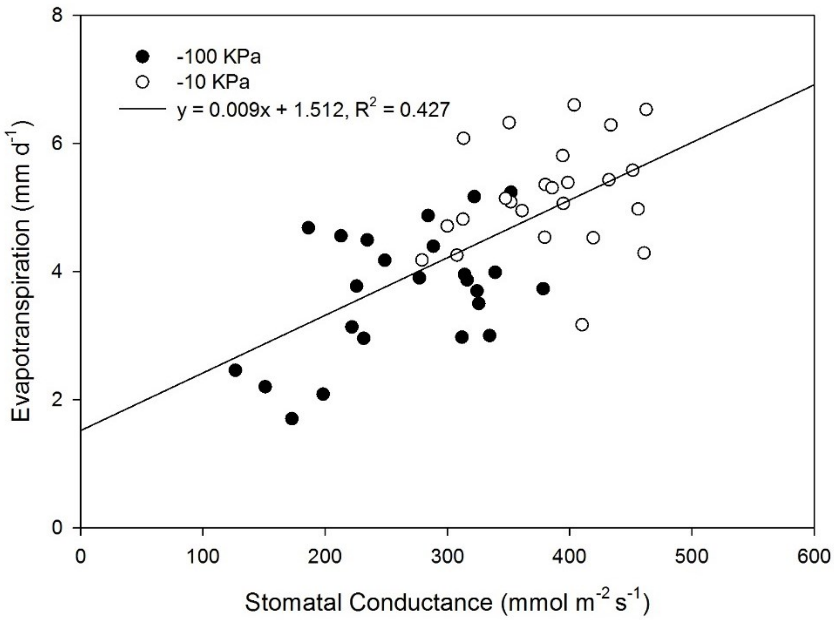

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Chapter 3. Evaluation of Field Scale Modeling Methods and Spatial Heterogeneity of Soil Quality from Implementation of Controlled Traffic Farming

3.1 Abstract

The employment of controlled traffic farming (CTF) can yield improvements to soil quality attributes through the confinement of equipment traffic to tramlines with the field. There is a need to quantify and explain the spatial heterogeneity of soil quality attributes influenced by CTF to further improve our understanding and modelling ability of field scale soil dynamics. Soil properties such as available nitrogen (AN), soil pH, soil total nitrogen (STN), soil organic carbon (SOC), bulk density, macro pore volume, soil quality S-Index, plant available water capacity (PAWC) and unsaturated hydraulic conductivity (K_m) were analyzed and compared among trafficked and un-trafficked areas. We contrasted regression models with standard geostatistical methods, such as ordinary kriging (OK) and covariate kriging (COK), as well as the hybrid method of regression kriging (ROK) to predict the spatial distribution of soil properties across two annual cropland sites actively employing CTF in Alberta, Canada. Field scale variability was quantified more accurately through the inclusion of terrain covariates only in soil nutrient properties; however, the use of ROK was shown to improve model accuracy despite the regression model composition limiting the robustness of the ROK method for soil physical and hydraulic properties. The exclusion of equipment traffic in the un-trafficked areas of CTF displayed significant improvements to bulk density, macro pore volume and K_m while subsequently displaying non-significant enhancements of AN, STN and SOC. The ability of the regression models and the ROK method to account for spatial trends led to the highest goodness-of-fit and lowest prediction error for the soil physical properties, as the rigid traffic regime of CTF altered their spatial distribution at our field scale. Conversely, the COK method produced the most optimal predictions for the soil nutrient properties and K_m. The use of terrain covariates derived from light detection and ranging (LiDAR), such as of elevation and topographic position index (TPI), yielded the best models via the COK method. The spatial variation of bulk density, macro pore volume, S-Index and PAWC were shown to be heavily influenced by traffic management,

with AN, pH, STN and SOC observed to vary as a function of landscape dynamics while K_m was determined to be driven by both management and landscape features.

3.2 Introduction

Univariate and multivariate geo-statistics have recently been applied to study the spatial heterogeneity of soil properties and compute predictive maps of soil properties at both the field and regional scale (Baveye & Laba 2015). The employment of geo-statistics to analyze variability in agriculture has been part of the shift towards precision agricultural systems, which is in part due to the advent of economically viable global positioning systems (GPS). Precision agriculture, which was defined by Whelan & McBratney (2000) as "matching resources application and agronomic practices with soil and crop requirements as they vary in space and time within a field", can be carried out in many forms. Controlling the layout of traffic regime within a field is a form of precision agriculture, which is defined as controlled traffic farming (CTF). This management system has been widely adopted in Australia and to some extent in Europe, as it has been shown to improve soil quality and aid in the recovery of soil structure (Chamen et al. 2015; McHugh et al. 2009). The implementation of CTF reduces the overall coverage and intensity of spatial compaction by restricting the movement of farm equipment to permanent traffic lanes, called tramlines (Tullberg et al. 2007). Reducing the field area which receives traffic induced compaction can improve key soil physical properties in the un-trafficked areas, such as bulk density, pore volume and unsaturated hydraulic conductivity (McHugh et al. 2009; Unger 1996), as well as potentially reduce overall soil greenhouse gas emissions (Antille et al. 2015; Gasso et al. 2013; Gasso et al. 2014). Thus, it is imperative to quantify and understand how key soil quality parameters and their heterogeneity vary within CTF landscapes with the aim of informing potential adoption of this management system in the Canadian Prairies.

Geo-statistics, in its early form, was used to accurately predict the grade of gold ore in South African mines (Krige 1966), but within the past few decades it has become a common methodology that soil scientists have utilized to determine the spatial variability of soil properties. However, caution should be used when employing geo-statistics to quantify the spatial structure of soil properties, as the spatial correlation trends and the subsequent predictive maps produced from kriging largely depend upon sample size and scale of the plot area (Baveye & Laba 2015). Thus, it is prudent to utilize calculated spatial correlations responsibly and to the scale of which they were intended (Oliver & Webster 2014). Furthermore, the employment of standard interpolation methods, such as ordinary kriging (OK) or co-kriging (COK), may not be sufficiently adequate forms of quantification; hybrid methods, such as regression kriging (ROK), may be necessary to properly define soil spatial structures (Heuvelink et al. 2016) and account for multiple spatial variability sources. The art of obtaining accurate realizations of correlations and trends within spatial distributions of soil properties at specific scales through different geostatistical approaches poses the question as to which method yields the best goodness-of-fit and reduces the prediction uncertainty. The use of ROK has been shown to have a better performance when compared to OK (Hengl et al. 2004; Maynard et al. 2011; Odeh et al. 1995) and COK (Knotters et al. 1995; Mirzaee et al. 2016; Simbahan et al. 2006); conversely, Piccini et al. (2014) and Watt & Palmer (2012) have also shown a lack of improvement of ROK over OK. Additionally, the use of covariates in the COK method has been shown to improve model fit (Ceddia et al. 2015; Wang et al. 2013). As terrain covariates derived from topographic data becomes easier gradually to access, it may provide a means to enhance spatial models at the field scale (Tripathi et al. 2015). Therefore, comparisons among different methods of predictive mapping may be necessary to further decipher which interpolation method suits the field scale and CTF environments.

To develop a solid foundation for the quantification and ultimate goal of mapping the variability in soils at various scales, an understanding of both the field and regional scales must be achieved. The integration of access to data of finer spatial resolution, such as light detection and ranging (LiDAR) terrain data, with advancements in computing processing capacity and the development of improved spatial modeling techniques can lead to an enhanced understanding and documentation of field scale variability (Mirzaee et al. 2016; Simbahan et al. 2006). Numerous studies have been completed worldwide on predictive mapping of the pedosphere and understanding the spatial variation of soil properties over regional scales (Huang et al. 2007; Li et al. 2014; Raczkowski et al. 2012). However, focus on the field scale variability within agricultural settings has not been comprehensively covered (Alletto et al. 2010), particularly in the Canadian Prairies. Furthermore, investigation into the spatial correlation of soil properties within a controlled traffic environment has to our knowledge, not been examined yet. Quantifying the combined effects of landscape and management systems on soil spatial variability can expand our explicit knowledge of these relationships and aid to develop robust mapping tools (Zhang et al. 2011).

Regression and semivariogram analyses with both standard and hybrid geostatistical methods applied to key soil quality parameters may be able to reveal the existing spatial structure of soil heterogeneity and inform future spatial models which could be applicable to comparable landscapes. Thus, the objectives of our project were (i) quantify the field scale spatial variation of soil properties within CTF fields and determine if the underlying spatial structure is a function of the traffic management system, the landscape or a combination of both factors, (ii) determine which geostatistical method yields optimal spatial models within the field scale, and (iii) examine which LiDAR-derived terrain covariate contributes in explaining the variation and reducing prediction uncertainty for soil properties at the field scale.

3.3 Materials and Methods

3.3.1 Study Sites

Two commercial controlled traffic study sites (~1 ha) located near Dapp and Lacombe, Alberta were the geographic focus of this study (Table 3.1). The Dark Grey Luvisol at Dapp (SW&SE-35-62-1-W5M) and Black Chernozem at Lacombe (NE-34-40-26-W4M) are common soils used within commercial agricultural production centers throughout Alberta, Canada. The site at Lacombe had large undulations throughout the northern half of the field, with flat relief throughout the southern portion. Surface and subsurface drainage was directed from the northeastern corner towards the southwestern corner using a tile drainage system. Conversely, Dapp had slight undulations throughout the field, with a mainly flat relief. Surface drainage was directed from north to the south and flowed into drainage ditches parallel to the field. Annual spring cropping with differing crop rotations occurred at both sites; however, at the time of sampling each site was planted with spring wheat (*Triticum aestivum* L.). Prior to the employment of zero till controlled traffic farming (CTF) at each site in 2011, conventional management practices such as reduced tillage and random traffic patterns were utilized.

The commercial fields at both study site locations represent parcels of land commonly used by farmers in the region, with each field entailing an area of approximately 64 ha. The management techniques of CTF were similar across both sites, with tramline spacing occurring at 9 m accompanied by a wheel gauge width of 3.05 m (120 inches) at Dapp and 3.40 m (134 inches) at Lacombe. As described by Guenette, Chapter 1 (2017), applications of additional or imposed traffic (IT) were applied to specific swaths throughout each field to simulate random traffic patterns at both sites. The inclusion of the IT application served as a baseline comparison between conventional and controlled traffic management in the previous study.

3.3.2 Sampling Design and Collection

The 108 m x 110 m (11,880 m^2) plot for each study site was located near the central point within each field and encompassed twelve 9 m swaths. Each plot consisted of one IT swath, eight CTF swaths and three CTF swaths exposed to sprayer traffic. Collection of the soil samples took place from 16 to 18 June 2015 at Lacombe and from 23 to 25 June 2015 at Dapp. The sampling procedure employed a cyclic sampling design (Fig. 3.1a) as outlined by Clinger & Van-Ness (1976), through which a cyclical variation in the sample grids was applied to capture maximum sampling efficiency (Bond-Lamberty et al. 2006; Loescher et al. 2014). A vertical sample spacing distribution of 0, 2, 8, 18, 38, 42 and 48 m from the first sampling point was repeated twice in each vertical row from the left to the right of the plot, with a 10 m offset from the first point applied to every second vertical row. The horizontal sample spacing for each vertical row was distributed by 0, 10, 40, 70, 100, and 110 m from the first vertical row, progressing from the top to bottom of the plot (Fig. 3.1a). This sampling design enabled a minimum of 20 pairs for each 2 m lag distance class to be realized while simultaneously reducing a large accumulation of small scale lag pairs for sampling efficiency (Orr et al. 2014). However, to account for potential field scale interactions per swath, a nested sampling design (Fig 3.1b) was also included within the larger cyclic sampling design. The nest was confined within a 9 m CTF swath and was composed of four vertical rows of three sampling points spaced at specified distances. The sampling distribution allowed for sampling points to be categorized into different traffic types and compared between trafficked and un-trafficked areas. Additional separation of the trafficked areas sprayer tramlines (CTF tramline with sprayer traffic) and regular CTF tramlines was also performed and contrasted against the un-trafficked areas to analyze the differences among tramline type.

Prior to sampling, the top layer of the soil and organic litter (0-5 cm) was removed from each sampling point to thoroughly expose the soil. Soil samples were collected at a depth increment of 5-10 cm in the cyclic sampling design, yielding a total 72 sampling points. Additional samples were collected at depth increments of 5-10 cm and 15-20 cm within the nest, comprising of a total of 24 samples taken from 12 sampling points in the nest. Each sample was taken within 1/3 of the crop inter-row, with universal transverse mercator (UTM) coordinates and elevation values of each sampling point recorded through a Pro 6T (Trimble® Inc., Sunnyvale, CA, USA) differential global positioning system (DGPS) with an accuracy of ± 30cm. Collectively, 96 soil samples were obtained for each study site, as sample sizes substantially smaller than 100 samples are not recommended due to the potential for noisy variograms and uncertain calculations of the sill or autocorrelation distance (Oliver & Webster 2014). Undisturbed soil core samples that were collected for the determination of soil physical and hydraulic properties consisted of a stainless steel soil core with a diameter of 8 cm and height of 5 cm (~250 cm^3). A handheld sampler and rubber hammer was used to collect the undisturbed soil core, with a shovel being used to remove the soil core from the sampling location to avoid any alterations to the soil structure. Additionally, quantification of soil nutrient properties was accomplished by compositing four push probe soil core samples (~150 cm^3) at the same depth increment and within 2 cm of the undisturbed soil core sampling point. Following sealing of the soil samples, they were stored at 5°C until laboratory analysis began.

3.3.3 Sample Analysis

Soil physical and hydraulic properties were measured for each undisturbed soil core from the water retention and unsaturated hydraulic conductivity curves by means of the simple evaporation method. The simple evaporation method used porous ceramic cup tensiometers in a HYPROP® system (UMS GmbH, Munich, Germany), which recorded the matric potential of water throughout the evaporation process; a detailed explanation of the method is described by Guenette, Chapter 1 (2017). The HYPROP® system recorded variations in water tension every 10 minutes, with sample weights measured two to four times daily. Upon completion of the experiment, dry weights and the respective bulk density (ρ_B, g cm^{-3}) of the samples were calculated by placing the samples in an oven for 24 hours at 105°C and weighed.

Utilization of the HYPROP® system allowed for the quantification of data from matric potentials ranging from 0 to -100 KPa; therefore, to obtain data in the dry range of the water retention curve, a WP4C PotentiaMeter® (Decagon Devices Inc., Pullman, WA, USA) was used to calculate matric potentials through the dew point method (Schindler & Müller 2006; Schelle et al. 2013; Schindler et al. 2010). Push probe soil samples were ground and placed into four separate plastic cups, with 5 g of dry ground soil combined with four different water volumes of 0.05, 0.1, 0.3 and 0.4 mL. The contents of the plastic cups were mixed and sealed for 24 hours to enable water distribution and equalization before being placed into the PotentiaMeter®. Subsequently, the gravimetric water content of the soil was calculated upon completion of the PotentiaMeter® test by drying the soil sample in an oven at 105°C for 24 hours. Water retention and unsaturated hydraulic conductivity curves were modeled from the HYPROP® and PotentiaMeter® measured data points and fit to the van Genuchten model (van Genuchten 1980) as implemented by the HYPROP® FIT software (Pertassek et al. 2015).

Pore volume fractions (PVF, $cm^3\, cm^{-3}$) representing the macroporosity (0 to -5 KPa), mesoporosity (-5 to -33 KPa), microporosity (-33 to -100 KPa), nanoporosity (-100 to -1500 KPa) and residual porosity (< -1500 KPa) of the soil were derived from the van Genuchten modeled curves, as described by Guenette, Chapter 1 (2017) and Hernandez-Ramirez et al. (2014), with pore diameters ranging from >60 µm, 60 to 9 µm, 9 to 3 µm, 3 to 0.2 µm and <0.2 µm, respectively. Plant available water capacity (PAWC, $cm^3\, cm^{-3}$) was quantified in a similar manner, with matric potential ranging from -33 to -1500 KPa, which corresponded to pore diameters from 9 to 0.02 µm. Dexter (2004) postulated an index (S-Index, unitless) to define soil physical quality based on the slope of the inflection point of the van Genuchten modeled water retention curve, where a threshold value of 0.035 indicated the change from poor and good soil physical quality. The S-Index was used as an indicator of the general soil physical quality in our study. Unsaturated hydraulic conductivity (K_m, cm d^{-1}) related to the movement of water through the macropores of the soil and was analyzed from matric potentials between 0 and -5 KPa on the modeled unsaturated hydraulic conductivity curve.

Available soil nitrogen (AN, mg kg^{-1}) was obtained as a summation of ammonium (NH_4^+) and nitrate (NO_3^-) through a 2 mol potassium chloride (KCl) extraction, where major cations and micro nutrients were obtained through the Mehlich #3 extraction. Each extraction utilized 5 g of field moist soil that was corrected to its corresponding dry weight and mixed with specified amounts of extraction solution for approximately 30 minutes. Soil extracts were filtered with Whatman #40 filter paper and tested through the atomic absorption spectroscopy and colorimetric methods. Soil pH was attained through the use of AR20 pH/Conductivity meter (Fischer Scientific Inc., Pittsburgh, PA, USA) in a 2:1 solution, which was standardized against buffers of pH 7.0 and 10.0. Soil organic carbon (SOC, mg kg^{-1}) and soil total nitrogen (STN, mg kg^{-1}) were obtained for each sample through the dry combustion method. An ECS 4010 elemental analyzer (Costech Analytical Technologies Inc., Valencia, CA, USA) was used to determine the carbon and nitrogen contents from our ground and dried soil samples. The soil particle size distribution was determined through averaging results from eleven different sampling locations in the 5-10 cm depth at each site through the hydrometer method (Table 3.1).

3.3.4 Digital Elevation Model

Light detection and ranging (LiDAR) data was acquired via an airborne imaging Leica sensor, with a 2 m x 2 m resolution for Dapp and a 1 m x 1 m resolution for Lacombe. The corresponding accuracy of the LiDAR data was ± 30 cm vertically and ± 50 cm horizontally. Terrain covariates used in the geostatistical analyses included: aspect (direction of the slope), elevation, curvature (derivative of the surrounding cells surface), hillshade (illumination coefficient of the surface), slope and topographic position index (TPI). The TPI is described by De Reu et al. (2013) as the difference in elevation between surrounding cells and the central cell. When calculating the TPI for each grid cell, a frame of the 12 nearest neighbors was used, with the remainder of the covariates being derived from the LiDAR elevation through ArcGIS ver. 10.43 (ESRI 2016).

3.3.5 Statistics

The goodness-of-fit (R^2) and root mean square error (RMSE) was used as a guide to model the van Genuchten fitted water retention and unsaturated hydraulic conductivity curves, as the curves with the highest R^2 and lowest RMSE values were chosen. Assumptions of normality were ensured through the Kolmogorov-Smirnov test, while the homogeneity of variance was verified through the Bartlett Test. The NH_4^+, NO_3^-, AN and K_m data did not meet the aforementioned assumptions and were log (base 10) transformed. Differences among traffic types were determined through an analysis of variance (ANOVA). When the ANOVA yielded significantly different results between traffic types ($\alpha = 0.05$), a Tukey HSD post-hoc analysis was carried out. A Kruskal-Wallis rank sum test was carried out on variables that did not meet the assumptions of normality and homogeneity of variance to ensure continuity in the assessment of traffic effects on the un-transformed data. The data analysis was completed in two software, R ver. 3.3.1 (RDCT 2015) and SigmaPlot ver. 11.1. (SYSTAT 2008). Multiple linear regressions were used as a baseline comparison among the different geostatistical modeling methods. Optimum regressions were obtained using the stepwise function and followed the variance inflation factor (VIF) criterion; variables that contributed less than 5% additional improvement to goodness-of-fit (R^2) were removed. All available variables were classified *a priori* as response or predictor based upon their biophysical importance and our interest for conducting geospatial analysis (Table 3.2).

3.3.6 Geo-statistics

Oliver & Webster (2014) describe geo-statistics as the determination of the modeled experimental semi-variogram, ϒ(h), which is a graph that is used to calculate the semi-variance of the data to display the effective range of correlation. Coupled with the variogram, the interpolation method known as kriging, was applied to predict the values of the un-sampled void spaces (Matheron 1963). The various methods of kriging estimators utilize variogram parameters to describe the variance, where: the nugget (c_o) is described by the sampling variance, the spatial correlation (c) illustrates the spatial variance, the sill (c_o + c) is representative of the sampling variance combined with the spatial variance, and the autocorrelation range demonstrates the distance beyond which spatial correlation no longer exists (Oliver & Webster 2014). Analysis of the variogram's nugget-to-sill ratio, as described by

Cambardella et al. (1994), was used as means to potentially determine the driving force behind the spatial structure of each variable, as ratios <25% portray strong spatial dependence, ratios between 25% and 75% display moderate dependence and ratios >75% show weak spatial dependence.

Variograms were created in the geostatistical software GS+ ver. 10.0 (Robertson 2008), with the respective lag class size and lag range determined by calculating which variogram had the highest coefficient of determination (R^2) coupled with the lowest residual sum of squares (RSS). Upon calculation of the variogram, it was fitted to either linear, Gaussian, spherical or exponential models, with comparisons between model type achieved via the cross-validation analysis using R^2 and RSS. Additionally, the mean square deviation ratio (MSDR) was used to compare variogram models, as values closest to 1 (Oliver & Webster 2014) were used to choose the appropriate model type determined through the following equation [3.1]:

$$MSDR = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(Z(X_i)-\hat{Z}(X_i)\right)^2}{\sigma_K^2(X_i)} \qquad [3.1]$$

where n is the number of measured data values, $Z(X_i)$ is the measured value, $\widehat{Z}\,(X_i)$ is the predicted value and $\sigma_K^2(X_i)$ is the variance from kriging.

Three types of kriging were employed on soil data from the 5-10 cm depth increment to explore and model potential spatial structure between the variables. These geostatistical methods consisted of the standard methods of ordinary kriging (OK) and co-kriging (COK) as well as the hybrid method of regression kriging (ROK). The method of OK consists of the prediction of a value at an un-sampled location which used a linear combination of sampled locations within a specified sphere of influence to make the estimate, whereas COK used spatial and correlation relationships between the primary variate and covariate to make informed estimates in un-sampled locations (Goovaerts 1999). The method of ROK is the hybrid combination of regression models with the ordinary kriging of the regression residuals

(Odeh et al. 1995). Formulas for OK, COK and ROK are respectively shown by equations [3.2], [3.3] and [3.4] below:

$$OK = \widehat{Z}\,(X_i) = \sum_{i=1}^{n} \lambda_i \; Z(X_i) \qquad [3.2]$$

$$COK = \widehat{Z}\,(X_i) = \sum_{i=1}^{n} a_i \; Z(X_i) + \sum_{i=1}^{n} b_i \; Z\big(X_j\big) \qquad [3.3]$$

$$ROK = \widehat{Z}\,(X_i) = Z(X_R) + \sum_{i=1}^{n} \lambda_i \; R(X_i) \qquad [3.4]$$

where λ_i, a_i, and b_i, are weighted constants used to reduce the error in prediction of the variance, $Z\big(X_j\big)$ is the covariate value, $Z(X_R)$ is the predicted value from the regression and $R(X_i)$ is the residual measured value. Comparisons among geostatistical methods was done based on the criteria of R^2, as well as the mean error (ME) and root mean square error (RMSE), which are shown in the following equations [3.5] and [3.6]:

$$ME = \frac{1}{n} \sum_{i=1}^{n} \Big(\widehat{Z}\,(X_i) - Z(X_i)\Big) \qquad [3.5]$$

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^{n} \Big(\widehat{Z}\,(X_i) - Z(X_i)\Big)^{2}\right)^{\frac{1}{2}} \qquad [3.6]$$

3.3.7 Sample Size

Minimum sampling size calculations were performed to determine the required amount of samples to be collected to achieve a specified confidence threshold. The thresholds of 5% (N_5), 10% (N_{10}), 25% (N_{25}) and 50% (N_{50}) provide a reasonable distribution of accuracy levels. The sample sizes were obtained through two methods: (i) an analysis of the spatial mean and variography parameters (type 1) as described by Loescher et al. (2014) and (ii) analyzing the overall raw data variance (type 2) as shown by Metcalfe et al. (2008), which are described by equations [3.7] and [3.8], respectively.

$$N(type\ 1) = \frac{{t_\alpha}^2 \left(\frac{\sqrt{2(c_0+c)}}{\bar{X}}\right)}{D^2} \qquad [3.7]$$

$$N(type\ 2) = \left[\frac{t_\alpha\, CV}{D}\right]^2 \qquad [3.8]$$

where t_α is the t-value (1.96) for an alpha of 0.05, $c_o + c$ is the sill value for the modeled soil property variogram, $\bar{X}$ is the mean of the soil property, D (%) is the chosen confidence threshold and CV (%) is the coefficient of variation.

3.4 Results

3.4.1 Nutrient Properties

Analysis of the available nitrogen (AN, as a summation of the NH_4^+ and nitrate NO_3^- ions) showed that the soil property was mainly comprised of NO_3^-, as only 15-20% of AN consisted of the NH_4^+ (Table 3.2). Comparing the trafficked areas of the tramlines versus the un-trafficked areas yielded statistically significant ($\alpha = 0.05$) increases in the un-trafficked soils at the Dapp site, while displaying marginal non-significant gains in the un-trafficked soils at Lacombe (Table 3.3). Moreover, a trend of trafficked areas having lower amounts of mean AN within the soil was observed in both the composited site data set and site specific data (Table 3.4). A lower mean pH within the un-trafficked areas was witnessed when contrasted to the trafficked areas at both sites; however, no significant differences were observed between the traffic types (Table 3.3). Differences between mean pH values at each site displayed a higher pH at Dapp, with nearly 40% less variability observed in the Dapp data (Table 3.2).

A similar trend observed in the AN generally occurred within the major cations and micro nutrients, where trafficked soils generally displayed higher concentrations. The Lacombe site displayed approximately 65% more mean phosphate and zinc coupled with reductions in boron (51%) and calcium (84%) when compared to the Dapp site, which may explain the overall higher mean pH at Dapp (Table 3.2). Soil total nitrogen (STN) and soil organic carbon (SOC) generated higher mean concentrations in the un-trafficked areas (Table 3.4) and displayed no significant differences in both STN and SOC within each of the sites (Table 3.3). Greater amounts of SOC present at the Dapp site led to the wider C:N ratio witnessed within the Dark Grey Luvisol when compared against the Black Chernozem at Lacombe (Table 3.2). Despite general differences in soil nutrient properties between trafficked (tramlines) and un-trafficked areas, no soil property other than AN at the Dapp site displayed significant differences between traffic types.

3.4.2 Physical Properties

Soil physical properties, such as the dry bulk density (ρ_B) and pore volume fractions (PVF), displayed significant differences between the traffic types when analyzing each site individually or as a composited set (Table 3.3). As expected with the confinement of wheel traffic to the tramlines, un-trafficked areas displayed significantly lower ρ_B values at Dapp and Lacombe by 13% and 10%, respectively (Table 3.4). Increases in ρ_B with greater depth were also witnessed at both sites; however, greater differences between traffic types in density values occurred in the 5-10 cm depth compared to the 15-20 cm depth (data not shown). Furthermore, this trend only applies to the nest area, but can represent the existence of subsurface compaction and could allude to the longer time needed to alleviate compaction following the cessation of wheel compaction (Guenette, Chapter 1 2017). Macro, meso and micro pore volume fraction interactions between traffic types were symmetrical with the ρ_B trend, as significant increases in un-trafficked macro pore volume was observed (Table 3.3). Significant gains in soil macro PVF of 124% at Dapp and 119% at Lacombe were observed in the un-trafficked soils (Table 3.4), with these areas displaying decreases in pore volume with depth at both sites (data not shown). The nano and residual PVF displayed significant increases in the trafficked areas (tramlines) between 11-28%, as increases in larger pore diameter translated to decreases in smaller pore diameter. These trends in PVF suggest that the confinement of traffic to tramlines elicited a greater response at the Dapp site, as greater shifts in pore volume fractions displayed greater soil amelioration occurring when compared to Lacombe (Table 3.2).

The soil S-Index, a representation of the formation of structural pores (Dexter 2004), was as an indicator of soil physical quality contrasted across the traffic types. Contrary to substantial differences observed in properties from which the S-Index may correlate with, no significant differences between traffic types were observed at either site (Table 3.3). Mean values for both the trafficked and un-trafficked areas were very similar; however, the Dapp site displayed values that were higher than Lacombe and closer to the 0.035 threshold for good soil physical quality (Table 3.4). Differences in S-Index mean values with depth were inconsistent between sites and traffic intensity, although the soil quality index generally increased with depth (data not shown). Improvements witnessed in un-trafficked soil physical parameters (Guenette, Chapter 1 2017) can showcase the positive effects that the removal of traffic has on the structural properties of soil.

3.4.3 Hydraulic Properties

Soil hydraulic properties measured in this study were based on the van Genuchten modeled curves and included the plant available water capacity (PAWC) and unsaturated hydraulic conductivity (K_m). Regardless of the PAWC parameter being derived from the PVF, a calculation of the water holding capacity of the soil coupled with a quantification water movement through the large pore radii may reveal more detailed relationships between soil hydraulic dynamics and traffic types. Significant differences between traffic types were observed at both sites for both PAWC and K_m (Table 3.3), with decreases in un-trafficked zones by 8-11% in PAWC countered by increases of 150 to 300 times in K_m (Table 3.4). Reductions observed in un-trafficked PAWC are likely due to significant increases in macro PVF enhancing soil structure and reducing the pore volume attributed to smaller pore diameter. Contrasting changes in both PAWC and K_m occurred between the 5-10 cm and 15-20 cm depth at both sites; PAWC decreased with depth in Dapp in both traffic types and alternately increased in Lacombe, with K_m following the opposite trend of observed gains in Dapp and losses in Lacombe (data not shown).

Despite only sampling in the 15-20 cm depth within the nest area, opposite effects witnessed at both sites showcased the highly variable nature of soil hydraulic properties.

3.4.4 Geostatistical Modeling

Multiple stepwise regressions were performed on the predictor variables as shown in Table 3.2, with soil pH, SOC, density and macro PVF considered as both a response variable and predictor variable (Table 3.5). Regression models were considered the baseline for comparisons with the standard and hybrid geostatistical methods, with the aim of identifying the optimal modeling method for each response variable. The regression equations were determined on the composited site data set and then applied to each site to calculate the goodness-of-fit (Table 3.6). The regression models performed better at the Lacombe site for the soil nutrient properties when compared to the Dapp site; meanwhile, the soil physical properties were quantified better at the Dapp site through the regression models, with Dapp generally yielding lower RMSE values (Table 3.6). The variables that were considered both response and predictors were considered as the master variables of biophysical interest in our study, as knowledge of these parameters may generate predictions encompassing the majority of the variables measured (Table 3.2). Furthermore, the regression analyses was able to adequately predict the soil pH, STN, SOC, ρ_B, macro PVF and PAWC with an R^2 generally above 0.4, but was unable to sufficiently predict the AN and K_m parameters (Table 3.6).

The standard kriging and hybrid methods were executed on each response variable once the optimum variogram parameters and appropriate models were calculated (Table 3.6). Comparison between each spatial modeling method versus the baseline regression was done through the cross-validation process. Cross-validation consists of using the created model to predict the measured points that were originally used to inform the model; however, cross-validations in small areas may overestimate the goodness-of-fit due to bias from the surrounding measured points (Heuvelink et al.

2016). Contrasting the hybrid method of regression kriging (ROK) with the baseline method yielded an improvement to the R^2 for nutrient response variables at both sites. Although, the goodness- of-fit for the physical or hydraulic response parameters was not always improved when comparing the baseline regression with the ROK method (Table 3.6). Conversely, the ROK method generally decreased the ME and RMSE for most of the response variables when compared to the baseline regression, which was especially noted for the soil physical properties when contrasted the standard kriging methods (Table 3.6). Ordinary kriging (OK) was unable to improve the model when compared to both baseline regression and ROK in all response variables except for pH and SOC (Table 3.6). Generally, the OK method reduced the ME and RMSE values for the soil nutrient properties, but was unable to achieve the same effect for the soil physical properties when compared to the baseline regression and ROK methods (Table 3.6).

Covariate kriging (COK) vastly improved nutrient response variable R^2 values while simultaneously reducing the ME and RMSE error metrics. Increases in R^2 from 2% to 1827% were witnessed between the comparison of COK with the baseline regression method on the nutrient variables, while additionally reducing the RMSE values by 43-93% (Table 3.6). However, the COK method did not improve model goodness-of-fit or model prediction error for the physical parameters. The use of the COK method had conflicting results with the hydraulic properties, where the PAWC followed the same trend as the physical response variables. Conversely, the COK method simultaneously improved the prediction of K_m both in terms of increasing R^2 and decreasing the RMSE values for the K_m parameter by 27% and 56% when compared to the baseline regressions at Dapp and Lacombe, respectively (Table 3.6).

Correlations among response variables and covariates were used as an initial screening method for determining the optimal covariate for each property (Table 3.8). Covariates were modeled with each soil parameter, where the ideal covariate was selected based on the criteria of the highest R^2 and lowest error metric. However, linear correlations between covariates and response variables did not always display the entire spatial relationship. This was shown as the covariate TPI had poor correlations with the response variables, yet it yielded the most optimal covariate for STN, SOC and K_m (Table 3.5). Selection of the ideal covariates progressed to the elevation and TPI covariates displaying the highest improvements to nutrient spatial modeling. Additionally, the curvature covariate yielded the optimal COK model for the K_m parameter at Lacombe, with TPI displaying the optimal COK model at Dapp. Despite the curvature covariate producing the greatest model predictability with K_m at Lacombe, the TPI covariate was only marginally worse, with a difference in R^2 of 0.3% (data not shown). Thus, the use of covariates contributed to enhanced model development for variables that displayed well defined intrinsic spatial dependence.

3.4.5 Minimum Sample Size

Determination of the sample size used to measure each response variable within a specified confidence threshold was based on two methods: (i) type 1 utilizing the spatial mean and variogram parameters and (ii) type 2 using the overall variability within the raw data. Soil response variables observed in our study with high variability and poor spatial model prediction, namely AN and K_m, yielded noticeably higher sample size estimations compared to the other variables. Minimum sample sizes based on the type 1 method generally gave much larger estimates then the type 2 method. Type 1 sample size estimations with a threshold of 10% gave results generally consistent with our study, meanwhile estimations with type 2 at a threshold of 5% produced similar sample sizes. The consideration of the spatial variation for each parameter in the type 1 estimates is the likely cause for higher sample size requirements and thus should be used if geostatistical analysis is to be pursued.

3.5 Discussion

3.5.1 Management and Landscape Effects on Soil Properties

Differences in soil properties identified as a function of the CTF management system correlate well with previous studies (Blanco-Canqui et al. 2010; McHugh et al. 2009), as the CTF management system revealed improvements in soil properties within the un-trafficked areas. However, inherit differences observed in soil physical alterations between sites suggest that the act of confining the compactive effects to tramlines may have variable influences on soil structure for different soil types (Guenette, Chapter 1 2017). The heterogeneity of ρ_B values between trafficked and un-trafficked areas was expected due to the design of the management system, indicating that pore volume changes may lend further insights into the dynamics of the contrasting traffic types. The greater pore volume in the diameter ranges classified as meso, micro, nano and residual PVF at the Dapp site indicate that substantial soil amelioration was occurring in the Dark Grey Luvisol (Table 3.2).

Additional evidence suggesting the Dark Grey Luvisol may benefit more from reductions in spatial compaction than the Black Chernozem was shown through the higher trafficked and un-trafficked soil S-Index at Dapp (Table 3.4). However, smaller differences between trafficked and un-trafficked means for most soil properties at Lacombe indicate that the Black Chernozem may be a more resilient soil, as evident by its ability to buffer between traffic types. Intrinsic differences between sites may yield dissimilar alterations to the soil structure when controlling traffic, indicating that site specific variability due to the management system, soil order and soil texture can have profound effects on the spatial variation of soil properties (Alletto et al. 2010). However, the overarching increases to un-trafficked macro pore volume suggest improved water transmission occurring throughout each site as a function of CTF implementation (Table 3.4).

Improvements to the soils ability to transmit water throughout the un-trafficked areas can have an amplified effect in CTF, as sites that implement this management system can have spatial compaction coverage reduced from 40-70% (Tullberg et al. 2007). Despite CTF employment generally encountering management challenges, such as equipment size uniformity and tramline establishment, the benefits derived from reductions in the spatial distribution of compaction become an important factor in water-plant relationships. This observation holds true, as the un-trafficked K_m values were significantly higher than their traffic counterparts at both sites. Taking into consideration the highly variable nature of hydraulic conductivity data (Strudley et al. 2008), perceived benefits in these soils to transmit water through the macro PVF should still be relevant. Conversely, decreases witnessed in un-trafficked PAWC due to alterations in the pore size distribution may not necessarily imply that less water will be available for plants, as the overall increases in total porosity coupled with the substantial improvements to un-trafficked K_m should culminate in more effective water collection and transmission. Potential increases in PAWC (due to different PVF distributions) witnessed in conventional traffic systems and tramlines within CTF (as in our case) may have never been expressed to their full capacity, as a prevalence of increased runoff would lead to reduced water capture and storage (Strudley et al. 2008).

Soil physical and hydraulic properties were shown to be highly influenced by the traffic management system; however, the nutrient properties did not display a similar spatial dependency as a source of variation. Similar improvements witnessed in un-trafficked areas were found for AN, STN and SOC parameters. The STN and SOC results displayed similar trends at both sites; although, the lack significant differences between traffic types suggests that the confinement of wheel traffic to designated permanent tramlines was not the driving factor for spatial patterns. This finding was consistent works of Mzuku et al. (2005) and Huang et al. (2007), which generally describe intrinsic factors caused by the incorporation of residues and use of diverse crop rotations as being the influencing force of spatial structure. Since both sites in our study employed zero tillage with similar crop rotations, it is plausible to suggest that the primary source of variation was due to inherit differences in the landscape, and by proxy, the movement and localized accrual of water. Although significant increases to AN were observed between traffic types at Dapp, temporal variability of plant available nitrogen may also often a factor in its distribution, as it is highly dependent on soil organic matter, texture and water movement (Dharmakeerthi et al. 2005). When the dependence of AN variability on many factors is paired with the similar spatial properties and structure of SOC, plausible implications that the existence of temporally stable AN may also be a function of the landscape. Differences in soil pH occurred between traffic types; however, the high inverse correlation of pH with elevation (Table 3.8) suggests that the spatial patterns for pH are also influenced by similar landscape-driven mechanisms as observed for AN, STN and SOC.

Minimal differences in soil S-Index between trafficked and un-trafficked areas allude to no apparent divergences in soil physical quality over the field scale. Regardless, increases in STN and SOC paired with improvements to soil structure, due to improved aggregation in the absence of traffic, could suggest improved soil quality (Mzuku et al. 2005). Further categorization of the tramlines into their respective levels of compactive effort, as determined by the type and frequency of equipment traffic received, displayed no significant differences between the sprayer tramlines and regular CTF tramlines (Table 3.3). The additional traffic received in the sprayer tramlines increased the mean density compared to the CTF tramlines at the Lacombe site, while displaying a lower average at the Dapp site (Table 3.4). Furthermore, the sprayer tramlines saw reductions to S-Index K_m at both sites when compared to the regular CTF tramlines (Table 3.4). Generally, detrimental alterations in the soil physical quality indicators when comparing both tramline types to the un-trafficked areas at both sites could indicate that the management system is a main underlying spatial driver for soil physical property alterations (Fig. 3.2).

3.5.2 Comparing Prediction Mapping Methods

The heavy impact of equipment traffic on soil physical and hydraulic properties as revealed by differences in the PVF was captured through the regression equations (Table 3.5). The underlying influence from the management structure was captured through the regression and ROK methods as model trend was accounted for through relationships in the set of predictor variables. The use of soil bulk density and macro PVF as both a predictor and response variable shows the existing inter-relationship between compaction and pore volume. Additionally, the confinement of wheel compaction to the tramlines was shown to be a main driving force of the spatial structure, as high R^2 values for the regression and ROK methods corresponded to low R^2 values for the OK and COK methods for the soil physical properties. Moreover, prediction of macro PVF through the inclusion of available calcium and phosphorus content in the models can also show that the response of soil properties to management regimes also relies upon aggregate formation as influenced by the cation exchange capacity and chemical composition of the soil (Mzuku et al. 2005).

Oliver & Webster (2014) make mention that the absence or existence of trend within the data can lead to a difference in how the data is kriged, as when trend is not accounted for, the estimations of kriging are woefully inadequate. Relationships established through the regressions in our study accounted for the effects of traffic confinement and allowed for the hybrid method of ROK to either enhance the predictability of the model or greatly reduce the error of the predictions (Table 3.6). This effect was likely due to the composition of the model residuals, which allowed for an uninfluenced prediction to occur (Mirzaee et al. 2016). Furthermore, reductions in ME and RMSE were not always accompanied by increases in R^2, which may be due to the residuals not being completely random and possessing some remainder of spatial structure (Knotters et al. 1995). Increased prediction ability from the quantification of trend in ROK culminated to the advent of Gaussian models used with our variograms, which accounted for the field scale variability in half of our soil physical properties.

Although, the Gaussian model may not always be a good fit, as it is modeled near the acceptable limit of random process and can cause difficulty for model convergence (Duffera et al. 2007; Oliver & Webster 2014). However, in a CTF environment this may be useful, as the residuals from the soil physical properties might not be solely influenced by random process but also by the spatial impacts of wheel traffic confinement that were not encapsulated by the regression.

The use of ROK to account for known spatial structure and reduce the uncertainty in kriging for croplands has been shown to be more effective than COK (Odeh et al. 1995; Simbahan et al. 2006), but was also outperformed by OK as shown by Eldeiry & Garcia (2010). However, the poor performance of both OK and COK in the soil physical properties in our study may be partially explained by Simbahan et al. (2006), where using OK with reduced sample sizes was shown to be less effective at field scale predictions than using OK with a comprehensive sample set. Thus, the accuracy of OK in our study may have been reduced due to the employment of the cyclic sampling design instead of traditional gridded sampling, despite the number of lag pairs being greater than 20 for each lag class from 2-60 m. Conversely, reduced sample sizes in ROK, such as the one used in our study, did not see reductions in accuracy or spatial detail as was observed in the OK methods (Simbahan et al. 2006). Moreover, the use of OK and COK methods operates under the assumption that correct correlations between the sampling point and its neighbours exists (Baveye & Laba 2015); however, the advent of tramlines breaks that assumption as the extrinsic management factors between trafficked and un-trafficked areas are inherently different. These sharp boundaries between trafficked and un-trafficked areas explain the poor performance of the OK and COK methods, as our un-trafficked soil physical and hydraulic properties were significantly different at a distance of > 1 m away from a respective tramline (Table 3.4). At the 1 m boundary of the tramline, significant increases in macro PVF and K_m paired with significant decreases in ρ_b and PAWC (at Lacombe) indicated substantial changes to the pore size distribution were caused from a lack of traffic (Table 3.3).

The ROK method was shown to be the optimal choice for quantification of the PAWC, while the K_m was better explained through the COK method (Table 3.6). The differences between PAWC and K_m may be explained through the measurement of PAWC, as it is based upon a specific range of pore diameter (9-0.02 μm) and is a function of the soils physical state. Conversely, the K_m of the soil is directly measured by the HYPROP® system through the evaporation method (Schindler & Müller, 2006). The significant variation of K_m between the trafficked and un-trafficked areas coupled with the COK method yielding the optimal model suggests that K_m is both a function of the management system and the landscape. The poor models created for K_m from the ROK and OK methods correlate well with Motaghian & Mohammadi (2011), where the ROK method displayed the lowest goodness-of-fit and produced the highest prediction error of saturated hydraulic conductivity compared to the COK method (Table 3.6). The optimal covariates used in the COK method for K_m was TPI at Dapp and curvature at Lacombe. The curvature covariate was likely the ideal choice for Lacombe due to the undulating nature of this site; however, TPI may be able to represent water movement on a smaller scale, which would suggest why TPI yielded optimal models despite its poor correlation with K_m (Table 3.8). The diversity of optimal models for the soil properties reflects the alternating driving forces of the corresponding underlying spatial structure, as no single prediction model suits all variables (Odeh et al. 1995).

The use of COK in conjunction with terrain derived covariates, such as aspect, curvature and slope, was shown in an earlier study to yield optimal model improvement for describing field scale variability (McBratney et al. 2003). However, our observed improvements in model R^2 and reductions in ME and RMSE values through the COK method for nutrient properties occurred from the inclusion of covariates such as elevation and TPI, with aspect, curvature and slope producing lesser contributions regardless of their higher correlations (Table 3.8). Although, as noted by Motaghian & Mohammadi (2011), covariates weakly correlated with primary variates sometimes produced better COK models than those with highly correlated covariates. The TPI covariate was able to quantify potential water movement and accumulation within the landscape better than elevation for the spatial prediction of STN and SOC, as TPI is based upon the relative elevations of surrounding cells (De Reu et al. 2013).

Covariate kriging methods have been shown to be the optimal method for the prediction of STN (Wang et al. 2013) and SOC (Ceddia et al. 2015) as well as both STN and SOC (Li et al. 2014) at regional scales. As the spatial structure of multiple soil nutrient properties was found to be mainly a function of the landscape in our study, the use of COK and terrain derived covariates that quantify elevation changes unsurprisingly aided in model optimization within our field scale of CTF croplands. Conversely, Heuvelink et al. (2016) determined that pH, STN and SOC were modelled well with regression co-kriging, while Hengl et al. (2004) and Mirzaee et al. (2016) observed that SOC was modeled better with ROK when compared to COK over regional scales. Differences observed between the COK and ROK methods for AN, pH and SOC in our study may be explained by the difference of mapping scales and relatively low ability of the regression model to capture explanatory relationships using our available predictor variables. As described by Baveye & Laba (2015), the scale in which soil is sampled can lead to skewed perception of the spatial heterogeneity, since large scale sampling leads to large autocorrelation distances and vice versa.

Comparisons among the predictive maps produced to display mean values for the soil nutrient properties in our study (AN, pH, STN and SOC) showed little visual differences. However, the COK method generally decreased the standard error of the predicted data when compared to the conventional OK method. Mirzaee et al. (2016) observed that the use of remote sensing data in predictive mapping approaches (e.g., LiDAR data in our study) accounted for substantial portions of the variation, highlighting the improvement of the COK method over the OK method in our case. A visualization of the reductions in prediction error for SOC from the OK to the COK method is shown by Fig. 3.3 (i) and 3.3 (ii), respectively. The increase in observed error with the OK method may be caused by reduced sample sizes (Simbahan et al. 2006), as this was likely due to the cyclic sampling design used in our study. Further research into reducing inconsistencies in prediction methods across regional and field scales warrants the testing of more robust hybrid techniques, such as artificial neural networks, with the incorporation of remote sensing (e.g., LiDAR or normalized difference vegetation index) to further decipher field scale dynamics.

3.5.3 Interpretation and Structure of the Spatial Heterogeneity

Spatial variation of soil properties has been shown to be a function of both the management system (Alletto et al. 2010) and landscape (Mzuku et al. 2005) at the field scale, with different properties being influenced through different mechanisms. These observations are consistent with our study; however, the accurate quantification of spatial heterogeneity also depends on stable temporal relationships between properties and sites. Alletto & Coquet (2009) and Raczkowski et al. (2012) both found temporal variability between soil physical and hydraulic properties when contrasting tillage methods, while Huang et al. (2007) observed temporal but not spatial variability between STN and SOC at regional scales. Consequently, homogenous duration and continual usage of CTF at both sites in our study coupled with sampling campaigns occurring at nearly the same time may allow for assumptions of temporal stability and continuity between comparisons to be employed.

The spatial structure of the soil dynamics at both sites can be further deciphered through an analysis of the nugget to sill ratio of the variogram, as postulated by Cambardella et al. (1994). The nugget to sill ratio is used to indicate the spatial dependence of a soil property, where ratio values determine if the spatial dependence is strong (< 25%), moderate (25-75%) or weak (> 75%). Nonetheless, both Oliver & Webster (2014) and Baveye & Laba (2015) agree that the nugget, and by extension the nugget to sill ratio, represents the variability within the smallest sampling distance. Low variability in the smallest sampling distance (i.e., strong spatial dependence) may indicate intrinsic effects are mainly responsible (Cambardella et al. 1994). As the management system in our study operates with tramlines spaced at ~3 m (wheel gauge) and 9 m (swath width) apart, large nugget to sill ratios (i.e., weak to moderate spatial dependence) would suggest high variability in the respective small sampling distance. Spatial dependencies for pH, STN and SOC were shown to be high by Heuvelink et al. (2016) and correlate well with nutrient properties in our study (Table 3.6), implying a heavy influence of the landscape. Additionally, in agreement with Duffera et al. (2007), the soil physical and hydraulic properties in our study displayed moderate spatial dependence (Table 3.6). This is likely due to the management structure influencing changes in the soil physical properties, as moderate to weak spatial dependence implies extrinsic influence (Cambardella et al. 1994). As extrinsic factors were shown to drive the variability of soil physical properties, intrinsic elements were presumably identified as the main driving force for the soil nutrient properties.

Differences in soil pH correlated the highest to corresponding changes in elevation and displayed the most visible structure with its regressors (Fig. 3.4). Additionally, the high correlations of pH with both calcium and boron (Table 3.8) suggest that knowledge of pH within the landscape paired with LiDAR elevation as a covariate can enable predictive mapping of both calcium and boron concentrations. Furthermore, the mapping of SOC in our study was also improved with the explicit incorporation of LiDAR elevation and TPI as model covariates. Improved SOC models may result in increased carbon inventory and reduced uncertainty, as the spatial determination of SOC has become an important issue (Heuvelink et al. 2016; Mirzaee et al. 2016). Our negative correlations observed between elevation and SOC (Table 3.8) in the field scale indicated enhanced carbon accrual in landscape mid-slopes and depressions. This observation is contrary to increases of SOC with elevation found by Mirzaee et al. (2016), where their study was established in Iranian croplands over the regional scale which contrasts our field scale study in the Canadian Prairies. Conversely, in line with our findings of reduced SOC content and increased ρ_B within trafficked areas, Mzuku et al. (2005) witnessed field scale reductions in SOC paired with increases to ρ_B within croplands in Colorado, U.S.A. For our Lacombe site, the relatively wide elevation range (Fig. 3.5 (i)) and spatial distribution of pH (Fig. 3.5 (ii)) and SOC (Fig. 3.5 (iii)) mapping predictions provide visualization to the lack of influence derived from the management system (i.e., CTF tramlines) and the predominance of lower pH values and higher SOC contents within low elevation areas.

Disparity in field scale variability witnessed between the study sites may be explained by the differences in elevation change observed between Dapp (range of 0.72m) and Lacombe (range of 3.50m). The greater elevation changes and overall higher undulations observed at Lacombe may have masked management induced heterogeneity, as wheel traffic induced variation can often be masked by variability of the natural landscape (Strudley et al. 2008). Shorter autocorrelation ranges for Lacombe in soil nutrient properties may also suggest that elevation change was playing the foremost role in field scale variability (Table 3.6). Furthermore, the increases in type 1 and type 2 sample size quantities for the Lacombe site to achieve the same accuracy threshold at Dapp displays the influence elevation changes can have on field scale heterogeneity (Table 3.7). Although, the autocorrelation ranges and sample sizes calculated at both sites were in relative agreeance with Loescher et al. (2014) for agricultural sites. Maximum autocorrelation ranges of soil properties for agricultural soils were described to be 30 m ±20 m with the corresponding sample size used for determining these points at 45 samples ±20 samples (Loescher et al. 2014). Additionally, the existence of a more homogeneous landscape, as witnessed at the Dapp site, may enable higher susceptibility to management effects. This is shown through the greater differences between trafficked and un-trafficked soil as well as an overall higher S-index value at Dapp (Table 3.4). Despite Lacombe showing nearly 5 times wider elevation range, a congruent spatial heterogeneity of soil properties was witnessed between sites and further supports Cambardella et al. (1994) observation of how spatial relationships can be applicable to sites with similar landscape features.

3.6 Conclusion

The use of precision agriculture may be described as not always being accurate, as the spatial heterogeneity of soil properties can be miscalculated, and thus, the solutions created can be misrepresented and built on unsupported assumptions. On the other hand, the use of precision agriculture must be appealing to producers to be fully utilized. Therefore, the shift away from static soil sampling and towards the incorporation of high spatial resolution elevation data from light ranging and detection (LiDAR), remote sensing data and minimal static soil sampling data is necessary to reduce costs and improve accuracy. This goal can be achieved using geostatistical methods, such as ROK and COK with LiDAR-derived covariates, which can estimate and map soil physical and nutrient properties at the field scale, respectively. Dependency of the spatial heterogeneity of soil pH and SOC on the movement of water across the landscape led to both the elevation and TPI covariates yielding the most optimal predictions while using the COK method. In general, the soil nutrient properties in our study were shown to be driven by the landscape and associated hydrologic features within the field scale.

The uniform traffic structure of CTF (i.e., tramlines) created a predictable spatial pattern of soil physical properties that were heavily influenced by this management system. Variations in soil physical properties can be easily predicted through regression models that were derived and captured through key soil properties such as soil bulk density and macro pore volume. Armed with the knowledge of how both the landscape and management system influence the spatial distribution of soil quality parameters within the field scale, management strategies related to precision agriculture techniques utilized in CTF (e.g., management zone delineation) may be designed and implemented more efficiently.

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3.9 List Figure of Captions

Fig. 3.1a: Cyclic soil sampling design with distance dimensions in meters. Sampling locations represent locations of undisturbed soil core sample, with composite samples taken within 2 cm of each sampling location (n=96). Plot orientation at Dapp encompassed tramline orientation from east to west, with tramlines oriented north to south at Lacombe.

Fig. 3.1b: Nest sampling design within cyclic sampling design with dimensions in meters. Both undisturbed soil core samples and push probe samples taken within the nest (samples #73-84) were taken at two depths, 5-10 cm and 15-20 cm (n=24).

Fig 3.2 Comparison of (i) macro pore volume fraction (PVF) and (ii) bulk density across traffic types (sprayer tramline, CTF tramline and un-trafficked zones) that are commonly displayed in a CTF landscape.

Fig. 3.3: The Lacombe site soil organic carbon (SOC) standard error (SE) spatial distribution shown through the ordinary kriging method (i) and the covariate kriging method (ii). The ordinary kriging method (i) has larger error variation when compared to the covariate kriging method (ii). Not the different z-scales across both SE predictions for each method.

Fig. 3.4: Soil calcium (i) and boron (ii) concentrations as a function of pH for two field sites in Alberta using controlled traffic farming.

Fig. 3.5: Lacombe site LiDAR elevation (i), soil pH (ii) and soil organic carbon (iii) spatial distributions. The elevation (i) spatial distribution is derived from the LiDAR bare earth data in meters above sea level (masl). The soil pH (ii) spatial distribution in the 5-10 cm depth is derived from the covariate kriging method with LiDAR elevation as a covariate. The soil organic carbon (iii) spatial distribution in the 5-10 cm depth is also derived from the covariate kriging method with LiDAR elevation as a covariate.

3.10 Tables and Figures

Table 3.1 Study site characteristics at the 5-10 cm soil depth for two controlled traffic farming (CTF) sites in Alberta.

Site	Year of CTF Implementation	Soil Order	Soil Type	Clay (%)	Silt (%)	Sand (%)
Dapp	2011	Dark Grey Luvisol	Sandy Clay Loam	21.41	43.13	35.46
Lacombe	2011	Black Chernozem	Sandy Loam	10.77	30.98	58.25

Table 3.2 Soil properties at the 5-10 cm depth for two controlled traffic farming sites in Alberta. Predictor and response variables for spatial model development are indicated.

Property	Units	Type	Dapp		Lacombe		Composited Sites	
			Mean	SE	Mean	SE	Mean	SE
NH^{4+}	mg kg^{-1}	Predictor	1.56	1.05	1.84	1.08	2.45	0.40
NO^{3-}	mg kg^{-1}	Predictor	20.37	1.06	19.68	1.07	24.22	1.14
AN	mg kg^{-1}	Response	22.28	1.06	22.28	1.07	26.67	1.32
pH		Response/Predictor	7.02	0.08	6.26	0.11	6.64	0.07
$P0_4^{3-}$	mg kg^{-1}	Predictor	69.41	4.08	193.33	6.11	131.04	5.80
K^+	mg kg^{-1}	Predictor	163.08	25.44	267.04	14.23	214.79	15.05
Ca^{2+}	mg kg^{-1}	Predictor	801.23	66.43	435.59	108.19	619.37	64.54
Mg^{2+}	mg kg^{-1}	Predictor	325.36	21.27	258.68	14.91	292.20	13.20
Fe^{2+}	mg kg^{-1}	Predictor	1419.23	30.23	1409.43	34.38	1414.36	22.82
Mn^{2+}	mg kg^{-1}	Predictor	125.81	4.67	182.38	4.35	153.95	3.79
Na^+	mg kg^{-1}	Predictor	2281.45	25.91	2828.90	22.54	2553.74	26.23
Cu^{2+}	mg kg^{-1}	Predictor	5.37	0.86	5.65	0.22	5.51	0.44
Zn^{2+}	mg kg^{-1}	Predictor	7.85	0.30	21.75	0.83	14.76	0.67
B^-	mg kg^{-1}	Predictor	3.01	0.23	1.99	0.21	2.50	0.16
STN	%	Response	0.38	0.01	0.37	0.01	0.37	0.01
SOC	%	Response/Predictor	4.95	0.13	4.19	0.11	4.58	0.09
C:N		Predictor	13.52	0.24	11.35	0.09	12.44	0.15
Density	g cm^{-3}	Response/Predictor	1.25	0.01	1.33	0.01	1.29	0.01
S-Index	unitless	Response	0.030	0.000	0.026	0.001	0.028	0.000
Macro	cm^3 cm^{-3}	Response/Predictor	0.047	0.003	0.059	0.003	0.052	0.002
Meso	cm^3 cm^{-3}	Predictor	0.092	0.003	0.088	0.003	0.088	0.002
Micro	cm^3 cm^{-3}	Predictor	0.088	0.001	0.069	0.001	0.077	0.001
Nano	cm^3 cm^{-3}	Predictor	0.130	0.003	0.106	0.004	0.116	0.003
Residual	cm^3 cm^{-3}	Predictor	0.113	0.002	0.098	0.003	0.103	0.002
PAWC	cm^3 cm^{-3}	Response	0.219	0.003	0.175	0.004	0.192	0.004
K_m	cm d^{-1}	Response	2.40	1.38	0.65	1.45	14.47	2.24

SE: standard error; AN: available nitrogen; STN: soil total nitrogen; SOC: soil organic carbon; C:N: carbon to nitrogen ratio; Macro: soil macroporosity; Meso: soil mesoporosity; Micro: soil microporosity; Nano: soil nanoporosity; Residual: residual soil porosity; PAWC: plant available water capacity; K_m: macro unsaturated hydraulic conductivity

Table 3.3 Soil property significance for ANOVA statistical analysis in the 5-10 cm depth separated by factors of traffic (trafficked versus un-trafficked) and site (Dapp versus Lacombe) for data composited from both sites. Further analysis between the sites was separated by a factor of traffic (trafficked versus un-trafficked). Additional analysis was done between sites for factors of tramline type (sprayer tramline versus CTF tramline) and distance of un-trafficked soils from a tramline (0 - 1 m versus > 1 m).

Site	Factor	AN (mg kg^{-1})	pH	STN (mg kg^{-1})	SOC (mg kg^{-1})	Density (g cm^{-3})	S-Index (unitless)	Macro (cm^3 cm^{-3})	PAWC (cm^3 cm^{-3})	K_m (cm d^{-1})
Composited	Traffic	*	NS	NS	NS	***	NS	***	***	***
	Site	NS	***	NS	***	***	***	**	***	*
	T x S	NS	NS	NS	NS	NS	NS	NS	NS	NS
Dapp	Traffic	*	NS	NS	NS	***	NS	***	**	***
Lacombe	Traffic	NS	NS	NS	NS	***	NS	***	**	***
Dapp	Tramline	NS	NS	NS	NS	NS	NS	NS	NS	NS
Lacombe	Tramline	NS	NS	NS	NS	NS	NS	NS	NS	NS
Dapp	Distance	NS	NS	NS	NS	***	NS	***	NS	***
Lacombe	Distance	NS	NS	NS	NS	***	NS	***	*	***

*indicates $P < 0.05$; ** indicates $P < 0.01$; *** indicates $P < 0.001$; NS: no significant interaction occurring with $P > 0.05$; Traffic (T): fixed effect factor of trafficked versus un-trafficked; Site (S): fixed effect factor of Dapp versus Lacombe; Tramline: fixed effect factor of sprayer tramline versus CTF tramline; Distance: fixed effect factor of un-trafficked soil from tramline at 0 - 1 m versus > 1 m. AN: available nitrogen (mg kg^{-1}); STN: soil total nitrogen (%); SOC: soil organic carbon (%); Density: soil bulk density (g cm^{-3}); Macro: soil macroporosity (cm^3 cm^{-3}); PAWC: plant available water capacity (cm^3 cm^{-3}); Km: macro unsaturated hydraulic conductivity (cm d^{-1})

Table 3.4 Selected soil parameters attributed for the 5-10 cm soil depth for two controlled traffic farming sites in Alberta compared between traffic type (trafficked and un-trafficked areas), tramline type (sprayer tramline versus CTF tramline), and distance of un-trafficked soils from tramline (0 – 1 m versus > 1 m).

Property	Site	Traffic Type	Traffic Mean	Tramline Type	Tramline Mean	Distance (m)	Distance Mean
AN ($mg\ kg^{-1}$)	Dapp	Trafficked	17.67a	Sprayer	33.95	0 - 1	1.29
		Un-Trafficked	24.30b	CTF	20.27	> 1	1.37
	Lacombe	Trafficked	23.39	Sprayer	19.52	0 - 1	1.34
		Un-Trafficked	24.40	CTF	20.14	> 1	1.37
pH	Dapp	Trafficked	7.10	Sprayer	6.20	0 - 1	7.06
		Un-Trafficked	6.97	CTF	6.35	> 1	6.90
	Lacombe	Trafficked	6.25	Sprayer	6.93	0 - 1	6.35
		Un-Trafficked	6.07	CTF	7.11	> 1	6.33
STN ($mg\ kg^{-1}$)	Dapp	Trafficked	0.38	Sprayer	0.40	0 - 1	0.35
		Un-Trafficked	0.41	CTF	0.35	> 1	0.37
	Lacombe	Trafficked	0.37	Sprayer	0.37	0 - 1	0.36
		Un-Trafficked	0.38	CTF	0.35	> 1	0.38
SOC ($mg\ kg^{-1}$)	Dapp	Trafficked	4.98	Sprayer	4.56	0 - 1	4.69
		Un-Trafficked	5.24	CTF	3.94	> 1	4.85
	Lacombe	Trafficked	4.24	Sprayer	4.85	0 - 1	4.14
		Un-Trafficked	4.32	CTF	4.70	> 1	4.29
Density ($g\ cm^{-3}$)	Dapp	Trafficked	1.36b	Sprayer	1.38	0 - 1	1.36b
		Un-Trafficked	1.18a	CTF	1.41	> 1	1.22a
	Lacombe	Trafficked	1.39b	Sprayer	1.44	0 - 1	1.40b
		Un-Trafficked	1.26a	CTF	1.32	> 1	1.27a
S-Index (unitless)	Dapp	Trafficked	0.031	Sprayer	0.023	0 - 1	0.030
		Un-Trafficked	0.030	CTF	0.028	> 1	0.030
	Lacombe	Trafficked	0.026	Sprayer	0.030	0 - 1	0.027
		Un-Trafficked	0.026	CTF	0.031	> 1	0.025
Macro ($cm^3\ cm^{-3}$)	Dapp	Trafficked	0.027a	Sprayer	0.035	0 - 1	0.027a
		Un-Trafficked	0.059b	CTF	0.032	> 1	0.055b
	Lacombe	Trafficked	0.035a	Sprayer	0.015	0 - 1	0.033a
		Un-Trafficked	0.076b	CTF	0.032	> 1	0.073b
PAWC ($cm^3\ cm^{-3}$)	Dapp	Trafficked	0.234b	Sprayer	0.170	0 - 1	0.230
		Un-Trafficked	0.213a	CTF	0.194	> 1	0.213
	Lacombe	Trafficked	0.184b	Sprayer	0.232	0 - 1	0.189b
		Un-Trafficked	0.163a	CTF	0.234	> 1	0.164a
K_m ($cm\ d^{-1}$)	Dapp	Trafficked	0.22a	Sprayer	0.03	0 - 1	0.29a
		Un-Trafficked	6.66b	CTF	0.22	> 1	8.27b
	Lacombe	Trafficked	0.13a	Sprayer	0.05	0 - 1	0.10a
		Un-Trafficked	2.14b	CTF	0.57	> 1	1.84b

ab: letters indicate significant differences between treatment mean groupings within each site at a critical level of 0.05; AN: available nitrogen ($mg\ kg^{-1}$); STN: soil total nitrogen (%); SOC: soil organic carbon (%); Density: soil bulk density ($g\ cm^{-3}$); Macro: soil macroporosity ($cm^3\ cm^{-3}$); PAWC: plant available water capacity ($cm^3\ cm^{-3}$); K_m: macro unsaturated hydraulic conductivity ($cm\ d^{-1}$)

Table 3.5 Regression model details, optimal prediction method and selected terrain covariate for each selected soil parameter at the 5-10 cm soil depth for two controlled traffic farming sites in Alberta.

Property	Regression Equation	Optimum Model	Covariate
AN (mg kg^{-1})	1.971 - 0.0938(pH)	COK	Elevation
pH	6.516 - 0.00376(PO_4^{3-}) + 0.000343(Ca^{2+}) + 0.162(B^-)	COK	Elevation
STN (mg kg^{-1})	0.0133 + 0.0789(SOC)	COK	TPI
SOC (mg kg^{-1})	0.555 + 12.229(Macro) + 27.728(Residual) + 0.177(B^-)	COK	TPI
Density (g cm^{-3})	2.062 - 2.785(Macro) - 2.336(Meso) - 3.978(Residual)	ROK	N/A
S-Index (unitless)	-0.00208 + 0.127(Meso) + 0.160(Nano)	ROK	N/A
Macro (cm^3 cm^{-3})	0.215 - 0.131(Density) - 0.00000852(Ca^{2+}) + 0.000088(PO_4^{3-})	ROK	N/A
PAWC (cm^3 cm^{-3})	0.124 - 0.432(Macro) - 0.614(Meso) + 1.918(Micro)	ROK	N/A
K_m (cm d^{-1})	0.505 + 20.331(Macro) + 19.954(Meso) - 0.00129(Na^+)	COK	TPI/Curvature

AN: available nitrogen (mg kg^{-1}); STN: soil total nitrogen (%); SOC: soil organic carbon (%);Density: soil bulk density (g cm^{-3}); Macro: soil macroporosity with pore radii >60 µm (cm^3 cm^{-3}); Meso: soil mesoporosity with pore radii from 60 to 9 µm (cm^3 cm^{-3}); Micro: soil microporosity with pore radii from 9 to 3 µm (cm^3 cm^{-3}); Residual: soil residual porosity with pore radii < 0.2 µm (cm^3 cm^{-3}); PAWC: plant available water capacity (cm^3 cm^{-3}); K_m: macro unsaturated hydraulic conductivity (cm d^{-1}); $P0_4^{3-}$: soil phosphate ion concentration (mg kg^{-1}); Ca^{2+}: soil calcium ion concentration (mg kg^{-1}); B^-: soil boron ion concentration (mg kg^{-1}); Na^+: soil sodium ion concentration (mg kg^{-1}); COK: covariate kriging method; ROK: regression kriging method; TPI: topographic position index; N/A: no optimum covariate available as it was not the optimum model

Table 3.6 Model development for the variogram analysis, goodness-of-fit, error metrics for the regression, regression kriging, ordinary kriging, and covariate kriging methods for each selected soil parameter at the 5-10 cm depth for two controlled traffic farming sites in Alberta.

Property	Site	Model	Nugget	Sill	Range	Spatial	R^2	RSS	MSDR	Regression (R)			Regression Kriging (ROK)			Ordinary Kriging (OK)			Covariate Kriging (COK)		
			c_o	$c_o + c$	(m)	Dependence				R^2	ME	RMSE	R^2	ME	RMSE	R^2	ME	RMSE	R^2	ME	RMSE
AN	D	S	66.300	355.900	6.0	Strong	0.842	3892.000	0.142	0.049	-4.926	16.904	0.104	0.442	15.984	0.105	0.570	15.929	0.952	0.059	4.894
(mg kg^{-1})	L	E	15.000	432.700	9.5	Strong	0.994	96.200	0.237	0.065	-3.549	20.564	0.038	-0.302	20.805	0.005	0.016	21.238	0.982	0.008	7.015
pH	D	S	0.139	0.778	75.9	Strong	0.888	0.053	0.110	0.405	0.019	0.599	0.608	-0.004	0.514	0.736	-0.010	0.398	0.928	-0.004	0.223
	L	E	0.039	1.011	30.3	Strong	0.775	0.132	0.010	0.430	0.115	0.782	0.714	0.039	0.561	0.849	0.004	0.418	0.994	-0.003	0.097
STN	D	E	0.003	0.014	50.1	Strong	0.665	0.000	0.040	0.905	0.021	0.039	0.935	-0.006	0.028	0.664	-0.003	0.063	0.188	-0.012	0.193
(mg kg^{-1})	L	S	0.001	0.013	49.1	Strong	0.868	0.000	0.055	0.948	-0.028	0.037	0.951	0.000	0.023	0.822	0.001	0.043	0.671	-0.010	0.062
SOC	D	E	0.001	1.819	48.6	Strong	0.843	0.406	0.005	0.187	-0.390	1.265	0.355	-0.050	1.241	0.639	-0.025	0.740	0.996	-0.004	0.093
(mg kg^{-1})	L	S	0.002	1.343	32.1	Strong	0.932	0.092	0.004	0.469	-0.049	0.929	0.530	-0.022	0.924	0.799	0.010	0.528	0.997	0.002	0.067
Density	D	S	0.003	0.005	50.6	Moderate	0.715	0.000	0.247	0.799	0.019	0.071	0.813	0.001	0.063	0.167	-0.040	0.169	0.311	-0.002	0.121
(g cm^{-3})	L	G	0.065	0.159	52.0	Moderate	0.376	0.000	0.818	0.528	-0.006	0.096	0.242	-0.055	0.207	0.147	0.006	0.129	0.086	0.047	0.252
S-Index	D	S	0.000	0.000	12.0	Strong	0.188	0.000	0.300	0.836	0.000	0.001	0.742	0.000	0.002	0.001	-0.001	0.005	0.002	-0.013	0.023
(unitless)	L	G	0.000	0.000	61.0	Strong	0.836	0.000	0.229	0.808	0.000	0.003	0.812	0.000	0.003	0.088	0.000	0.006	0.020	-0.006	0.025
Macro	D	G	0.000	0.000	2.5	Moderate	0.652	0.000	0.940	0.445	0.004	0.020	0.422	0.000	0.020	0.011	-0.001	0.027	0.022	0.016	0.068
(cm^3 cm^{-3})	L	E	0.000	0.001	26.6	Moderate	0.613	0.000	1.998	0.364	-0.004	0.026	0.328	0.001	0.026	0.000	0.001	0.034	0.064	0.015	0.077
PAWC	D	S	0.000	0.000	65.1	Moderate	0.810	0.000	0.292	0.666	-0.004	0.016	0.748	0.001	0.014	0.009	-0.007	0.036	0.040	0.033	0.248
(cm^3 cm^{-3})	L	G	0.000	0.001	30.0	Moderate	0.764	0.000	0.520	0.639	0.003	0.023	0.631	0.000	0.024	0.078	0.000	0.038	0.012	0.024	0.153
K_m	D	S	2.584E+04	1.208E+05	65.6	Strong	0.525	3.860E+09	2.142	0.145	-78.184	334.872	0.028	-51.308	334.286	0.003	-46.731	341.619	0.506	-2.871	244.651
(cm d^{-1})	L	G	3.980E+04	1.444E+05	38.3	Moderate	0.610	6.250E+11	0.490	0.000	-49.165	299.305	0.000	-37.050	305.224	0.026	-60.511	294.577	0.867	2.116	132.092

AN: available nitrogen (mg kg^{-1}); STN: soil total nitrogen (%); SOC: soil organic carbon (%);Density: soil bulk density (g cm^{-3}); Macro: soil macroporosity (cm^3 cm^{-3}); PAWC: plant available water capacity (cm^3 cm^{-3}); K_m: macro unsaturated hydraulic conductivity (cm d^{-1}); D: Dapp site; L: Lacombe site; S: spherical; E: exponential; G: Gaussian; R_{NS}: spatial dependence represented by the nugget to sill ratio; Strong: strong spatial correlation with R_{NS} <25%, Moderate: moderate spatial correlation with R_{NS} 25-75%; R^2: coefficient of determination; RSS: residual sum of squares; MSDR: mean square deviation ratio; ME: mean error; RMSE: root mean square error

Table 3.7 Sample size calculation for using sampled data to predict the actual vale at confidence levels within 5% (N_5), 10% (N_{10}), 25% (N_{25}) and 50% (N_{50}) of the actual value for each selected soil parameter at the 5-10 cm soil depth for composited (Dapp and Lacombe) controlled traffic farming sites in Alberta. Type 1 sample size calculation is based upon the variability of the modeled variogram, where type 2 sample size calculation is based on the overall variability within the data.

Property	Type 1 Sample Size				Type 2 Sample Size			
	N_5	N_{10}	N_{25}	N_{50}	N_5	N_{10}	N_{25}	N_{50}
AN (mg kg^{-1})	1575	394	63	16	737	184	29	7
pH	338	84	14	3	41	10	2	0
STN (mg kg^{-1})	324	81	13	3	121	30	5	1
SOC (mg kg^{-1})	579	145	23	6	108	27	4	1
Density (g cm^{-3})	393	98	16	4	67	17	3	1
S-Index (unitless)	176	44	7	2	98	24	4	1
Macro (cm^3 cm^{-3})	935	234	37	9	496	124	20	5
PAWC (cm^3 cm^{-3})	242	60	10	2	99	25	4	1
K_m (cm d^{-1})	10086	2521	403	101	24786	6196	991	248

AN: available nitrogen (mg kg^{-1}); STN: soil total nitrogen (%); SOC: soil organic carbon (%);Density: soil bulk density (g cm^{-3}); Macro: soil macroporosity (cm^3 cm^{-3}); PAWC: plant available water capacity (cm^3 cm^{-3}); K_m: macro unsaturated hydraulic conductivity (cm d^{-1}); N_5: sample size for confidence level within 95% of actual value; N_{10}: sample size for confidence level within 90% of actual value; N_{25}: sample size for confidence level within 75% of actual value; N_{50}: sample size for confidence level within 50% of actual value

Table 3.8 Selected soil parameters correlations with key soil nutrients and terrain derived covariates in the 5-10 cm depth for composited (Dapp and Lacombe) controlled traffic farming sites in Alberta.

Property	B^-	Ca^{2+}	PO_4^{3-}	Aspect	Curvature	Elevation	Hillshade	Slope	TPI
AN (mg kg^{-1})	-0.260***	-0.203**	0.080	0.020	0.157*	0.278***	-0.050	0.213**	0.051
pH	0.859***	0.809***	-0.330***	-0.240**	0.046	-0.629***	0.021	-0.321***	0.021
STN (mg kg^{-1})	0.707***	0.675***	-0.022	-0.172**	0.045	-0.326***	-0.209**	-0.100	0.020
SOC (mg kg^{-1})	0.775***	0.795***	-0.202**	-0.331***	0.047	-0.483***	-0.309***	-0.299***	0.053
Density (g cm^{-3})	-0.493***	-0.477***	0.124	0.245**	0.052	0.316***	0.273***	0.191*	0.050
S-Index (unitless)	0.151	0.193*	-0.224**	-0.306***	0.046	-0.342***	-0.038	0.213***	0.118
Macro (cm^3 cm^{-3})	-0.034	-0.154*	0.164*	0.138***	-0.009	0.251**	-0.035	0.213**	-0.027
PAWC (cm^3 cm^{-3})	0.374***	0.484***	-0.448***	-0.366***	0.143	-0.567***	-0.149	-0.471***	0.181*
K_m (cm d^{-1})	-0.027	-0.119	-0.013	0.035	-0.019	0.023	-0.085	0.033	0.012

*indicates $P < 0.05$; ** indicates $P < 0.01$; *** indicates $P < 0.001$; AN: available nitrogen (mg kg^{-1}); STN: soil total nitrogen (%); SOC: soil organic carbon (%); Density: soil bulk density (g cm^{-3}); Macro: soil macroporosity (cm^3 cm^{-3}); PAWC: plant available water capacity (cm^3 cm^{-3}); K_m: macro unsaturated hydraulic conductivity (cm d^{-1}); $P0_4^{3-}$: soil phosphate ion concentration (mg kg^{-1}); Ca^{2+}: soil calcium ion concentration (mg kg^{-1}); B^-: soil boron ion concentration (mg kg^{-1}); TPI: topographic position index

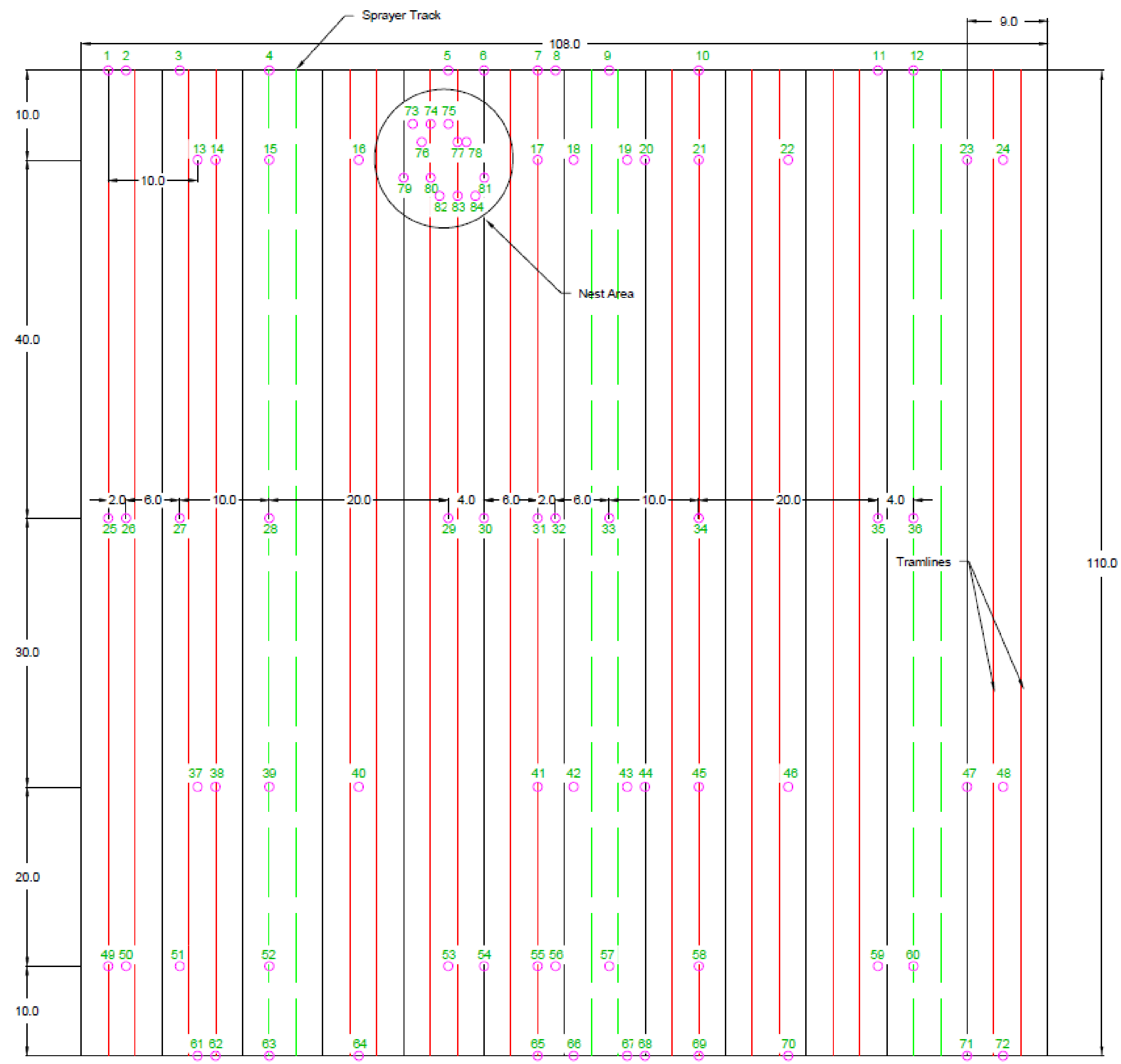


Fig. 3.1a Cyclic soil sampling design with distance dimensions in meters. Sampling locations represent locations of undisturbed soil core sample, with composite samples taken within 2 cm of each sampling location (n=96). Plot orientation at Dapp encompassed tramline orientation from east to west, with tramlines oriented north to south at Lacombe.

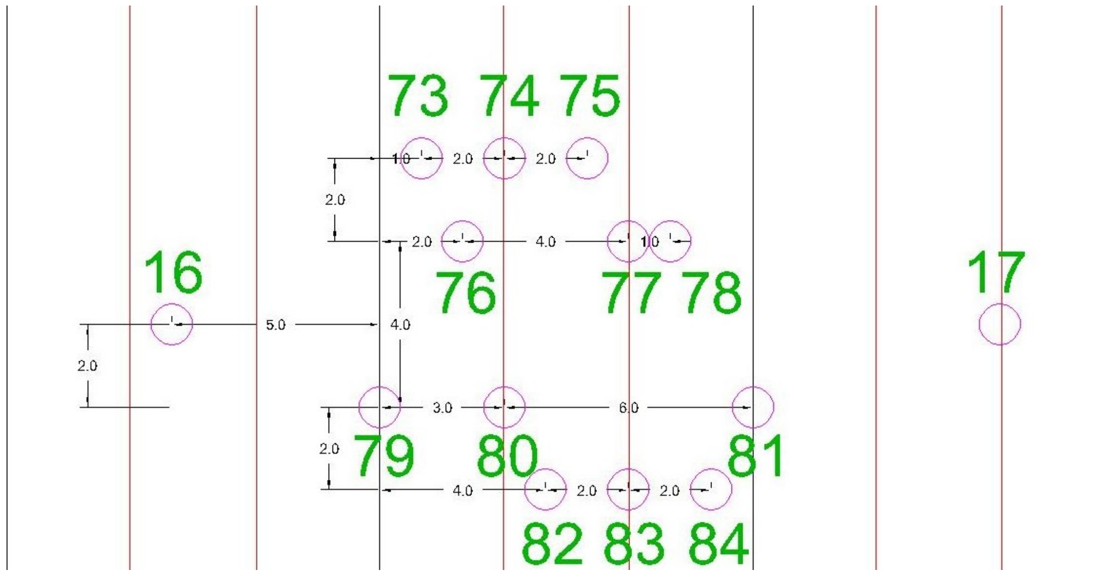


Fig. 3.1b Nest sampling design within cyclic sampling design with dimensions in meters. Both undisturbed soil core samples and push probe samples taken within the nest (samples #73-84) were taken at two depths, 5-10 cm and 15-20 cm (n=24).

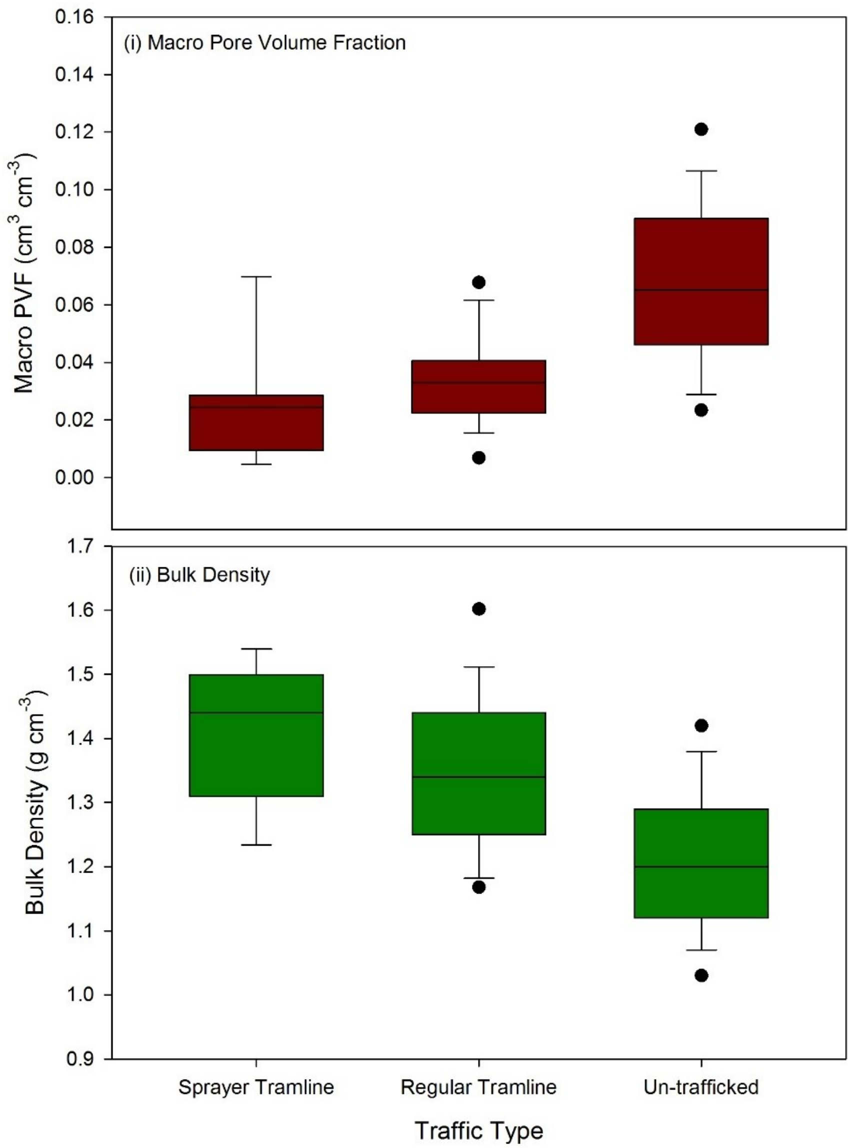
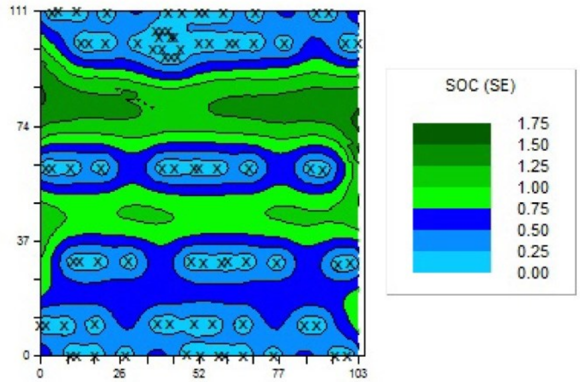
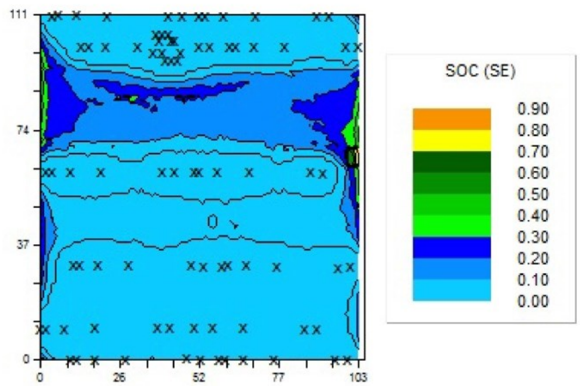


Fig 3.2 Comparison of (i) macro pore volume fraction (PVF) and (ii) bulk density across traffic types (sprayer tramline, CTF tramline and un-trafficked zones) that are commonly displayed in a CTF landscape.



(i) Ordinary Kriging Standard Error (mg kg^{-1})



(ii) Covariate Kriging Standard Error (mg kg^{-1})

Fig. 3.3 The Lacombe site soil organic carbon (SOC) standard error (SE) spatial distribution shown through the ordinary kriging method (i) and the covariate kriging method (ii). The ordinary kriging method (i) has larger error variation when compared to the covariate kriging method (ii). Not the different z-scales across both SE predictions for each method.

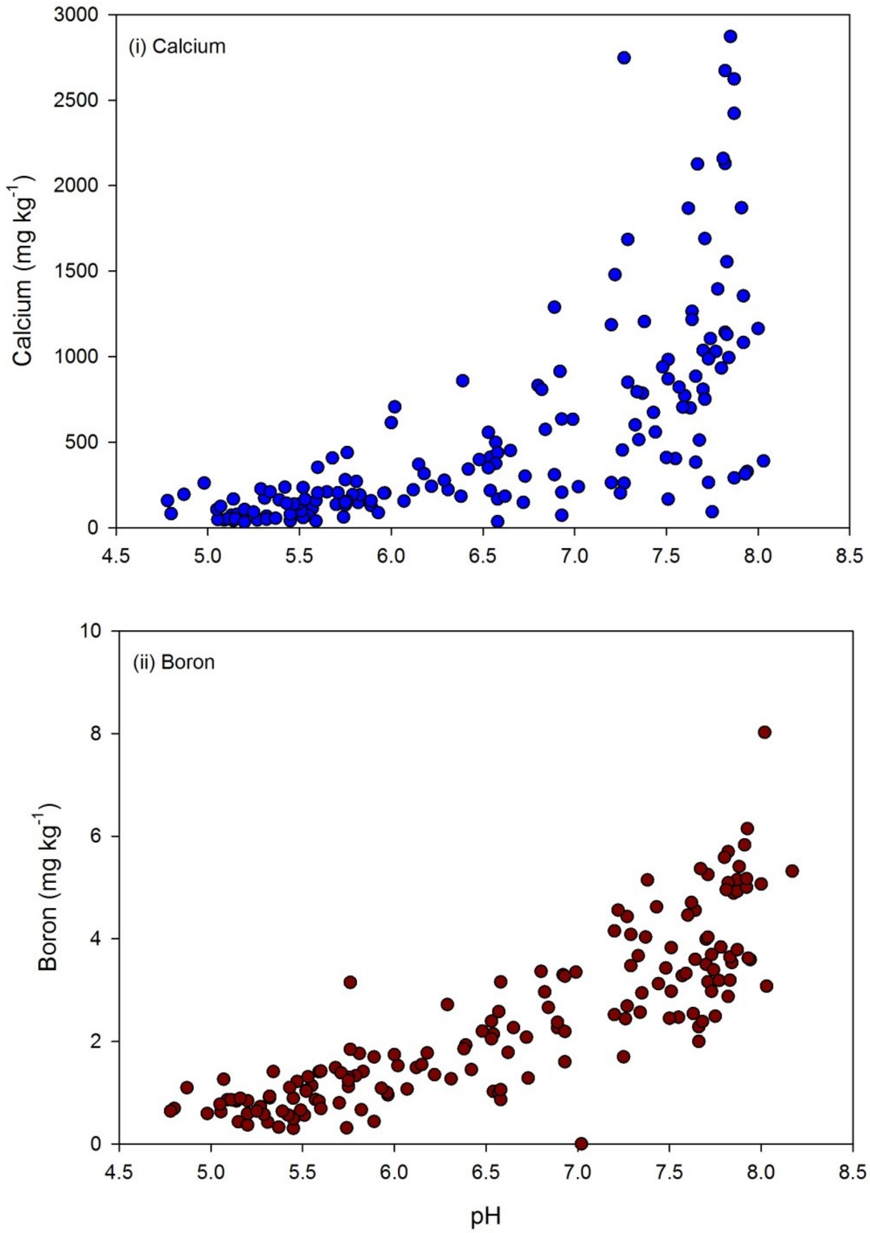
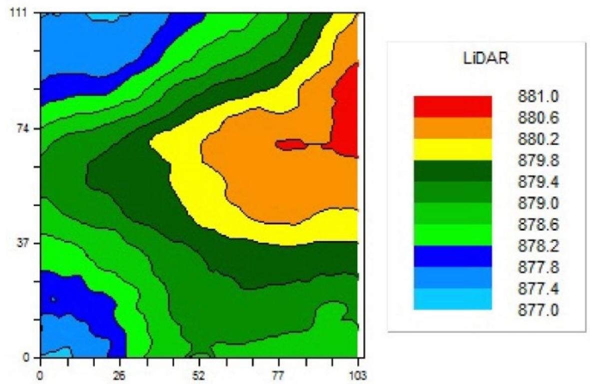
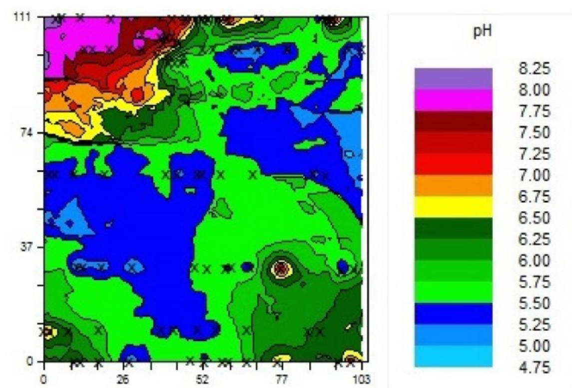


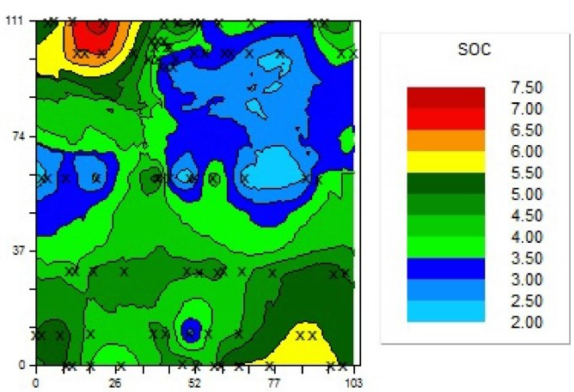
Fig. 3.4 Soil calcium (i) and boron (ii) concentrations as a function of pH for two field sites in Alberta using controlled traffic farming.



(i) LiDAR Elevation (masl)



(ii) Soil pH



(iii) Soil Organic Carbon (mg kg^{-1})

Fig. 3.5 Lacombe site LiDAR elevation (i), soil pH (ii) and soil organic carbon (iii) spatial distributions. The elevation (i) spatial distribution is derived from the LiDAR bare earth data in meters above sea level (masl). The soil pH (ii) spatial distribution in the 5-10 cm depth is derived from the covariate kriging method with LiDAR elevation as a covariate. The soil organic carbon (iii) spatial distribution in the 5-10 cm depth is also derived from the covariate kriging method with LiDAR elevation as a covariate.

Conclusion

The incorporation of innovative management techniques to existing farming practices should ultimately help producers increase efficiencies while reducing the environmental footprint associated with agricultural activities. Evolution within the agriculture industry has led to the exploration and adoption of precision techniques that are aimed to reach the goal of sustainability. Despite the concept of sustainability being broadly defined and loosely used more frequently across multiple industries, increases in agricultural production are greatly needed and must be accomplished while simultaneously reducing detrimental effects on the environment. Controlled traffic farming (CTF), the act of confining traffic to specific areas within a field, is a means of reducing the harmful effects of soil compaction and facilitating soil amelioration of un-trafficked areas. However, improvements to crop output that have been observed and predicated by various CTF researchers across the globe were not found at most sites in our study. These mostly null yield improvements could have likely occurred due to higher than average growing season precipitation during the years since CTF was initiated at our sites. Thus, we have found that CTF is a management technique that can decrease the anthropogenic impacts and degradation effects on soils in the Canadian Prairies and if coupled with other sustainable practices, such as zero till and diverse crop rotations, improvements to crop yield may be realized.

The alteration of soil quality parameters that resulted from the implementation of controlling traffic has had positive effects within the un-trafficked areas throughout most regional areas in Alberta. This is vital to the management style of CTF, as 65-80% of the field can be considered as un-trafficked areas. The un-trafficked zones displayed general improvements to soil structure that were realized through increases in overall porosity, water transmission pore volume and unsaturated hydraulic conductivity. These enhancements were also shown through increases to the un-trafficked soil physical quality metric (i.e., S-Index) and a heightened tendency for hierarchical aggregation. Although, the observed enrichments to soil physical quality were variable across the regional areas of Alberta and were likely due to the varying duration of CTF implementation, where longer durations of CTF usage displayed more robust soil amelioration. Furthermore, the regional areas that encompassed the soil types of Black Chernozems and Dark Grey Luvisols produced more visible responses to the reduction of traffic.

Undesirable alterations in soil structure and crop productivity due to simulated wheel traffic compaction were evident in our greenhouse study. The incorporation of pulse crops into cropping systems, such as faba beans, have shown an increasing trend in the Canadian Prairies and could be combined with other precision techniques (i.e., CTF) to aid in crop output. The inclusion of faba beans into crop rotations in Alberta has driven the need to determine optimal growing conditions and how different management practices can influence the production of faba beans. Analysis of four different compaction treatments indicated that some amount of compaction is required throughout the soil to achieve ideal plant productivity, with the optimal bulk density for faba beans corresponding to the un-trafficked soil and represented for both the Dark Grey Luvisol and Black Chernozem by 1.2 g cm^{-3}. Large amounts of compactive effort that was witnessed in the soil beneath the tramlines, or in the case of excessive equipment traffic, was shown to produce significantly less than ideal growing conditions. The compaction treatments of 1.2/1.4 g cm^{-3} (representing plow pan formation) and 1.4 g cm^{-3} (representing tramlines) displayed reduced faba bean biomass production and stomatal conductance, despite improved water-use efficiencies. Furthermore, the inclusion of water availability near field capacity with the compaction treatments displayed the prevalence of high water contents to mask poor soil conditions. Compaction treatments with a high water availability (-10 KPa) representing field capacity performed better than those with a relatively lower water availability (-100 KPa) representing field moist conditions, as the level of compaction became a larger driving force for plant productivity at lower water contents. Therefore, a lack of yield improvements observed throughout the regional study is further corroborated and solidified through the observation of the influence the soil water availability has on effectively counteracting potential underlying effects of existing poor soil structure conditions.

The important role that the availability and movement of water plays within CTF agroecosystems was further shown through the field scale geostatistical examination of the spatial heterogeneity of soil properties. Soil nutrient properties were found to be largely dependent on the landscape and associated movement and accumulation of water, to which the spatial distribution of nutrient properties showed minimal association to the CTF management system. This was shown as soil pH, soil organic carbon (SOC) and soil total nitrogen (STN) were highly correlated with topographic elevation and nutrient concentrations. The field scale variability of soil nutrient properties was optimally quantified through the geostatistical method of covariate kriging (COK), with both the elevation and topographic position index (TPI) covariates yielding the best goodness-of-fit and lowest prediction errors. The implication of covariates that best described the movement of water throughout the landscape yielding the best models further strengthened the reliance of soil nutrient heterogeneity and spatial patterns on water dynamics across these landscapes.

Relative to the clear spatial relationship between nutrient and landscape attributes, the physical and hydraulic properties of the soil at the field scale were influenced mostly by the management system (CTF) and partially by landscape characteristics. Wherein, significant differences between trafficked and un-trafficked treatment areas only occurred for the soil physical and hydraulic properties. Additionally, linear regression models for the soil bulk density, S-Index, plant available water capacity (PAWC) and unsaturated hydraulic conductivity (K_m) were mostly comprised of different soil pore volume fractions as explanatory predictors. The use of the hybrid method of regression kriging (ROK) provided predictive models with the best goodness-of-fit or lowest prediction error for the soil physical and hydraulic properties, with the sole exception of the K_m. The K_m displayed significant variations between tramlines and un-trafficked areas, but was best predicted through the COK method with the inclusion of the TPI covariate in the spatial model. Thus, soil physical quality was mainly a function of the confinement of the compactive effort and cessation of random traffic regimes, with soil nutrient availability being mainly a function of the geomorphology of the landscape.

Further improvements to provide a complete picture of field scale modelling may be found through the incorporation of sensor based data, such as normalized difference vegetation index (NDVI) and stomatal conductance, with more advanced spatial modeling techniques such as artificial neural networks. Use of proximal sensor based measurements on the plant canopies of our greenhouse study revealed that the NDVI was a good indicator for plant biomass production, with stomatal conductance adequately displaying variations in the evapotranspiration and water use efficiency of faba beans. Variations between the two heavily studied regional areas of Alberta encompassing the Dark Grey Luvisol at Dapp and the Black Chernozem at Lacombe collectively revealed general trends found in both the field scale study and greenhouse experiment. The Black Chernozem was observed to be a more resilient soil shown by a low occurrence of differences between trafficked and un-trafficked areas as well as an overall better plant productivity in the greenhouse study. However, the Dark Grey Luvisol responded better to the removal of traffic, as un-trafficked soil properties displayed a higher quality when compared to the Black Chernozem. Greater responses to management at the Dapp site may also be attributed to its narrower elevation fluctuation when compared to Lacombe, as we have found that more dynamic landscapes (i.e., greater undulations and slopes) can mask, counterbalance, or even negate management effects.

Apart from the need to further quantify field scale spatial soil variability through the inclusion of remote sensing crop and topographic derived data with more robust prediction techniques, future research should be directed towards the accurate and efficient delineation of coherent management zones based upon comprehensive knowledge of field scale heterogeneity and the spatial management structure. Furthermore, the testing and incorporation of geospatial data, such as topographic geomorphology and historical yield map data, should be completed to enhance the prediction ability of future models. Additionally, longer temporal scales are needed to further quantify the long-term effects and variability of CTF as well as its applicability for widespread commercial use in the Canadian Prairies. The inclusion of larger plots of conventional traffic systems versus controlled traffic systems is needed to account for variability between drought and moist growing seasons to properly ascertain a true difference in crop yield. To further push the effort in reaching sustainability, greenhouse gas emissions should be monitored between the conventional and controlled traffic systems to verify any findings under a broad range of edaphic-climatic conditions worldwide. To maintain the projected increase on demand of agricultural products and services, the need to develop and study innovative approaches to land management and food production must be undertaken to mitigate future risk for our global society. The looming threat of climate change and food security is increasingly tangible, making the achievement of sustainability an imperative directive for the human population.

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