Diversified No-Till Crop Rotations: Soil Health Attributes across Multiple Ecozones on the Canadian Prairies

by

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ABSTRACT

Traditional cereal-based cropping systems on the Canadian prairies have contributed considerably to soil and environmental degradation, increased production costs, and a threat to agricultural sustainability. To address global food demand, there is a need for sustainable cropping systems that enhance soil health (SH) in current climate conditions while reducing the use of agrochemicals. This dissertation focuses on understanding the impact of diverse crop rotations on SH. Chapter 2 presents a meta-analysis, which revealed that increased crop diversity significantly reduces bulk density, enhances soil aggregation, improves total porosity, and saturated hydraulic conductivity. Although it did not significantly change the infiltration rate, the benefits were more pronounced in medium- and fine-textured soils with >900 mm mean annual precipitation, especially when managed with conservation practices for 5 to 10 years. Chapters 3 and 4 document a multi-year field study conducted at three Canadian prairie sites (Lethbridge, Swift Current, and Scott). Six 4-year crop rotations [denoted as conventional (control), pulse/oilseed intensified, diversified, market-driven, high-risk and high-reward, and soil health-enhanced rotations] were established under no-till in 2018. Chapter 3 explores short-term soil organic matter (SOM) and aggregate stability (AS) dynamics, showing no improvement in SOM fractions but significant changes in AS at two sites (Lethbridge and Swift Current), with the soil health-enhanced and high-risk and high-reward rotations having the highest AS. Chapter 4 investigates how diverse crop rotations can alter soil hydraulic and physical quality, demonstrating moderate improvements in rotations with legumes and increased functional diversity, depending on the site. Chapter 5 assesses overall SH using a minimum dataset, revealing that the diversified rotation at Lethbridge and Swift Current, along with the high-risk and high-reward rotation at Scott exhibited the highest SH index. However, the number of indicators varies across sites, with common indicators such as soil organic carbon, bulk density, macroporosity, and plant-available water capacity. In conclusion, increasing the crop and functional diversity in rotations has the potential to sustain SH and contribute to sustainable agroecosystems but may require a longer period to become more evident.

PREFACE

This dissertation is an original research work authored by Ekene Mark-Anthony Iheshiulo, which comprises a general introduction, four Chapters written in manuscript format, and a general conclusion. Overall, I was responsible for sampling protocol, laboratory analysis, data curation, writing of original draft and reviewing, journal submission, and revisions for each Chapter included herein, under the supervision of Dr. Guillermo Hernandez Ramirez. Dr. Guillermo Hernandez Ramirez, along with other collaborators [Drs. F.J. Larney, M. St. Luce, H.W. Chau, and K. Liu] were responsible for funding acquisition, methodology, project administration, and manuscript reviewing and editing.

Chapter 2 of this dissertation presents a meta-analytical study summarizing previous research findings. The study has been published as "E.M.-A. Iheshiulo, F.J. Larney, G. Hernandez-Ramirez, M. St. Luce, K. Lui, and H.W. Chau, "Do diversified crop rotations influence soil physical health? A meta-analysis," *Soil & Tillage Research*, 233 (2023), 105781. The candidate was solely responsible for study design, data curation and analysis, interpretation, and manuscript writing and editing.

Chapter 3 of this dissertation presents original research published as E.M.-A. Iheshiulo, F.J. Larney, G. Hernandez-Ramirez, M. St. Luce, H.W. Chau, and K. Lui, "Soil organic matter and aggregate stability dynamics under major crop rotations on the Canadian prairies," *Geoderma*, 442 (2024), 116777. The field experiment was conceived before the candidate's arrival; however, the candidate was responsible for sampling protocol, laboratory analysis, data curation, and manuscript writing.

Chapter 4 of this dissertation presents original research published as E.M.-A. Iheshiulo, F.J. Larney, G. Hernandez-Ramirez, M. St. Luce, H.W. Chau, and K. Lui, "Crop rotations influence soil hydraulic and physical quality under no-till on the Canadian prairies," *Agriculture, Ecosystems & Environment*, 361 (2024), 108820. The field experiment was designed before the candidate's arrival; however, the candidate was involved in the sampling protocol, laboratory analysis, data curation, and manuscript writing.

Chapter 5 of this dissertation has been submitted for publication as E.M.-A. Iheshiulo, F.J. Larney, G. Hernandez-Ramirez, M. St. Luce, H.W. Chau, and K. Lui, "Quantitative evaluation of soil health based on a minimum dataset under various short-term crop rotations on the Canadian prairies" to *Science of the Total Environment* (under review). The candidate was solely responsible for study design, data analysis and interpretation, and manuscript writing and editing.

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1. INTRODUCTION

One of the major challenges facing the agriculture industry is developing a better way of producing enough food as the global population continues to increase, while protecting soil and environmental health (Foley et al., 2011; Davis et al., 2012). By 2050, the world population is expected to reach 9.6 billion, meaning that at least 60% more food will be needed than is available today (Food and Agricultural Organization - FAO, 2011). This increased need for food production is required for the same or even diminishing arable land area, meaning that there is need for sustainable intensification. Therefore, a substantial modification is required to current cropping systems without adversely affecting soil and environmental quality, particularly under future climate change scenarios.

Future climate change could significantly disrupt crop and agricultural production. Climate variables like temperature and precipitation have the greatest direct impact on crop production. On the Canadian prairies, projected increases in seasonal temperatures and changes in precipitation patterns may reduce crop yield and quality (Cohen et al., 2019). This is due to droughts and soil moisture deficits, when evaporation and transpiration due to increased temperatures exceed precipitation, especially in the southern prairies, where such conditions are expected to be more frequent and intense (Cohen et al., 2019). Furthermore, increased prevalence of pest and weed species are also potential effects of climate change due to increased atmospheric carbon dioxide and temperature, and changes in precipitation, hence creating newer problems for crops and potential yield reduction (Peters et al., 2014; Korres et al., 2016). Therefore, the adaptation of agriculture to climate change requires both the modification of current rotation systems and changes in cultivation practices.

Crop rotations mostly drive agricultural land-use activities (Barbieri et al., 2017). Rotating crops is one of the oldest, most effective, and useful agronomic tools used by growers for centuries to maintain and improve soil health (SH) (Aziz et al., 2011; Alhameid et al., 2017; Kiani et al., 2017), crop yield (Mohammed and Chen, 2018; St. Luce et al., 2020), and to control plant disease and pest infestation (Holm et al., 2006; Kutcher et al., 2011). It can also enhance N fertilizer (Gan et al., 2015; St. Luce et al., 2020) and water use efficiencies (Gan et al., 2015), and improve succeeding crop yield (Davis et al., 2012; Kremen and Miles, 2012). However, crop rotations have been considerably simplified and shortened over the past decades, by decreasing the number of crop species included in the rotations, resulting in increased areas of monoculture systems or less diverse rotations (Plourde et al., 2013; Hijmans et al., 2016). This is due to increased industrial demand for cereals, pedoclimatic conditions, and unpredictable economic return of other crops, specifically grain legumes (Cernay et al., 2015; Zander et al., 2016).

Conventional rotations within the Canadian prairies revolve around cereal-based systems, and are heavily reliant on agrochemicals to maintain crop yield (Karlen et al., 1994; Martens et al., 2015). Such systems may be the chief contributor to soil and environmental degradation and increased costs of production, threatening the sustainability of agricultural production (Kremen and Miles, 2012; Malézieux, 2012). Most of the problems caused by conventional rotations arise from the over-dependence on the simple nature of the system (Martens et al., 2015). According to Altieri (1999) and Phelan (2009), conventional rotations can be related to loss of biodiversity, inefficient use of resources, and are prone to pest infestation. Therefore, urgent attention is required in developing sustainable cropping systems with improved crop yield, resource use efficiencies and improved SH (Tilman et al. 2011; Mueller et al. 2012).

Intensification and diversification of conventional cereal-based rotations on the Canadian prairies has led to more sustainable cropping systems (Angadi et al., 2008). The economic and environmental benefits of diversifying crop species included in rotations have promoted a steady increase in the production of alternative pulse and oilseed crops over the past decades (Zentner et al., 2002). Inclusion of pulse and oilseed crops in conventional cereal-based rotations has proven to significantly increase agroecosystem resilience (Lin, 2011; Bowles et al., 2020), and cropping systems stability (Altieri et al., 2015; St. Luce et al., 2020) via agronomic (Cutforth et al., 2013; Angus et al., 2015), economic (Entz et al., 2002; Zentner et al., 2004; Lemke et al., 2012c), and environmental (Davis et al., 2012; Lemke et al., 2012b) benefits – today and into the future. Previous studies have shown that increased diversity of crops in rotation increased crop yield (Davis et al., 2012; Kremen and Miles, 2012; Li et al., 2018; Bowles et al., 2020; St. Luce et al., 2020) compared with less diverse rotations. Therefore, more diverse rotation systems could be beneficial towards meeting increasing food demands as the human population continues to rise.

1.1. Study Justification

Agricultural land use throughout the Canadian prairies was dominated by cereal-based rotations, mostly centered on spring wheat (*Triticum aestivum* L.) (Smith et al., 2001). The simplified nature of this rotation provides limited options in terms of possible crops to include in rotations due to pedoclimatic conditions, cropping system management, and increased food and industrial uses for cereal crops. Traditionally, the candidate break crops in a cereal-based rotation are pulse or oilseed crops. The inclusion of pulses in rotations is still limited due to the risks of disease pressures such as root rot, higher yield variability, and lower market prices (Cernay et al., 2015; Zander et al., 2016) compared to cereals and other break crops like canola. However, pulses can significantly improve subsequent crop yield by 0.2 to 1.6 Mg ha^{-1} and reduce the cost of agrochemicals by 20 to 50% in cereals (Preissel et al., 2015; Zander et al., 2016). Also, lower N requirements following pulses may reduce N fertilizer costs for farmers.

Additionally, soil moisture is a major limiting factor to crop productivity on the Canadian prairies, especially the drier southern prairies (Campbell et al., 1990). Increasing competition for water resources, coupled with future predicted increases in temperature, precipitation (although the uncertainty is high), and evapotranspiration (Cohen et al., 2019) could significantly impact water use in crop production. Diversifying crops in rotation with deep- and shallow-rooted crops under moisture-limited conditions can help conserve water and improve water-use efficiency. For instance, the inclusion of shallow-rooted pulse crops such as pea *(Pisum sativum)* and lentil *(Lens culinaris)* can help conserve soil water, which can benefit subsequent deep-rooted cereal and oilseed crops. This is because shallow rooted crops tend to use the available water within the root zone during the growing cycle (Merrill et al., 2002; Gan et al., 2007; Angadi et al., 2008; Liu et al., 2010; Cutforth et al., 2013; Ding et al., 2018). Generally, the inclusion of crops with diverse root distribution patterns promote soil permeability and aeration, thus enhance soil physical properties and functions (Campbell et al., 1990).

Previous diversified rotation studies predominantly focused on crop yield and quality, soil chemical or microbial properties, with few addressing soil physical or hydraulic properties. Moreover, most of the published studies on diversified crop rotation impacts on soil physical and hydraulic properties are mainly from the northern Great Plains of the US (Iheshiulo et al., 2023). Considering that soils often respond differently to agronomic practices (Castellini et al., 2014), and most soil physical properties may exhibit site-soil-specific interactions, the need to develop site-specific rotation systems is crucial for enhancing soil physical and hydraulic properties and crop productivity. In their benchmark publication, Campbell et al. (1990) summarized results from crop rotation studies on the Canadian prairies, with an emphasis on crop yield and soil fertility. More recently, Lafond and Harker (2012) updated results from long-term cropping system studies on the Canadian prairies, but again with a crop productivity/soil fertility focus. Information is still lacking on crop rotation diversity effects on soil health, particularly in physical and hydraulic properties within the Canadian prairie context.

Building on these premises, Chapter 2 of this dissertation presents a meta-analysis study conducted to understand the impact of crop diversity in rotations on soil physical health. The study combined and integrated published results from 1990 to 2020. By analyzing the existing literature, this Chapter aims to determine how crop diversity in rotations affected five key soil physical properties: bulk density, aggregate stability, porosity, infiltration rate, and saturated hydraulic conductivity, and also, explore how combined management practices and climatic and soil conditions modulated the effects of rotational diversity.

Chapters 3 and 4 document the findings from multi-year field experiments conducted at three sites with varying soil and environmental conditions on the Canadian prairies. These studies investigate the potential benefits of crop rotation diversification as a means of improving soil health attributes. These two Chapters focus on diversifying crops in rotations, which involves integration of both new and traditional crops.

Chapter 3 examines SOM and AS dynamics in the short-term. It also explored the interactions between SOM fractions and AS. In Chapter 4, the knowledge gap with respect to diverse crop rotation's ability to improve soil hydraulic and physical quality on the Canadian prairies in the short-term (4 year) was addressed. The study measured several indicators related to soil structure, porosity, and associated functions and processes such as water availability and movement and air exchange. This included but was not limited to, bulk density, total porosity, pore volume fractions, and hydraulic conductivity.

Chapter 5 evaluates overall SH based on a minimum dataset under various short-term diverse crop rotations. This Chapter uses data generated in Chapters 3 and 4 to determine a minimum dataset for evaluating SH, develop a site-specific SH diagnosis model to evaluate SH status, and quantify SH under different diverse crop rotations. Finally, Chapter 6 provide a summary of the entire study on diversified no-till crop rotation impacts on SH attributes.

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2. Do Diversified Crop Rotations Influence Soil Physical Health? A Meta-Analysis

Iheshiulo, E. M.-A., Larney, F. J., Hernandez-Ramirez, G., St. Luce, M., Lui, K., Chau, H. W., 2023. Do diversified crop rotations influence soil physical health? A meta-analysis. Soil Tillage Res., 233, 105781. https://doi.org/10.1016/j.still.2023.105781.

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2.1. Highlights

- Increasing crop diversity improved most soil physical health properties.
- Grain legumes in cereal-based rotations improved soil physical health properties.
- Diversity with conservation tillage enhanced soil aggregation, porosity, and saturated hydraulic conductivity.
- Crop diversity improved soil hydrologic properties in regions with mean annual precipitation >900 mm.
- Rotational diversity over long periods had greater benefits in medium- and fine-textured soils.

2.2. Synopsis

Crop management practices such as rotation, as well as climatic and edaphic factors, modulate soil physical health. However, the overall magnitude of crop rotation benefits on soil physical health properties across a broad range of different conditions remains uncertain. To address this, we conducted a meta-analysis on 865 paired comparisons from 148 rotation studies to examine i) how crop diversity affected soil physical health properties: bulk density, aggregate stability, porosity, infiltration rate, and saturated hydraulic conductivity, and ii) how management practices, climatic, and edaphic factors influenced crop diversity effects. Overall, increased crop diversity (i.e., number of crop species in the rotation) significantly reduced bulk density (−1.6 ± 1.3%), enhanced soil aggregation (15.9 ± 12.7%), improved porosity (3.1 ± 2.0%), and saturated hydraulic conductivity (112.8 ± 57.9%), but did not significantly change infiltration rate (92.2 ± 98.7%) compared to less diverse systems. Compared to using conventional tillage and cereals-only rotations, diverse rotations combined with conservation tillage or including grain legumes performed even better in enhancing both soil aggregation and porosity. Diverse crop rotations managed for 5 to 10 years showed greater benefits in regions experiencing mean annual precipitation >900 mm, and in medium- and fine-textured soils. Among soil physical health properties, saturated hydraulic conductivity was the most responsive to management practices. Based on this meta-analysis, we conclude that rotations including diverse crop species and grain legumes, managed under conservation tillage are best for improving soil physical health, and thus should be considered when designing and developing sustainable cropping systems that promote soil health, system resilience, and crop productivity.

Keywords: Crop rotations; Crop diversity; Conservation practices; Soil health; Soil physical properties; Meta-analysis.

2.3. Introduction

Understanding and identifying the impact of conservation management practices, such as crop rotation and diversification, legume integration in rotation, and no-till or reduced tillage, on soil physical health is crucial to developing sustainable cropping systems that can enhance and maintain soil productivity and environmental quality (Karlen and Rice, 2015; Lal, 2015). Although the benefits of different conservation management practices are well-known, the global adoption rate remains unsatisfactorily low (Kassam et al., 2015). Specifically, agricultural land use is dominated by the cereal-based system (Smith et al., 2001) due to higher demand and usage, coupled with higher economic returns, thereby limiting alternative crop adoption/inclusion (Roesch-McNally et al., 2018). Diversifying crop rotations with pulses is still limited due to the risks of wider yield variability, increased costs with low economic returns, water limitations in rain-fed systems (Cernay et al. 2015; Zander et al. 2016), farmers' perceptions, and lack of financial incentives to encourage alternative crop adoption (Roesch-McNally et al., 2018). These limitations partly drive the need for worldwide comprehensive documentation of the additive and synergistic benefits of combining such conservation management practices in cropping systems to contribute to the creation of proactive policies and markets that will enable a more diverse and sustainable agroecosystem.

The benefits of crop species diversification are mostly achieved through rotations implemented as an integral part of conservation management. Crop rotation involves growing diverse crop species sequentially in a defined succession over time (Karlen et al., 1994; Leteinturier et al., 2006). Moreover, crop rotation is an ecologically-oriented production system that can reduce the use of agrochemicals, improve soil health (Karlen et al., 2006; Kiani et al., 2017; Leteinturier et al., 2006), mitigate weed and pest pressures (Bullock, 1992; Weisberger et al., 2019), and increase crop yield (Kremen and Miles, 2012; St. Luce et al., 2020). However, in recent decades, crop rotation has often been simplified to cereal-based rotations, raising concerns over the decline of crop diversity. This decline in crop diversity can be linked to the replacement of rotations with cereal-based monocultures (McDaniel et al., 2014) due to increased industrial demand for cereals, pedoclimatic conditions, and unpredictable economic return of other crops, specifically grain legumes (Bullock, 1992; Cernay et al., 2015; Zander et al., 2016; Roesch-McNally et al., 2018). Furthermore, simple cereal-based rotations are heavily reliant on agrochemicals to maintain productivity (Karlen et al., 1994; Martens et al., 2015), and can often be perceived as a major contributor to soil and environmental degradation, and increased costs of production, threatening agricultural sustainability (Chan and Heenan, 1996; Kremen and Miles, 2012; Malézieux, 2012; Sun et al., 2018). However, incorporating grain legumes or cover cropping in cereal-based rotations can enhance soil water conservation, and increase system productivity (Gan et al., 2015), soil organic carbon (SOC), and microbial activity and diversity, due to increased C-rich root exudates, nutrients, moisture, and ambient oxygen, thus enhancing soil physical health (Farmaha et al., 2022; McDaniel et al., 2014; Tiemann et al., 2015). Moreover, when combined with conservation tillage, diversifying rotations with grain legumes or cover crops, can further promote SOC, aggregate stability, and biological soil health (DuPont et al., 2014; Franzluebbers et al., 2000; Kemper et al., 2011; Liebig et al., 2014; Nunes et al., 2020).

Nowadays, a growing body of cropping systems research focuses on developing sustainable practices that can promote economic, societal, and environmental benefits through crop diversification (Angadi et al., 2008; Lenssen et al., 2007; Lemke et al., 2012; Smith et al. 2001; St. Luce et al., 2020; Zentner et al., 2002). Furthermore, as climatic conditions become more uncertain, the ability of crop diversity to enhance resilience to climatic stressors (Bowles et al.,

2020) and improve yield stability with reduced external inputs (Degani et al., 2019; Gaudin et al., 2015) is becoming increasingly important in cropping systems. Diversifying rotations can mitigate the adverse effects of climate change on soil function (Hamidov et al., 2018) and crop production (Bowles et al., 2020; Degani et al., 2019; Gaudin et al., 2015).

Generally, increased crop diversity (i.e., the number of crop species in the rotation) significantly improved soil physical health compared to monoculture or less diverse systems (Alhameid et al., 2017, 2020; Aziz et al., 2011; Maiga et al., 2019; Nouri et al., 2019; Pikul et al., 2006, 2008). The beneficial effects on soil physical health were attributed to diverse root systems that increase the numbers and network continuity of micro- and macro-pores (Kumar et al., 2012a, 2012b), aggregation, and SOC (Alhameid et al., 2017). Although the existing literature supports these overall effects of rotational diversity on soil health indicators (Basche and DeLonge, 2019; McDaniel et al., 2014; West and Post, 2002), inconsistent interactions across climates, additional management practices, and other edaphic factors within the available reports make it challenging to draw general statements on the effects of crop diversity on soil physical health. For example, while some studies reported reduced bulk density, increased aggregate stability (Benjamin et al., 2008; Aziz et al., 2011; Alhameid et al., 2017), improved porosity, infiltration rate, and saturated hydraulic conductivity (Govaerts et al., 2007; Blanco-Canqui et al., 2010; Baumhardt et al., 2012), others reported no significant effects on the above-mentioned soil physical health indicators (Alemu et al., 1997; Benjamin et al., 2008, 2007; Govaerts et al., 2007; Baumhardt et al., 2012) compared to less diverse rotations.

Soil physical health properties such as bulk density, aggregate stability, porosity, infiltration rate, and saturated hydraulic conductivity influence other soil functions such as nutrient cycling, soil erosion (Fageria, 2002), water storage and availability (Kiani et al., 2017), and crop performance (Pittelkow et al., 2015). Improved SOC, aggregate structure, and stability affect water infiltration, thus reducing soil erodibility and increasing nutrient protection within aggregates (Six et al., 2000). Furthermore, infiltration rate and saturated hydraulic conductivity regulate water and nutrient movement in soils (López-Fando and Pardo, 2009); while increased bulk density can impede root penetration and water flow, thereby limiting crop yield (Batey, 2009). These soil physical properties are key indicators of soil health because of their significant influence on crop performance, water, and nutrient movement in soils (Sasal et al., 2010; Villamil et al., 2006; Bagnall et al., 2022).

A global meta-analysis is a useful statistical approach for combining and integrating published results and estimating overall effects of conservation management practices (Corbeels et al., 2014). Meta-analysis has been successfully applied in evaluating the overall effects of agricultural management practices on SOC (Du et al., 2017; King and Blesh, 2018; McDaniel et al., 2014; Powlson et al., 2016), soil microbial diversity and function (Li et al., 2018; Venter et al., 2015), greenhouse gas emissions (Mei et al., 2018), weed suppression (Weisberger et al., 2019), and crop yield (Corbeels et al., 2014; Fernandez et al., 2020; Knapp and van der Heijden, 2018; Zhao et al., 2020). While meta-analysis has also been used to evaluate management practices on soil physical health (Basche and DeLonge, 2017, 2019; Farmaha et al., 2022; Li et al., 2019; Nunes et al., 2020), none of the existing meta-analyses considered the combined and synergistic effects of management practices such as crop rotation, grain legume integration in rotation, and tillage options.

Although many studies have reported crop diversity effects on soil physical health across a wide range of management practices and climatic and edaphic conditions, the question of whether and how rotational diversity effectively improves soil physical health still needs to be answered. Given the decline in crop diversity over the last decades and the inconsistent interactions between crop rotation and soil physical health properties, the purpose of this study was to analyze whether diversity in crop rotation influenced soil physical health. A meta-analysis approach was used to comprehensively analyze peer-reviewed articles published between 1990 and 2020, to better understand rotational diversity effects, and provide scientifically-sound recommendations for growers, agronomists, researchers, and policymakers. The specific goals were to examine: (i) how crop diversity influenced five key soil physical properties (bulk density, aggregate stability, porosity, infiltration rate, and saturated hydraulic conductivity), and (ii) how combined management practices, and climatic and edaphic conditions modulated rotational diversity effects.

2.4. Materials and Methods

2.4.1. Literature search and selection criteria

To understand the impact of crop diversity on the five soil physical health properties of interest (bulk density, aggregate stability, porosity, infiltration rate, and saturated hydraulic conductivity) using a meta-analytic approach, the first step was to identify previously published studies that could be included. A comprehensive search was conducted using Web of Science (https://login.webofknowledge.com/) and Google Scholar (https://scholar.google.com/) with the keywords "crop rotation", "cropping system," "bulk density," "aggregate stability," "porosity," "infiltration rate," and "saturated hydraulic conductivity" OR "hydraulic conductivity". Searches were carried out between March and April 2021, restricted to peer-reviewed articles published between 1990 and 2020, and the resulting hits were compared to remove duplicate studies (Fig. 2.1).

To supplement Web of Science and Google Scholar searches, the reference lists of identified studies were used for more relevant studies. Based on the title and abstract of retrieved studies, irrelevant studies were excluded, yielding 148 peer-reviewed articles reporting at least one of the five soil physical health properties of interest (Fig. 2.1). The full text of the studies was examined for eligibility using the following criteria: (i) only field studies that reported less diverse rotations as controls and more diverse rotations as treatments (e.g., one vs. two or two vs. four species in rotation) were included, (ii) the rotational treatments were randomized with replications, and physical property means and study duration were reported, (iii) for studies that included other treatments (e.g., tillage, fertilizer), only rotation data were considered and interacting effects with other treatments were excluded, and (iv) for data from the same experiment reported in multiple publications, only data from one publication were considered. Information on the selected and rejected studies is reported in the preferred reporting items for systematic reviews and meta-analysis (PRISMA) chart (Fig. 2.1).

2.4.2. Database development

Relevant categorical variables from screened published articles such as crop diversity (i.e., number of crop species in rotation), inclusion of grain legumes, tillage systems, study location (including latitude and longitude), soil texture, mean annual precipitation (MAP), study duration (i.e., from experiment establishment to measurement year), number of replications, and the five soil physical health properties of interest (bulk density, aggregate stability, porosity, infiltration rate, and saturated hydraulic conductivity) were directly extracted to develop the database. Furthermore, the categorical variables were allocated to management, climatic and edaphic, and study duration sub-groups in order to explore how the response of soil physical health properties to crop diversity was modulated by these additional factors. The management sub-groups were grain legume inclusion [cereal-only and cereal-legume (only harvested annual grain legumes), *n* = 2], and tillage system [conventional and conservation , *n* = 2]. Climatic and edaphic sub-groups included geographic region (Africa, Asia, Australia, Europe, North America, and South America, *n* = 6); soil texture [coarse- (e.g., sand, loamy-sand, and sandy-loam), medium- (e.g., loam, silt-loam, and silt), and fine- (e.g., sandy-clay, sandy-clay-loam, clay-loam, silty-clay, and clay) textured soils, *n* = 3], and MAP (< 500, 500 to 900, and > 900 mm, *n* = 3); while the study duration sub-groups were < 5, 5 to 10, and > 10 years (*n* =3). When not reported in U.S. studies, MAP was obtained from the U.S. National Weather Service (https://www.weather.gov/), while soil texture data were extracted from the USDA's Web Soil Survey (Soil Survey Staff, 2012). For studies conducted in Canada, MAP was obtained from local Environment and Climate Change Canada weather stations.

Several pairwise comparisons within study locations were created. For a given pairwise comparison, the "control" rotation was always less diverse than the more-diverse "treatment" rotation. Data from different rotations were considered as independent observations when more than one rotation was reported. Also, when studies reported data from several years, each year was considered an independent observation, while in the case of multiple data within one year or multiple soil depths, data were averaged (McDaniel et al., 2014). For graphically represented data, WebPlotDigitizer software (ver. 4.4, Rohatgi, 2020) was used to extract the mean values. Additionally, when studies reported either bulk density or porosity, Equations 1 and 2 were used to estimate the unreported parameter, respectively.

$$Porosity\ (\%) = \left[1 - \frac{\rho_b}{\rho_s}\right] \times 100 \qquad (2.1)$$

$$\rho_b = (1 - Porosity) \times \rho_s \qquad (2.2)$$

where ρ_b and ρ_s represent bulk and particle density, respectively. If not reported, particle density was assumed to be 2.65 g cm^3.

2.4.3. Meta-analysis

To test the impact of crop diversity on soil physical health, several comparisons were created, including one vs. two species, one vs. three, one vs. four, two vs. three, two vs. four, and three vs. four species. Due to insufficient data, other comparisons, e.g., one vs. five, one vs. six, or five vs. six species, were not tested. To explore the response of soil physical health to crop diversity, the effect size was calculated using the response ratios (lnRR) in Equation 3, which is the comparison of the control to treatments (Hedges et al., 1999).

$$\mathrm{lnRR} = \ln\left(\frac{\chi_\mathrm{t}}{\chi_\mathrm{c}}\right) = \ln(\chi_\mathrm{t}) - \ln(\chi_c) \qquad (2.3)$$

where χ_t and χ_c are the means of the treatment and control of the response variables, respectively. The RR was normalized by natural logarithmic transformation. A weighted factor (Wi) is usually developed for meta-analysis to give more weight to studies with greater precision or lower within-study variability (Basche and DeLonge, 2017, 2019; Philibert et al., 2012). Most of the studies included in the database did not report standard deviations or errors, thus, a weighting factor was developed based on the number of replications using Equation 4 (Adams et al., 1997; Basche and DeLonge, 2017; McDaniel et al., 2014), which was included in the statistical model.

$$W_i = \frac{Experimental\ Reps.\ \times\ Control\ Reps.}{Experimental\ Reps.\ +\ Control\ Reps.} \qquad (2.4)$$

Statistically, a mixed-effects model (lmer4 package, version 1.1-27.1) was conducted in RStudio (R Core Team, 2016) to estimate mean effects. The model included a random effect of study, similar to a "block effect" as well as an experimental replication weighting factor. When more than one response ratio is reported for a study, the random effect accounts for similarities in climate conditions (Eldridge et al., 2016; St-Pierre, 2001). In addition to calculating the overall mean effects, studies were analyzed separately in sub-groups (based on grain legumes inclusion, tillage system, geographic region, soil texture, MAP, and study duration), that were treated as fixed effects. Effect sizes were considered non-significant when the 95% confidence intervals overlapped with zero (Adams et al., 1997), thus, the treatment groups were not significantly different from the control groups. To facilitate interpretation, the lnRR were back-transformed and converted to percentages (Equation 5) to explain the estimated response of soil physical health to crop diversity.

$$\%\,change = \left[e^{(lnRR)} - 1\right] \times 100 \qquad (2.5)$$

Analysis of publication bias in meta-analysis determines whether there are differences in the number of published studies as a function of effect sizes. This would reflect a preference for published studies showing no significant positive or negative effects (Koricheva and Gurevitch, 2014). To check for the presence of any bias in the assembled datasets, histograms were used to examine the data distributions for each target variable (Basche and DeLonge, 2017, 2019). Histograms were an effective way to examine bias in the dataset since the sample sizes are represented by experimental replications, and we did not have wide enough ranges to create funnel plots based on this metric (Basche and DeLonge, 2017, 2019; McDaniel et al., 2014; Philibert et al., 2012). Furthermore, the jackknife technique was used to test data sensitivity (Philibert et al., 2012), in which individual studies were excluded and the overall effect size of crop diversity on soil physical health indicators was recalculated using the statistical model (Basche and DeLonge, 2019; Philibert et al., 2012).

2.5. Results

2.5.1. Database overview

The database comprised 148 studies conducted under rainfed conditions from six regions worldwide. Most of the studies (43) were conducted in North America, with the majority (38) in the United States (Table 1). Overall, 867 paired comparisons from the 148 available publications were included in the meta-analysis database (Table 2.1). Twenty-eight percent of the studies in the database reported bulk density and porosity, while 13% reported saturated hydraulic conductivity or infiltration rate (Supplementary Fig. S2.1).

The lnRR ranged from −0.25 to 0.29 for bulk density, −1.13 to 1.22 for aggregate stability, −0.48 to 0.85 for porosity, −4.27 to 3.70 for infiltration rate, and −2.07 to 2.46 for saturated hydraulic conductivity (Table 2.1). Furthermore, 67 to 75% of the database showed a reduction in bulk density as well as increases in aggregate stability, porosity, infiltration rate, and saturated hydraulic conductivity as functions of increased crop diversity. Most studies compared monoculture to more diverse rotations, while few compared less diverse rotations to more complex ones (Supplementary Tables S2.1, S2.2, S2.3, and S2.4).

2.5.2. Analysis of data bias and sensitivity

No evidence of bias was found in the overall analysis of the data distributions for soil physical health properties (Fig. 2.2), indicating that experimental results were not skewed and had a weak or no clear tendency for smaller sample sizes to be associated with stronger positive or negative effects. Therefore, bias was not a limitation within this meta-analysis as the response ratios of the soil physical health properties were symmetrically distributed around the mean effect size. Additionally, a data sensitivity test for the mean effects indicated that the exclusion of studies did not alter the overall estimates for improvements in soil physical health with crop diversity, adding support for the robustness of the overall effect sizes, which showed that crop diversity significantly improved soil physical health (Supplementary Fig. S2.2).

2.5.3. Impact of crop diversity on soil physical health

The degree to which crop diversity affected soil physical health depended on specific physical properties. Compared to monoculture, two or more crop species in rotation significantly increased aggregate stability (Fig. 2.3b), porosity (Fig. 2.3c), and saturated hydraulic conductivity (Fig. 2.3e), but not bulk density (Fig. 2.3a) or infiltration rate (Fig. 2.3d). However, having four crop species in rotation did not improve bulk density, aggregate stability, porosity, infiltration rate, or saturated hydraulic conductivity, compared to two or three crop species (Fig. 2.3).

Overall, crop diversity significantly impacted bulk density (−1.6%, 95% confidence interval (CI) from −2.9 to −0.2%), aggregate stability (15.9%, 95% CI from 3.2 to 28.6%), porosity (3.1%, 95% CI from 1.1 to 5.0%), and saturated hydraulic conductivity (112.8%, 95% CI from 54.9 to 170.6%). These four soil physical health properties showed overall means significantly different from zero, but soil infiltration rate did not (92.2%, 95% CI from −6.4 to 190.9%) (Fig. 2.3).

2.5.4. Influence of management practices

Management practices such as the inclusion of grain legumes and tillage system choice were found to influence crop diversity impacts on soil physical health, but the influence varied among subgroup categories. The inclusion of grain legumes significantly reduced bulk density (−1.7%, 95% CI −3.1 to −0.2%), enhanced aggregate stability (20.8%, 95% CI 6.3 to 35.3%), improved porosity (4.1%, 95% CI 1.7 to 6.5%), and saturated hydraulic conductivity (119.5%, 95% CI from 52.1 to 186.9%), but did not increase infiltration rates (120.0%, 95% CI from −7.3 to 247.2%) compared to cereal-only rotations (Fig. 2.4).

Crop diversity combined with conventional tillage did not significantly improve bulk density (−2.0 ± 2.1%; Fig. 2.5a), aggregate stability (14.2 ± 17.5%, Fig. 2.5b), or porosity (2.5 ± 3.5%; Fig. 2.5c), but significantly increased infiltration rate (208.8 ± 149.4%; Fig. 2.5d) and saturated hydraulic conductivity (186.5 ± 120.6%; Fig. 2.5e). Conversely, crop diversity combined with conservation tillage practices significantly increased aggregate stability (18.3 ± 14.8%; Fig. 2.5b), porosity (3.5 ± 2.5%; Fig. 2.5c), and saturated hydraulic conductivity (95.6 ± 64.9%; Fig. 2.5e) but did not affect bulk density (−1.5 ± 1.7%; Fig. 2.5a) and infiltration rate (46.6 ± 113.1%; Fig. 2.5d).

2.5.5. Influence of climatic and edaphic factors

Crop diversity impacts on soil physical health varied across geographic regions (Supplementary Fig. S2.2). Crop diversity effects on bulk density and saturated hydraulic conductivity were more pronounced in Asia, while in North America, no significant influence was found on soil physical health properties, except for saturated hydraulic conductivity (Supplementary Fig. S2.3). However, crop diversity did not significantly improve aggregate stability, porosity, or infiltration rate across geographic regions, but positive trends were observed (Supplementary Fig. S2.2). Crop diversity impacts on soil physical health varied among different soil texture categories (Fig. 2.6). Crop diversity effects were found to significantly improve aggregate stability (24.1 ± 16.1%; Fig. 2.6b), infiltration rate (234.4 ± 141.2%; Fig. 2.6d), and saturated hydraulic conductivity (91.8 ± 75.6%; Fig. 2.6e) in trials conducted on medium-textured soils. Also, in fine-textured soils, crop diversity reduced bulk density (−2.3 ± 1.8%), increased porosity (2.8 ± 2.5%), and greatly improved saturated hydraulic conductivity (186.3 ± 91.6%). On coarse-textured soils, there were no significant effects on soil physical health properties, except for porosity (13.6 ± 6.7%; Fig. 2.6c).

Furthermore, the impacts of crop diversity on porosity (3.3 ± 3.0%), infiltration rate (173.7 ± 161.9%), and saturated hydraulic conductivity (139.3 ± 102.6%) were significantly stronger in geographic regions with MAP > 900 mm than in regions with MAP < 500 mm or 500–900 mm (Fig. 2.7). However, aggregate stability (41.7 ± 25.9%) was significantly improved in regions with MAP < 500 mm (Fig. 2.7b), while no significant effect on bulk density was found across regions with different MAP categories (Fig. 2.7a).

2.5.6. Influence of study duration

Study duration influence crop diversity impacts on soil physical health, but the influence varied among subgroup categories. Bulk density (−2.5 ± 2.3%), porosity (5.6 ± 3.8%), infiltration rate (306.1 ± 154.4%), and saturated hydraulic conductivity (137.2 ± 97.1%) were greatly improved when crop diversity was in place for 5 to 10 years (Fig. 2.8). Also, there was a significant increase in aggregate stability (19.9 ± 16.0%; Fig. 2.8b) and saturated hydraulic conductivity (108.7 ± 86.4%; Fig. 2.8e) with longer (> 10 years) than shorter rotation periods (< 5 years). Moreover, a shorter period (< 5 years) with crop diversity did not significantly influence any soil physical health properties (Fig. 2.8).

2.6. Discussion

2.6.1. Crop diversity impacts soil physical health

Overall, enhanced crop diversity reduced soil bulk density, and increased aggregate stability, porosity, and saturated hydraulic conductivity compared to less diverse systems (Fig. 2.3). These findings are in line with previous studies (Alhameid et al., 2020; Nouri et al., 2019; Pikul et al., 2006, 2008) and could be attributed to the diverse root architecture which increased root biomass, thereby, promoting the additions of plant organic materials, root exudates, nutrients, and ambient oxygen that enhanced biological communities and activities in the soil (DuPont et al., 2014; Franzluebbers et al., 2000; Kemper et al., 2011; Liebig et al., 2014). In addition, diverse root systems serve as sources of belowground C that alter SOC content, thus, affecting soil physical health (Soares et al., 2019; Tiemann et al., 2015; Venter et al., 2015; Zuber et al., 2018). The non-significant effect on infiltration rate observed in our study may be attributed to root priming, resulting from an increased rate of SOC decomposition by microbes in response to root exudates from diverse crop species (Stockmann et al., 2013). However, some studies have reported improved bulk density, porosity, and infiltration rates (Alhameid et al., 2020; Kemper et al., 2011; Pikul et al., 2006, 2008). These observed results point to changes in soil physical health, which in turn are associated with SOC and microbial biomass C. For instance, according to McDaniel et al. (2014), crop diversity increased total C by 3.6% and microbial biomass C by 20.7%, which was linked to increased biological and enzyme activities. Furthermore, Alhameid et al. (2017) also reported increased SOC, which subsequently reduced bulk density and increased aggregate stability.

2.6.2. Comparing crop diversity effects under different management practices

Conservation management practices, including crop rotation and diversification (inclusion of grain legumes) and no-till or reduced tillage are management strategies that are widely adopted to enhance and restore soil health (Lal, 2015; Bagnall et al., 2022). The combination of crop diversification, cover cropping, and conservation tillage could significantly influence soil physical health properties (Nunes et al., 2015, 2019; Suzuki et al., 2013). The inclusion of grain legumes (cereal-legumes) significantly improved soil physical health properties, except for infiltration rate when compared with no grain legumes (cereal only) (Fig. 2.4). These beneficial effects could be partly attributed to the biological N_2-fixing ability and N-rich residues of grain legumes (Chalk, 1998; Evans et al., 1991) that encouraged biological activity, enhanced growth-promoting substances, and nutrient cycling, thereby influencing soil physical health (Anderson, 2011, 2005; Wright and Anderson, 2000), and crop yield, compared to cereal-based rotations (Preissel et al., 2015; St. Luce et al., 2020). Although studies have reported that cereal crops detrimentally affected bulk density, porosity, soil water, and soil fertility (Chan and Heenan, 1996; Sun et al., 2018), the inclusion of grain legumes in cereal-based rotations significantly enhanced soil C and N, thus stimulating microbial growth and aggregation, which in turn improved other soil health properties (McDaniel et al., 2014; Tiemann et al., 2015; Zuber et al., 2018).

Furthermore, in our study, crop diversity effects on aggregate stability (Fig. 2.5b), porosity (Fig. 2.5c), and saturated hydraulic conductivity (Fig. 2.5e) were greatly improved under conservation compared to conventional tillage (Fig. 2.5). Observed results under conservation tillage may be linked to reduced soil disturbance and enhanced SOC that promoted microbial and enzymatic activities, resulting in increased soil aggregation, and thereby increased porosity (Adeli et al., 2020). Compared to conventional tillage, Liu et al. (2021) also reported reduced macro-aggregate destruction with conversation tillage. On the other hand, infiltration rate did not improve under conservation tillage practices (Fig. 2.5d), an observation corroborated by Basche and DeLonge (2019).

2.6.3. Comparing crop diversity effects across different climatic and edaphic conditions

Soil texture inherently exerts influence on many other soil attributes. Crop diversity impacts on soil physical health were strongly related to soil texture but varied among soil physical health properties (Fig. 2.6). Earlier studies found strong linkages of both soil texture and organic matter with soil physical health (Saxton and Rawls, 2006; Wösten et al., 2001). Generally, crop diversity effects on soil physical health were more pronounced in medium- and fine-textured soils than in coarse-textured soils. Medium- and fine-textured soils have greater soil C, water-holding capacity, and water availability than coarse-textured soils (Daryanto et al., 2016; Harrison-Kirk et al., 2014). Clay-size particles have greater ability to link together to form macro-aggregates than sand. These favorable conditions may promote and enhance biological activity and root development, thereby improving other soil properties as a cascading effect (Nunes et al., 2018). Also, soil texture strongly influences pore space between particles, aggregate formation and stability, and hence inter-aggregate spaces which in turn influence air and water movement thus affecting porosity, permeability, water retention, and infiltration rates (Kay, 2018). In our meta-analysis, porosity was not significantly influenced in medium- and fine-textured soils (Fig. 2.6c). Although Basche and DeLonge (2017) also found no significant influence, it could be possible that a decrease or no effect on porosity could be a result of root priming, when SOC decomposition rates increase in response to root exudates (Stockmann et al., 2013). Furthermore, Six et al. (2004)

also suggested adverse short-term impacts on porosity due to the root penetrating effect into macro-pores, reducing macro-aggregates.

The choice of crop species to be included in a given rotation is greatly influenced by mean annual precipitation (MAP) (McDaniel et al., 2014; Ryan et al., 2008). In other words, the effects of crop diversity within rotations could be indirectly shaped by local rainfall (McDaniel et al., 2014; Ryan et al., 2008). Porosity (Fig. 2.7c), infiltration rate (Fig. 2.7d), and saturated hydraulic conductivity (Fig. 2.7e) were significantly impacted by crop diversity in geographic regions with MAP ≥ 900 mm compared with regions with low or moderate MAP; while aggregate stability significantly improved in drier (< 500 mm yr^{-1}) regions (Fig. 2.7). Similar observations have been reported for porosity and infiltration rate in response to rainfall (Basche and DeLonge, 2017, 2019). Furthermore, McDaniel et al., (2014) reported that crop diversity increased total C, with greater increases linked with higher MAP. Although Lavee et al. (1996) reported decreased aggregate stability with increasing aridity, our study revealed increased aggregate stability in drier regions compared to regions with higher MAP (Fig. 2.7b). Therefore, these results indicated that heat and moisture availabilities in soil could exert significant influence on aggregate stability dynamics.

2.6.4. Influence of study duration on crop diversity impact

In our meta-analysis, crop diversity effects were modulated by the study duration, i.e., the period between study establishment and soil physical property measurement. However, the influence of study duration was inconsistent among soil physical health properties (Fig. 2.8). Bulk density (Fig. 2.8a), porosity (Fig. 2.8c), infiltration rate (Fig. 2.8d), and saturated hydraulic conductivity (Fig. 2.8e) were greatly improved when measured 5 to 10 years after rotation study establishment (Fig. 2.8). Basche and DeLonge (2017, 2019) reported significant improvement in soil hydrologic properties after a shorter duration (< 7 and > 4 years). On the other hand, a longer study period (> 10 years) significantly increased aggregate stability (Fig. 2.8a) and saturated hydraulic conductivity (Fig. 2.8e). Our findings are in line with the common convention that management practices need to be in place for an extended time period to elicit improvements in soil properties (Nunes et al., 2020; Poeplau and Don, 2015).

2.6.5. Study limitations and research gaps

The findings in our meta-analytic study revealed the varying relative abundance of studies assessing crop diversity impacts on soil physical health under diverse management practices. Most studies in the database compared two or three crop species against a monoculture, while fewer studies evaluated more complex or diverse rotation systems (crop species ≥ 4). This observation supports current findings indicating that more complex agroecological research receives relatively less research funding (DeLonge et al., 2016; Miles et al., 2017). Also, most of the studies on soil physical health were conducted within the US, with very few studies from other regions. This showed the geographic gap and the limited attention given to soil physical health due to the time-consuming nature in measuring these soil properties, in particular infiltration rate and saturated hydraulic conductivity that require measurement in the field. More complex and well-replicated long-term studies focusing on soil physical health properties, especially infiltration rate and saturated hydraulic conductivity are needed, while also considering the potential interactions between improved soil physical health and other ecological benefits such as soil biological processes, nutrient cycling, and drought tolerance. Additionally, climatic and edaphic conditions of the study location need to be reported. According to Eagle et al. (2017) and Gerstner et al.

(2017), these characteristics are required in field experiments in agronomy and ecology to be useful for conducting meta-analyses or synthesis reports. Furthermore, using management practices that improve soil physical health in combination with crop diversity may offer better prospects in mitigating or adapting to the escalating effects of climate change.

2.7. Conclusions

Our meta-analytic study highlights the benefits and potentials of increased crop diversity for soil health improvement when compared to monocultural systems. It also provides insights on how the combined effects of conservation management practices such as grain legume inclusion and reduced or no tillage, as well as the choice of diverse crop rotation modulate rotational diversity effects across a broad range of climatic and edaphic conditions under rainfed conditions. In doing so, this study sheds light on how the potential of crop diversity can effectively translate into actuality in farming systems as mediated by management choices. Overall, increased crop diversity improved soil bulk density, aggregate stability, porosity, and saturated hydraulic conductivity compared to less diverse rotations, although benefits were highly context dependent. Crop diversity combined with several other conservation practices showed stronger evidence of improving soil physical health compared with conventional practices, but not universally across geographic regions. Crop diversity performed better on medium- and fine-textured soils, indicating also that site- and regional-specific goals are required for optimizing crop diversity benefits. Short-term periods of conservation management practices limited soil physical health improvements, thus longer-term research across diverse environments will be more helpful to better understand and underpin their implementation in the future. In summary, increasing crop diversity largely improved soil physical health properties, but the direction and magnitude was influenced by management, climatic and edaphic factors, pointing to careful consideration when designing resilient cropping systems that simultaneously promote both agronomic and environmental benefits.

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Table 2.1. Number of paired comparisons for each study location/region (number of studies) and natural-log response summary of soil physical health properties included in the meta-analysis evaluation.

Study region	Number of paired comparisons (number of studies)				
	Bulk density	Aggregate stability	Porosity	Infiltration rate	Saturated hydraulic conductivity
Africa	43 (5)	3 (1)	36 (4)	14 (2)	7 (1)
Asia	40 (5)	16 (5)	40 (6)	21 (2)	17 (4)
Australia	–	6 (1)	–	9 (1)	9 (1)
Europe	9 (2)	–	10 (3)	–	11 (2)
North America	152 (28)	123 (21)	153 (28)	64 (14)	67 (10)
South America	–	–	–	–	6 (1)
	Natural-log Response Ratio				
Min.	−0.249	−1.125	−0.483	−4.271	−2.066
Median	−0.009	0.072	0.009	0.135	0.231
Mean	−0.017	0.084	0.023	0.178	0.294
Max.	0.292	1.22	0.847	3.701	2.461
Total paired comparisons	246	148	246	108	117
Total of studies	41	28	41	19	19

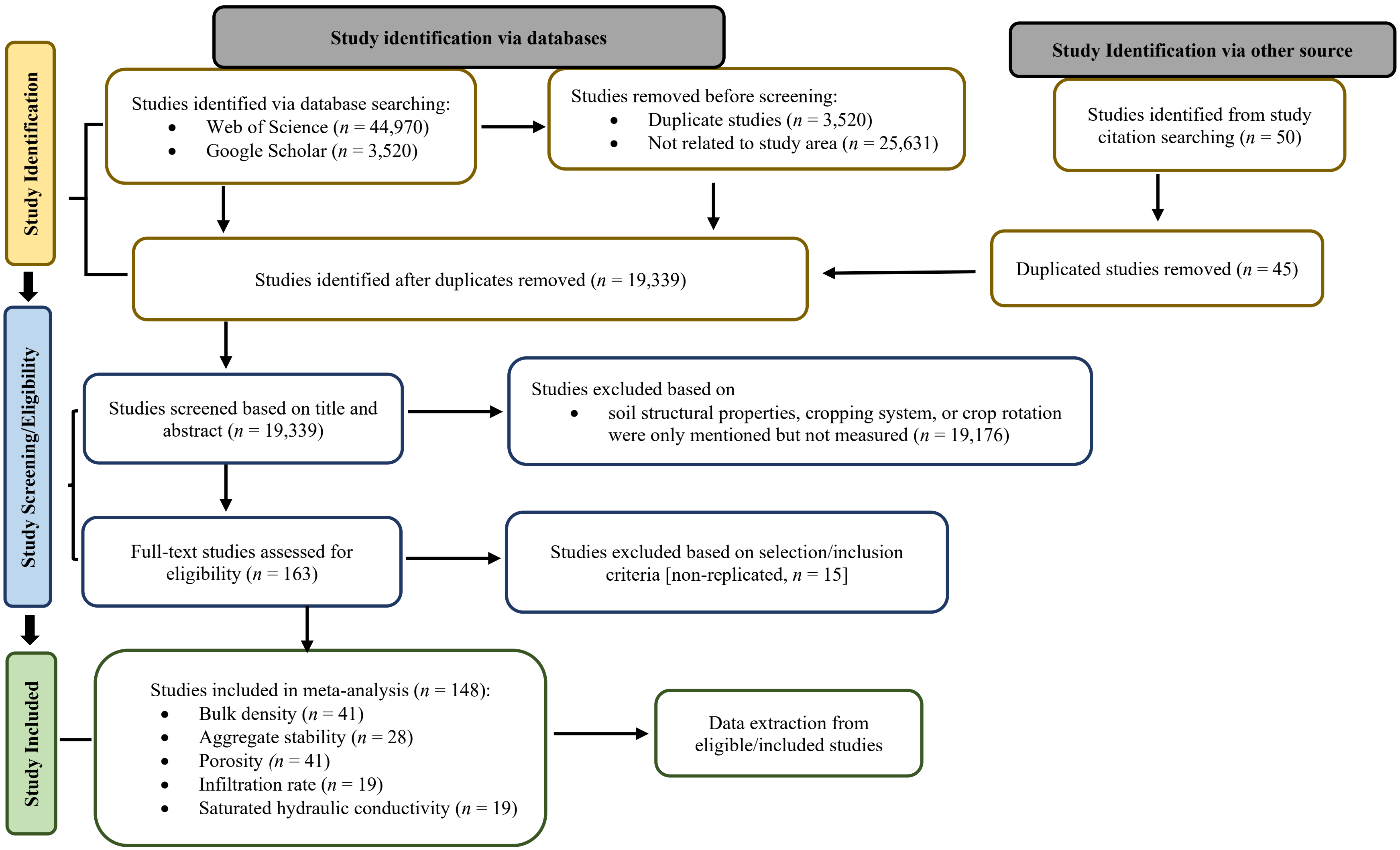

Figure 2.1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow chart illustrating the study selection procedure for the meta-analysis. Note: some studies presented more than one soil physical health property, while porosity was estimated from bulk density data, and vice versa.

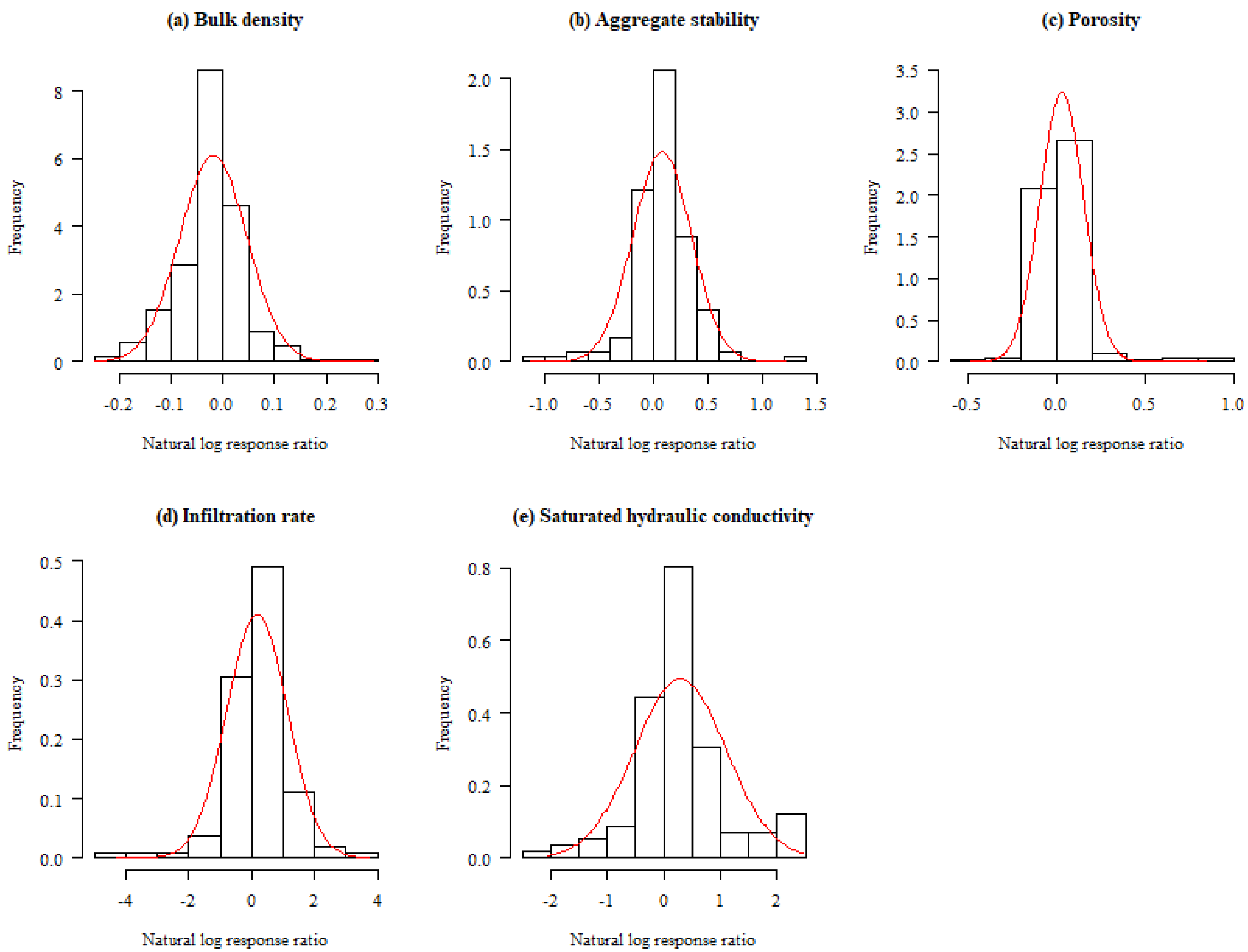

Figure 2.2. Bias analysis using histograms of response ratios. Normal distributions indicate no bias against studies reporting no significant effects.

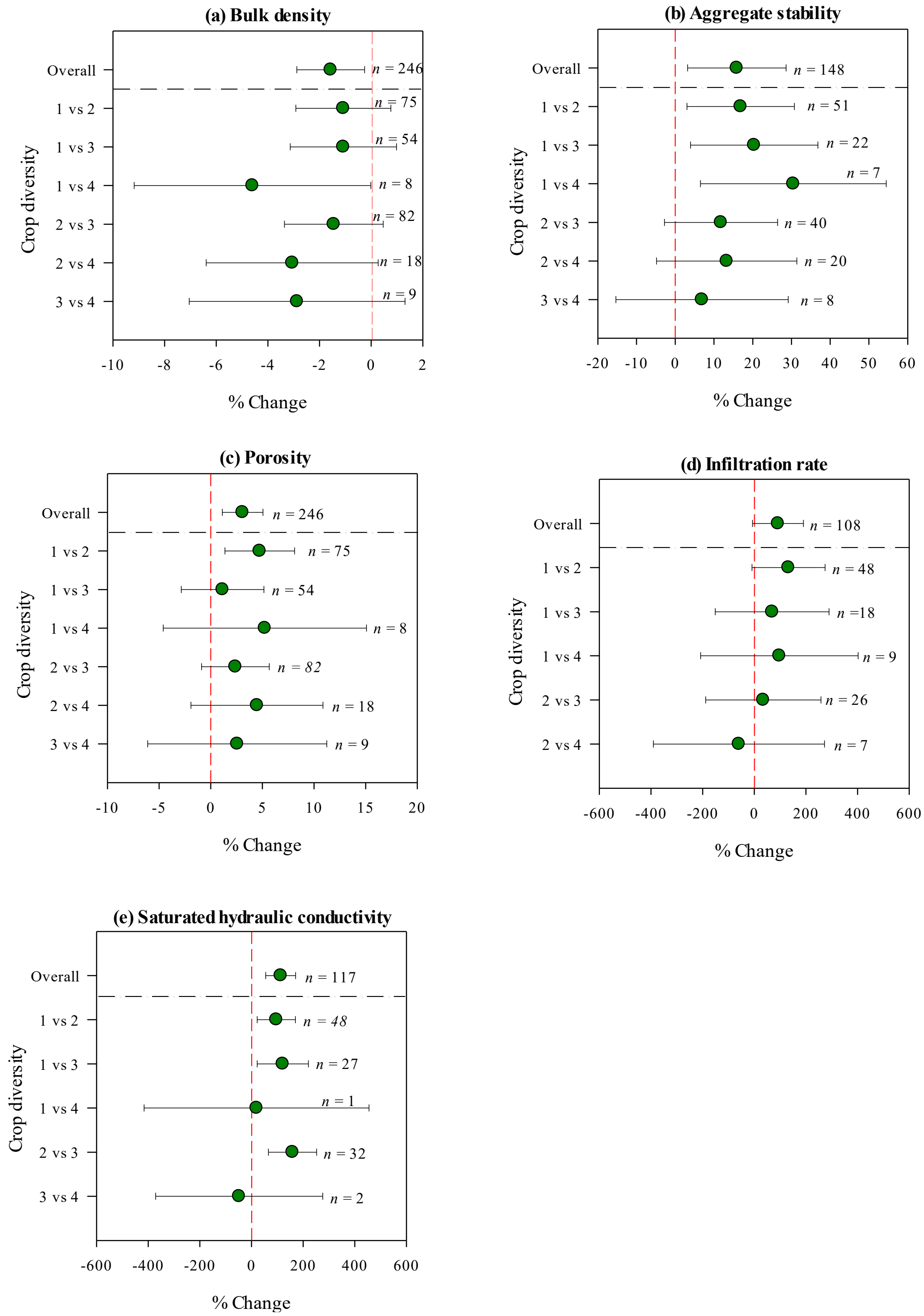

Figure 2.3. Crop diversity (number of crop species in rotation) effects on soil physical health properties. Means and confidence intervals (CI) are estimated using fixed effects for subgroups related to crop diversity. Horizontal bars indicate the 95% CI, while error bars not overlapping zero (broken vertical line) indicate a significant decrease or increase at $P < 0.05$ (n = number of paired comparisons).

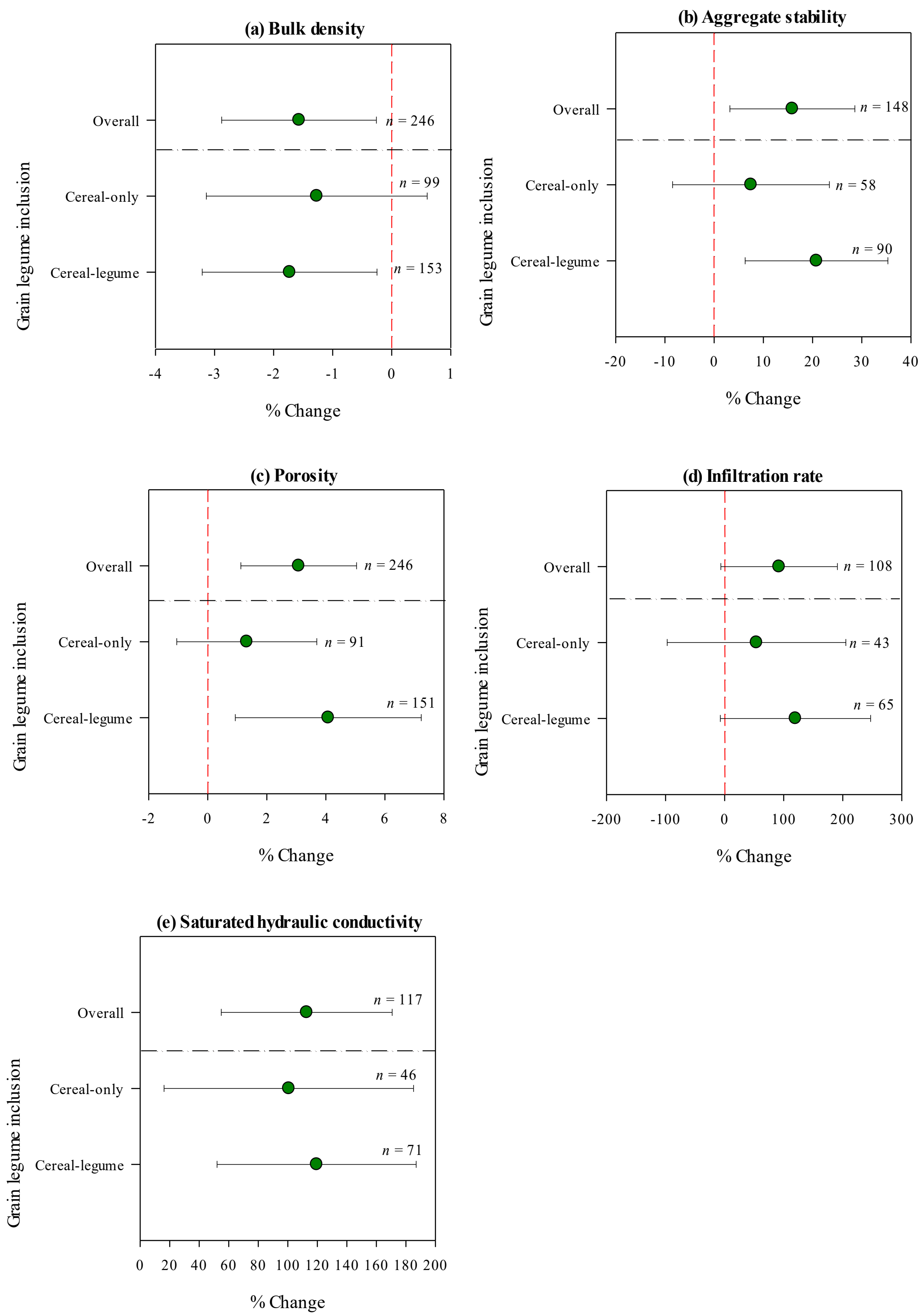

Figure 2.4. Crop diversity impact as modulated by grain legume inclusion on soil physical health properties. Means and confidence intervals (CI) are estimated using fixed effects for subgroups related to inclusion of grain legumes. Horizontal bars indicate the 95% CI, while error bars not overlapping zero (broken vertical line) indicate a significant decrease or increase at $P < 0.05$ (n = number of paired comparisons).

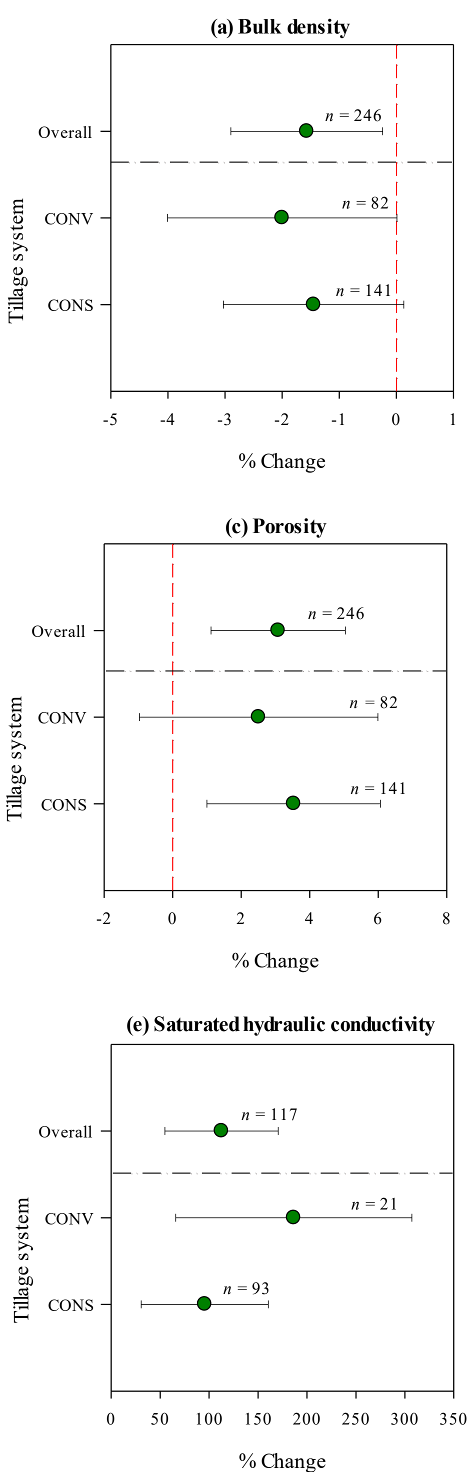

Figure 2.5. Crop diversity effects as modulated by tillage system on soil physical health properties. Means and confidence intervals (CI) are estimated using fixed effects for subgroups related to tillage practice. CONV, conventional and CONS, conservation tillage. Horizontal bars indicate the 95% CI while error bars not overlapping zero (broken vertical line) indicate a significant decrease or increase at $P < 0.05$ (n = number of paired comparisons).

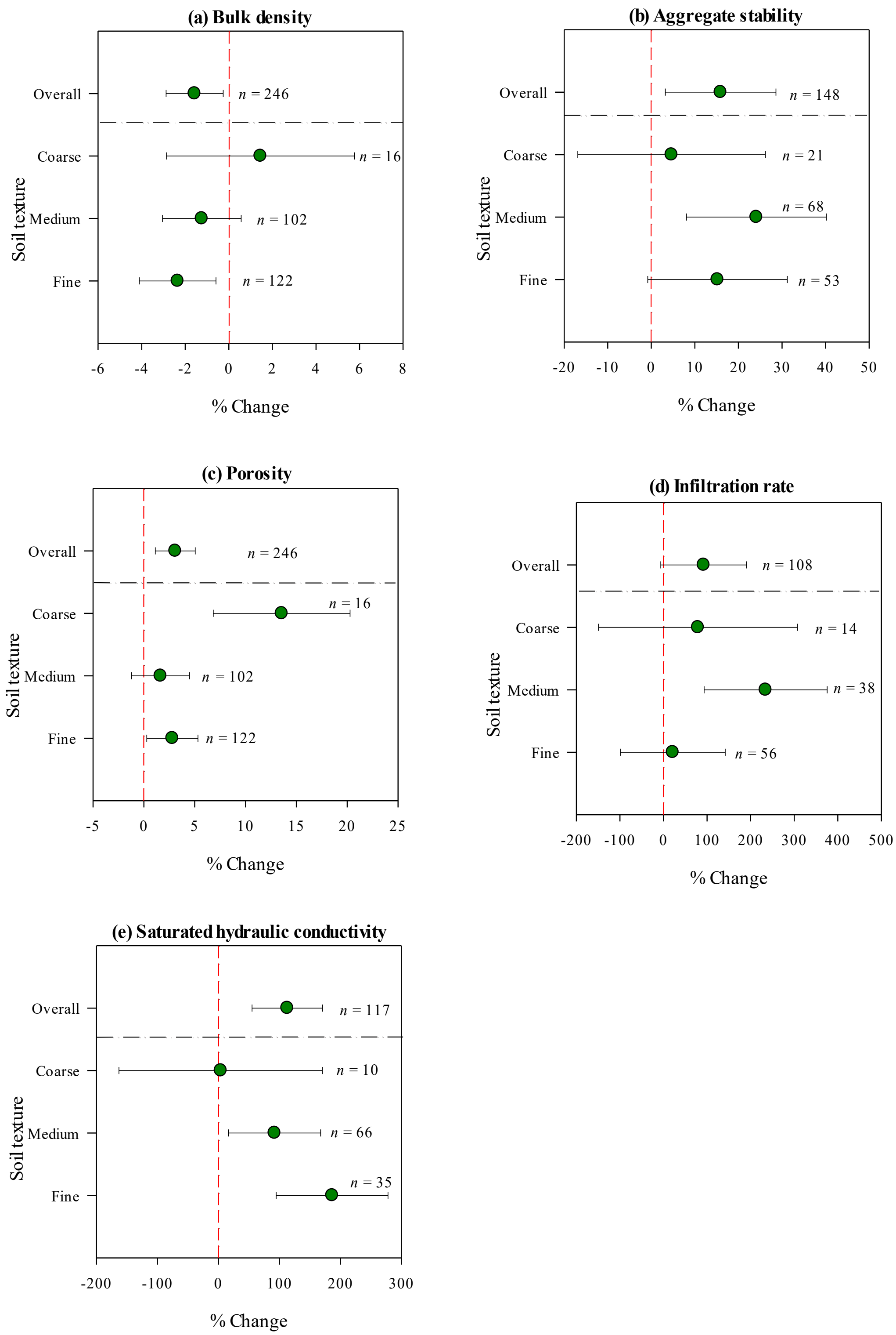

Figure 2.6. Crop diversity effects as modulated by soil texture on soil physical health properties. Means and confidence intervals (CI) are estimated using fixed effects for subgroups related to soil texture. Horizontal bars indicate the 95% CI while error bars not overlapping zero (broken vertical line) indicate a significant decrease or increase at $P < 0.05$ (n = number of paired comparisons).

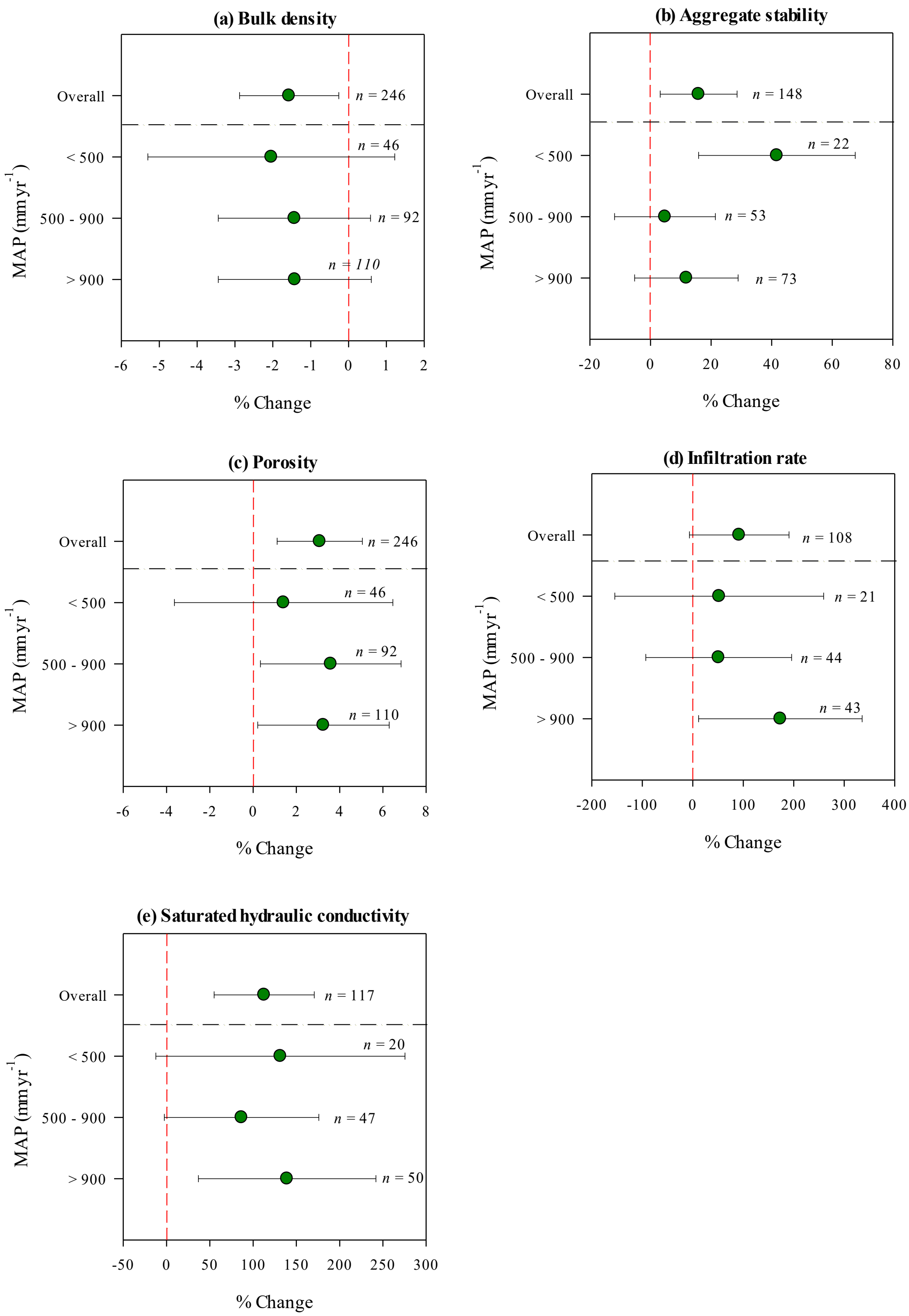

Figure 2.7. Crop diversity effects as modulated by mean annual precipitation (MAP) on soil physical health properties. Means and confidence intervals (CI) are estimated using fixed effects for subgroups related to MAP. Horizontal bars indicate the 95% CI while error bars not overlapping zero (broken vertical line) indicate a significant decrease or increase at $P < 0.05$ (n = number of paired comparisons).

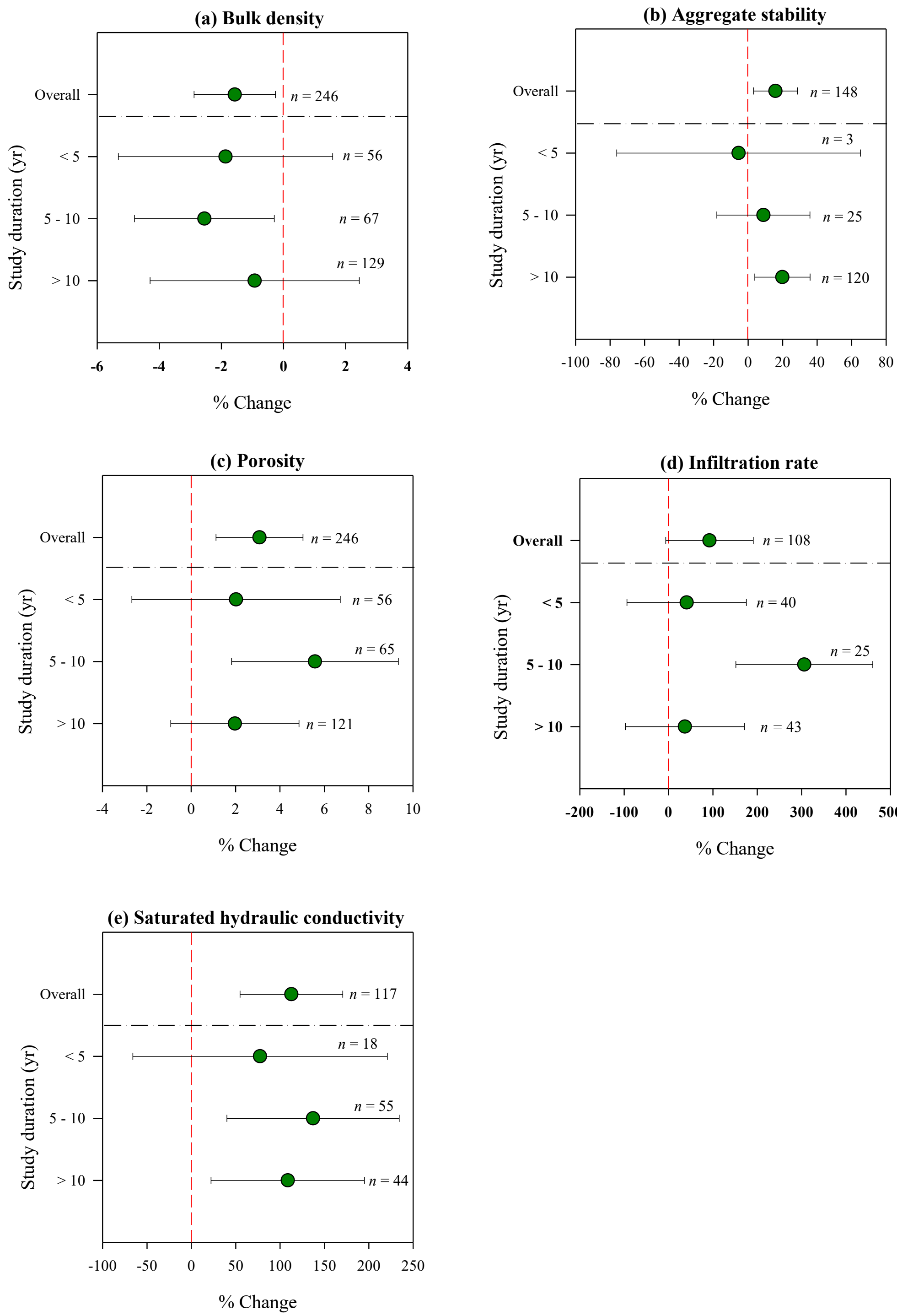

Figure 2.8. Crop diversity effects as influenced by study duration on soil physical health properties. Means and confidence intervals (CI) are estimated using fixed effects for subgroups related to study duration. Horizontal bars indicate the 95% CI, while error bars not overlapping zero (broken vertical line) indicate a significant decrease or increase at $P < 0.05$ (n = number of paired comparisons).

3. Soil Organic Matter and Aggregate Stability Dynamics under Major No-till Crop Rotations on the Canadian Prairies

Iheshiulo, E.M.-A., Larney, F.J., Hernandez-Ramirez, G., St. Luce, M., Chau, H.W., Lui, K., 2024. Soil organic matter and aggregate stability dynamics under major no-till crop rotations on the Canadian prairies. *Geoderma*, 442, 116777. https://doi.org/10.1016/j.geoderma.2024.116777

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3.1. Highlights

- Compared alternative vs. conventional rotations on SOM and aggregate stability (AS).
- Diverse crop rotations had no effect on SOM dynamics in the short term.
- Adding pulse crops to cereal-dominated rotations improved AS
- Mineral-associated organic matter fraction strongly correlated with AS.
- SOM and AS response to crop rotations depends on the study site.

3.2. Synopsis

There is a need to develop and adopt novel, more resilient, or "climate-smart" cropping strategies on the Canadian prairies, which are crucial for sustainable agroecosystem management. To examine how crop rotation influences soil organic matter and aggregate stability (AS) dynamics, six crop rotations: (i) conventional (control), (ii) pulse/oilseed intensified, (iii) diversified, (iv) market-driven, (v) high-risk and high-reward, and (vi) soil health-enhanced were established in 2018 at three field sites: Lethbridge, Alberta and Swift Current and Scott, Saskatchewan under no-till management. After 4 years, soil organic carbon (SOC), total nitrogen (TN), particulate organic matter carbon (POM-C) and nitrogen (POM-N), or mineral-associated organic matter C (MAOM-C) and N (MAOM-N) concentrations were not significantly affected by crop rotation in the 0−7.5 cm soil depth. However, crop rotation significantly altered AS at two of three sites, with both soil health-enhanced and high-risk and high-reward rotations having the highest AS at Lethbridge and Swift Current. Across all three sites, strong positive correlations were found among SOC, TN, MAOM, and AS. Moreover, MAOM-C and MAOM-N showed stronger relationships with AS than POM, perhaps suggesting a positive feedback loop on the stability of SOC and aggregation. Overall, the inclusion of pulses in rotations showed the potential to sustain soil quality, likely by offsetting low residue quantity with better residue quality and diversity, thereby supporting SOC accrual and AS similar to or greater than conventional cereal- or oilseed-dominated rotations.

Keywords: Soil organic matter; diverse rotation; particulate organic matter; mineral-associated organic matter; aggregate stability.

3.3. Introduction

Global warming may feedback into increased losses of soil organic carbon (SOC) from agricultural systems, causing compromised soil structure and function (Wiesmeier et al., 2016). To mitigate or reverse this trend, C inputs are needed to maintain or increase SOC stocks, which improve soil structural stability (Li et al., 2015; Lin et al., 2023; Zhou et al., 2020), crop yield, and long-term sustainability of agricultural systems (Lin et al., 2023; St. Luce et al., 2020, 2022). It is therefore necessary to adopt sustainable and "climate-smart" cropping strategies, which reduce C footprints (the amount of greenhouse gases generated) without negatively affecting crop production.

A better understanding of the dynamics of SOC and aggregate stability (AS) is essential for devising effective management practices for agroecosystems and agriculture sustainability. Soil OC, a measure of soil organic matter (SOM), is crucial for soil health, as it influences fertility, structural stability, and soil functions (Congreves et al., 2015; Zhou et al., 2020). The SOC interacts with silt and clay to form aggregates (Oorts et al., 2003), enhancing soil structure and its capacity to retain water and nutrients (Rawls et al., 2003). Another soil health metric, AS, encapsulates the physical, chemical, and biological attributes of soil (Doran and Parkin, 1997). The AS significantly affects soil pore size distribution, impacting soil porosity, water retention, and air and water movement (Nimmo, 2004). Furthermore, soils with higher AS are more erosion-resistant and have better water infiltration rates (Nimmo, 2004).

Crop rotation is an integral component of no-till (NT) cropping systems for the improvement of soil health (Iheshiulo et al., 2023, 2024; Li et al., 2018; Smith et al., 2016) and crop productivity (Gan et al., 2015; St. Luce et al., 2020). However, not all crop rotations have the same effects on soil quality. Simple conventional cereal-dominated rotations with high N-fertilizer rates, can reduce SOC (Hazra et al., 2019; Yan et al., 2022), and increase N_2O emissions (Yang et al., 2013). Conversely, introducing pulses into cereal-dominated cropping systems combined with NT can enhance SOC and total N (TN) (Fan et al., 2020; Liebig et al., 2014; Yan et al., 2022) and improve AS (Hazra et al., 2019; Iheshiulo et al., 2023; Yan et al., 2022) while decreasing the dependence on N-fertilizer (Gan et al., 2015; Yan et al., 2022), and reduce the C footprint (Gan et al., 2012), thus enhancing environmental sustainability (Gan et al., 2011). These benefits may result from higher diversity in plant residue and substrate (Gartner and Cardon, 2004; Tiemann et al., 2015; Yan et al., 2022), increased surface residue cover (West and Post, 2002), and lower surface temperature, as well as higher soil moisture, which create favorable conditions for higher microbial biomass and production of binding agents (Gartner and Cardon, 2004; Tiemann et al., 2015; Wright and Anderson, 2000).

To understand the dynamics of SOC, management-sensitive pools such as particulate organic matter (POM) and mineral-associated organic matter (MAOM) can provide valuable information into the sources and stability of SOM (Cotrufo et al., 2019; Kim et al., 2022). The POM and MAOM pools are affected by cropping systems and site climate conditions (Kim et al., 2022; Poeplau and Don, 2013), and can reflect changes in overall SOM dynamics (Samson et al., 2020).

While studies have evaluated the impact of pulse inclusion in conventional cereal-dominated rotations on SOM and AS dynamics, there is still limited data available on the Canadian prairies as most of the studies are focused on crop yield, soil fertility, and soil water conservation. Moreover, the effects of crop rotations on SOC and AS dynamics are complex and influenced by several factors, such as crop species (Iheshiulo et al., 2023), cropping frequency (Lemke et al., 2012c), quantity and quality of crop residues (Ardenti et al., 2023; Yan et al., 2022), soil texture, climate, and tillage practice (Iheshiulo et al., 2023; Poffenbarger et al., 2020). These factors partly explain the differences in results from several studies (e.g., Benjamin et al., 2010; Lasisi and Liu, 2023; Lin et al., 2023; Nunes et al., 2018; Poffenbarger et al., 2020). Therefore, it is important to understand how these factors interact, as changes in SOC and AS can affect soil functions, such as hydrology and nutrient cycling (Congreves et al., 2015). It is also crucial to understand the contributions of C inputs from contrasting rotations to become transformed into different functional and stabilized SOM pools. The study aims were to (i) compare the effects of alternative vs. conventional rotations on SOM and AS dynamics and (ii) examine the relationships among measured soil properties and their consistency across three sites. Therefore, we hypothesize that incorporating pulses in rotations as green manure, harvested crops, or intercropped with cereals would increase near-surface SOM and AS dynamics compared to conventional rotations at three different ecozones on the Canadian prairies due to a better combination of crop residue quantity and quality.

3.4. Materials and Methods

3.4.1. Study site description

Our study focused on a cropping system experiment that was initiated in 2018 with seven field sites across the Canadian prairies, where six crop rotations were examined with respect to long-term sustainability and soil health. This study was conducted at three of these field sites: Lethbridge, Alberta (49º 41’ N, 112º 46’ W), and Swift Current (50º 17’ N, 107º 47’ W), and Scott, Saskatchewan (52º 21’ N, 108º 50’ W) over 4 growing seasons (2018–21). Soils across the three sites ranged in texture from clay to loam and were classified as Brown to Dark Brown Chernozems (Larney et al., 2004). Site-specific precipitation data during the study, as well as 30-year normals from the closest Environment Canada weather stations, are shown in Figs. 3.1a–c, while Table 3.1 summarizes baseline soil properties for each site. Detailed initial soil physical and hydraulic properties related to each experimental site was reported by Iheshiulo et al. (2024b).

3.4.2. Experimental treatments and management

Before study establishment, durum wheat (*Triticum turgidum* L. var. *durum*) was planted at all three sites in 2017 to ensure comparable crop backgrounds. Six rotations were arranged in a randomized complete block design with four replications at each site. The six rotations had a uniform treatment typology across the sites, but the specific crop varied to match the conditions of each study site. Due to quite similar growing conditions, crop selections for Lethbridge and Swift Current rotations were comparable and anchored by durum wheat, while those at the more northerly Scott site were predominated by canola (*Brassica napus* L.) [Tables 3.2 and 3.3]. The rotations were: (i) conventional (control), using dominant crops and practices (e.g., herbicide fallow at Lethbridge and Swift Current) in each soil-climatic zone; (ii) pulse/oilseed intensified, to capture potential biological and economic benefits of pulses (Lethbridge, Swift Current) or oilseeds (Scott); (iii) diversified, involving four different crops in 4 year rotations; (iv) market-driven, with crops chosen each spring in response to market signals; (v) high-risk and high-reward, e.g., corn (*Zea mays* L.) and soybean (*Glycine max [L.] Merr.)* are high-risk at Lethbridge due to soil moisture deficits, but may produce high profits in wetter-than-normal growing seasons as heat units are adequate for these warm season crops; and (vi) soil health-enhanced, offering features for soil health enhancement. All rotations were 4-year, excluding the 2-year pulse/oilseed intensified rotation (spring wheat (*Triticum astivum* L.)–canola) at Scott.

At Lethbridge and Swift Current, five of the six rotations (excluding market-driven) were completely phased, i.e., every crop phase of each rotation were present every year, i.e., (5 rotations × 4 crop phases) + (1 rotation × 1 crop phase) = 21 crop phases × 4 replicates = 84 plots. At Scott, five of the six rotations (excluding market-driven) were fully phased i.e., (4 rotations × 4 crop phases) + (1 rotation × 2 crop phases) + (1 rotation × 1 crop phase) = 19 crop phases × 4 replicates = 76 plots. The plot size was 4 × 16 m, and the total plot area was 101 × 136 m with 8 m pathways (varied slightly at each site) and managed under NT and rainfed conditions. Detailed information on the cropping sequence for each site is provided in Tables 3.2 and 3.3.

Prior to spring seeding in 2018, the experimental sites were treated with glyphosate (900 g a.e. ha^{-1}) to control pre-seed weeds. All crops were seeded within the first half of May each year. At Lethbridge and Scott, a NT seeder (Model CP 129A, Conserva Pak, Indian Head, SK, Canada) with 23 cm row spacing was used, except for corn at Lethbridge (76 cm row spacing corn planter). At Swift Current, a NT hoe-drill (Fabro Manufacturing, Swift Current, SK, Canada) with 23 cm row spacing was used. The N fertilization strategy (urea as N source) was based on projected yield, crop requirements, residual nitrate, and previous cropping information (grain yield and stubble). Blanket mono-ammonium phosphate, potassium chloride, and potassium sulphate fertilizer rates were applied annually based on local recommendations and varied across the sites, while fallow plots received no fertilization. Herbicides were used for in-season weed control in cropped plots as well as for maintaining fallow plots. Detailed information on fertilizer application rates for each site is provided in Tables 3.2 and 3.3.

3.4.3. Soil sample collection and processing

Composite soil samples were collected prior to establishing the field experiments from the 0−15 cm soil depth increment in spring 2018 ($n = 4$, one per replicate) to determine baseline SOC, TN, POM, MAOM, AS, and other soil properties at each site (Table 3.1). At the end of the 4-year rotation cycle, composite soil samples (five cores per plot, 0−7.5 cm depth, $n = 244$) were collected at each site from each phase of the rotations after crop harvest in fall 2021 to measure SOC, TN, POM and MAOM pools, and AS. The bulk soil samples were collected using a hand-held soil probe, air-dried, and sieved to < 8 mm, with visible plant materials removed. Samples were then stored at 4 ºC before processing for SOM and AS analyses.

3.4.4. Soil quality analyses

3.4.4.1. Soil organic C and total N

Subsamples (20 g) of the bulk soil were 2 mm sieved and finely ground (< 0.15 mm) using a roller mill, weighed, and encapsulated. Inorganic C was removed with 1N HCl until all carbonates were completely burned off. Bulk SOC and TN were determined by dry combustion on a CNS-1000 Elemental Analyzer (EA, Carlo Erba Strumentazione, Milan, Italy).

3.4.4.2. Particulate organic matter fractionation

The POM fraction (> 53 µm) was separated from subsamples of bulk soil using the particle-size fractionation method (Kim et al., 2022; Li et al., 2018; Pansu and Gautheyrou, 2006). Briefly, 25 g of air-dried soils (8 mm sieved, $n = 244$) were agitated with 90 mL of distilled water and 10 glass beads (5 mm diam.) in plastic bottles for 16 hours on a reciprocating shaker at 180 rpm (Li et al., 2018). The suspensions were then wet-sieved through 2 mm and 53 µm sieves. Retained materials on both sieves were oven-dried at 60 ºC until constant weight and corrected for stones and larger plant material (> 2 mm sieve). The fraction, 2 mm−53 μm was regarded as POM and was finely ground (Kim et al., 2022; Li et al., 2018; Pansu and Gautheyrou, 2006). The C (POM-C) and N (POM-N) concentrations in the POM were then determined by dry combustion. In addition, MAOM-C and -N were determined by subtracting the POM-C and -N from the measured <2 mm SOC and TN (Kim et al., 2022).

3.4.4.3. Aggregate stability

Aggregate stability (AS) was measured using a modification of a wet-sieving method (Kemper and Rosenau, 1986). Briefly, 4 g of air-dried sieved soil aggregates from bulk soil between 1−2 mm diameter were evenly distributed on a 250 μm sieve and gently moistened (pre-wet). The soil was allowed to equilibrate for 3 min, then wet-sieved for another 3 min. The soil aggregate fractions were oven-dried at 105 ºC until constant weight, and the proportion of stable aggregates (%) retained on the 250 μm sieve was reported after correction for plant residue and sand content.

3.4.5. Above-ground straw biomass

At each site, the above-ground straw biomass (AGB) was measured in every rotation phase when the crops reached full maturity, except for the fallow phases at Lethbridge and Swift Current. All crops were harvested by hand from four rows that were 0.5 m long prior to combine harvesting, oven-dried at 20 ºC, and weighed. The AGB [dry matter (DM) weight] is reported as kg ha^{-1}.

3.4.6. Statistical analysis

Data analyses were performed using R Studio software version 4.2.3 (R Core Team, 2023). One-way analysis of variance was used to test the effect of crop rotation on SOC, TN, POM, MAOM, and AS separately for each site using a linear mixed-effects model in "*nlme*" R package. The crop rotation was considered a fixed effect, with block (replicates) as random effects. Model residuals were checked for normality and homoscedasticity assumptions using plot function, Shapiro-Wilk, and Leven tests, respectively. Where required, data were transformed using Box-Cox transformation to meet normality and homoscedasticity assumptions. When transformation did not meet normality and homoscedasticity, Kruskal-Wallis and Welch's ANOVA were respectively used to account for non-normality and unequal variance. Significance was determined at $\alpha = 0.05$, and pairwise comparisons were done with Tukey's honest significance post hoc tests. Spearman correlation analyses were performed using the *"corrplot" R* package (ver. 0.84) to evaluate the relationships among measured soil quality attributes at each study site.

3.5. Results and Discussion

3.5.1. Baseline soil properties in 2018

Baseline soil characteristics in the 0−15 cm soil depth increment varied across the three sites (Table 3.1). Bulk SOC concentration ranged from 14.9−18.7 g C kg^{-1} of soil, while TN ranged between 1.71−2.30 g N kg^{-1}, with the Lethbridge soil having the highest SOC and TN concentrations. The POM-C and POM-N concentrations were also highest at Lethbridge, while soils at Swift Current and Scott had similar POM-C and POM-N concentrations. On the other hand, MAOM-C and MAOM-N concentrations were highest at Scott. Moreover, Lethbridge soil had greater baseline AS (46%) than Swift Current (10%) or Scott (23%) [Table 3.1].

3.5.2. Environmental conditions

The mean 30-year (1981–2010) growing season (May 1 to August 31) normal precipitation across the three sites ranged from 212 to 216 mm, while mean air temperature ranged from 14.8 to 15.6 ºC. Growing season precipitation during the study ranged from 108 to 258 mm across the three sites (Figs. 3.1a−c). In three of four seasons, both Lethbridge and Swift Current had less rainfall than usual, from 51−79% of normal (Figs. 3.1a and 3.1b), while Scott had normal rainfall in two seasons and low rainfall in two seasons (61−69% of normal) [Fig. 3.1c].

3.5.3. Effects of crop rotation on straw biomass and soil properties after 4 years

3.5.3.1. Rotation effects on above-ground biomass

The choice of crops for rotation had an impact on the amount of biomass produced and returned to the soil, affecting the amount of SOC accretion (Ardenti et al., 2023; Fan et al., 2020; Maillard et al., 2018; Yan et al., 2022). Over a period of 4 years, crop rotation had a significant effect on the amount of AGB produced, with variations observed each year ($P < 0.05$; Supplementary Table S3.1). However, the interaction between rotation and year was not significant across the three sites. At Lethbridge, the average AGB produced across 2018−2021 by the soil health-enhanced rotation (2710 kg DM ha^{-1}) was significantly greater than the conventional, pulse/oilseed intensified or diversified rotations (1503−1884 kg DM ha^{-1}) but did not differ from market-driven and high-risk and high-reward rotations (Supplementary Table S3.1). Similarly, at Swift Current, the soil health-enhanced rotation resulted in significantly higher AGB compared to conventional, pulse/oilseed intensified, or high-risk and high-reward rotations ($P < 0.05$; Supplementary Table S3.1). At Scott, the market-driven rotation had significantly higher AGB compared to other alternative rotations. These findings are consistent with those of Liu et al.

(2020) and Fan et al. (2020), which showed that a high frequency of pulses such as in the pulse/oilseed intensified, diversified, and high-risk and high-reward rotations led to lower AGB produced and returned to the soil. Furthermore, the production of AGB (Supplementary Table S3.1) was influenced by precipitation patterns throughout the study period (Fig. 3.1). Notably, Lethbridge and Swift Current had significant increases in AGB in 2020, while Scott had higher AGB in 2019 than other years. Conversely, the lowest amount of AGB was observed in 2021 across all three sites, which was the driest year during the study period (Supplementary Table S3.1; Fig. 3.1a). These findings support previous research by Fan et al. (2020) and Maillard et al. (2018) and highlight the crucial role of moisture in crop production and SOC accrual.

3.5.3.2. Rotation effects on SOC concentration changes

The present study investigated the effect of alternative rotations against conventional cereal-fallow or cereal-dominated rotations on SOC and TN concentrations in 0−7.5 cm depth after four years in agricultural soils at three sites. The study found no significant influence of crop rotation on SOC and TN concentrations at each study site, despite higher N-fertilizer rates in the conventional rotations ($P > 0.05$; Tables 3.4, 3.5, and 3.6). This suggests that replacing fallow in conventional cereal-fallow rotations with pulses at Lethbridge and Swift Current or inclusion of pulses in cereal-dominated rotations at Scott, with reduced application of N-fertilizer can maintain SOC and TN concentrations in the short-term. These present findings are in line with previous cropping system studies that reported no significant change in SOC and TN in the short term (< 6 years) (Benjamin et al., 2010; Martínez-Mena et al., 2022; Yan et al., 2022). Also, a recent meta-analysis study by Lasisi and Liu (2023) reported that the effects of pulse inclusion in rotations on SOC may take at least 10 years to be detected.

The lack of significant difference among rotations in SOC and TN concentrations could be partly due to the short duration of this study (4 years) and environmental factors, such as low precipitation. Previous studies reported that changes in SOC and TN are highly variable across longer studies (Campbell et al., 2001; Nunes et al., 2018; Van Eerd et al., 2014). For instance, West and Post (2002) reported noticeable changes in SOC and N are likely to manifest within 5−10 years, reaching a new equilibrium in 15−20 years. On the other hand, no significant increases were reported for study duration > 8 years (Lin et al., 2023; Liu et al., 2020; Lemke et al., 2012c). In addition, both Lethbridge and Swift Current had low precipitation in three of four growing seasons, ranging between 51 and 74% of normal (Figs. 3.1a and 3.1b). On the other hand, Scott experienced two seasons with precipitation deficits (61−69%) and two seasons close to long-term normal precipitation (between 109−119%) (Fig. 3.1c). These predominantly drier-than-normal conditions reduced the quantity of crop residue produced and returned to the soil (Supplementary Table S3.1), which in turn may have hindered the processes of SOC and TN accumulation in this study (Aanderud et al., 2010; Ardenti et al., 2023; Chen et al., 2015; McConkey et al., 2018). Recent studies have reported that SOC sequestration is governed by residue quantity rather than quality (Ardenti et al., 2023; Fan et al., 2020).

The POM fraction has been identified as a sensitive indicator for examining change in SOM and decomposability (Gosling et al., 2013; Li et al., 2015; Poeplau and Don, 2013). After 4 years, our study showed no significant effects of crop rotation on POM-C and N pools ($P > 0.05$; Tables 3.4, 3.5, and 3.6). These results supported previous findings (Conant et al., 2003) and could largely be attributed to the short duration of this study (Gosling et al., 2013). However, inconsistent findings have also been reported due to site-specific conditions (Kim et al., 2022; Li et al., 2015) and management practices (Conant et al., 2003; Poeplau and Don, 2013). Furthermore, the MAOM pool is considered an older more stable part of SOM with slower turnover rates than POM (Baisden et al., 2002; Henderson et al., 2004). The present study results showed that the inclusion of pulses in cereal- or oilseed-dominated rotations had no significant effect on MAOM pools at any of the three sites ($P > 0.05$; Tables 3.4, 3.5, and 3.6). This suggests that MAOM is not responsive to changes in cropping systems in the short term (Poeplau and Don, 2013). In addition, over 75% of total SOC across the different crop rotations and sites was found in the MAOM fraction (Tables 3.4, 3.5, and 3.6). It is important to note that change in the MAOM fraction significantly influences the total SOC, as it constitutes a large proportion (Li et al., 2015; Poeplau and Don, 2013). This fraction has a medium turnover time of about 10–100 years (Lützow et al., 2006), which is similar to the time needed for temperate soils to reach a new equilibrium after management changes (Poeplau et al., 2011).

3.5.3.3. Rotation effects on aggregate stability

Soil aggregate stability is fundamental to improving soil function and crop performance, and thus, the criteria for evaluating a well-managed agricultural system that promotes soil health (Iheshiulo et al., 2023; Wright and Anderson, 2000). In this present study, AS measured in 1−2 mm size fractions was significantly influenced by crop rotations in two out of the three sites i.e., at Lethbridge and Swift Current despite the lack of significant changes in SOM (Figs. 3.2a−c). The soil health-enhanced rotation had significantly ($P < 0.05$) higher AS (78%) compared to the conventional, pulse/oilseed intensified, and market-driven rotations at Lethbridge (60−70%) but did not statistically differ from the diversified and high-risk and high-reward rotations (Fig. 3.2a). Green manures have been shown to enhance soil health attributes, including AS (Campbell et al., 2001). On the other hand, the high-risk and high-reward rotation had significantly ($P < 0.05$) higher

AS (39%) compared to the pulse/oilseed intensified, and market-driven rotations at Swift Current (26−28%) but did not differ from the other rotations (Fig. 3.2b). These results are in line with previous research by Yan et al. (2022), which showed that the inclusion of pulses in rotations improved AS in the short term. The increased AS was attributed to the diversity in substrates, especially pulse biomass that is easily decomposed by microbes, acting as a binding agent to promote and stabilize soil particles (Cotrufo et al., 2019, 2013; Yan et al., 2022). The increased AS may further promote other soil physical and hydraulic properties as reported from the same experiment by Iheshiulo et al. (2024).

Additionally, soil microbial community, fauna, and plant roots play key roles in the formation and stabilization of soil structure (Dowdeswell-Downey et al., 2023; Oades, 1993). The inclusion of pulses in these rotations may have increased microbial community and activity (Lupwayi et al., 1998), which in turn increased AS in this study (Dowdeswell-Downey et al., 2023). While not examined in this study, increased earthworm populations have been reported with the incorporation of pulses in rotations (Ashworth et al., 2017). Hence, increased earthworm activity may have contributed to the observed increase in AS at both Lethbridge and Swift Current through the formation of casts (Oades, 1993). Soil moisture and temperature are other factors that promote AS (Dowdeswell-Downey et al., 2023; Iheshiulo et al., 2023). During the 4-year study, both the Lethbridge and Swift Current sites experienced precipitation deficits and increased temperatures compared to the Scott site. According to Dowdeswell-Downey et al. (2023), AS increased with increasing temperature and decreased with increasing moisture. Furthermore, considering the projected 5−6.5% increase in annual mean precipitation in the prairie region for 2031−2050 (Cohen et al., 2019), the increased AS under these crop rotations may facilitate more water infiltration into the soil, thus increasing water storage and reducing water erosion.

At Scott, a non-significant difference (*P* > 0.05) in AS was observed among crop rotations (Fig. 3.2c), which could be due to several factors such as the study duration, soil texture, and precipitation. In terms of study duration, Iheshiulo et al. (2023) found that AS significantly increased in longer study durations (> 10 years). Moreover, inherent soil texture is key to the stability of soil aggregates. The soils at Scott had considerably higher sand and lower clay content, coupled with higher precipitation over the duration of the study compared to Lethbridge and Swift Current (Table 3.1), which in turn may have led to the insignificant response in AS at this site. According to Olagoke et al. (2022) and Oades (1993), increased clay content in soils promotes and enhances aggregate formation and stability. In addition, the amount and intensity of rainfall may also have a significant influence on AS. In a recent meta-analysis, Iheshiulo et al. (2023) found that crop rotational diversity studies conducted in drier conditions, i.e., low amounts of rainfall (< 500 mm yr^{-1}) tended to support increased AS than those conducted in wetter conditions. Also, Dowdeswell-Downey et al. (2023) reported that AS significantly decreased with increasing moisture content, which may explain the lack of response at the Scott site. Therefore, the difference in AS observed among the sites supports the idea that temperature and soil moisture content play significant roles in AS dynamics (Dowdeswell-Downey et al., 2023; Iheshiulo et al., 2023).

3.5.4. Relationships between soil quality attributes

Spearman correlation analysis on soil quality parameters measured at the 0−7.5 cm soil depth increment is presented in Figs. 3.3a-c. The correlation matrix revealed significant (*P*s < 0.001) positive correlations between C and N variables, with Spearman coefficients ranging from 0.83 to 0.97 across the three sites. For instance, SOC, POM-C, and MAOM-C were respectively strongly correlated to TN (*r* > 0.92), POM-N (*r* > 0.83), and MAOM-N (*r* > 0.91) across the three sites ($Ps < 0.001$). Moreover, SOC and TN were more strongly correlated to MAOM-C ($r > 0.84$; $Ps < 0.001$) and MAOM-N ($r > 0.72$; $Ps < 0.001$) than to POM-C and POM-N (Figs. 3.3a−c). Our study results are similar to the findings of Kim et al. (2022), who showed strong positive associations among these variables in perennial cropping systems. Meanwhile, St. Luce et al. (2022) found a negative association between POM-C and MAOM-C after 25 years in a corn-soybean rotation under humid temperate conditions in eastern Canada, whereas this study only found a weak significant association ($r = 0.25$, $P < 0.05$) at Swift Current (Fig. 3.3b), with no significant relationship observed at Lethbridge and Scott (Figs. 3.3a and 3.3c). Similar to this study's findings, Kim et al. (2022) also reported no significant association between POM-C and MAOM-C.

Furthermore, this study revealed significant positive relationships between AS and SOC, TN, and MAOM across the three sites ($Ps < 0.05$; Figs. 3.3a−c). Interestingly, at Scott, the AS correlations with SOC ($r = 0.86$) and TN ($r = 0.75$) were stronger than at Lethbridge and Swift Current. While some studies suggest that SOC increases AS (Carter, 2002; Chenu et al., 2000), others have reported contrary evidence (Carter et al., 1994; Gerzabek et al., 1995; Haynes, 2000). Similar correlations were observed between MAOM fractions and AS. Specifically, this present study found that MAOM-C ($r \geq 0.57$) and MAOM-N ($r \geq 0.58$) were more strongly correlated with AS, while POM-C and POM-N showed little or no significant association with AS (Figs. 3.3a−c). The results of this study agree with Li et al. (2015), who showed that AS is more affected by MAOM fractions than POM fractions. This is because MAOM determines the internal structures of aggregates, which makes them less prone to decomposition. At Lethbridge, AGB, SOC, TN, MAOM-C and -N, and AS were moderately correlated with each other ($0.45 \geq r \leq 0.52$; $P < 0.05$). However, there was little or no significant correlation at Swift Current and Scott ($r \leq 0.25$; $P >$

0.05; Fig. 3.3). This suggests to some extent that the relationship between AGB and SOC is more likely to be related to SOC influence on AGB, rather than AGB impacts on SOC, including AS (Zhao et al., 2023). Nonetheless, while some studies have demonstrated a positive correlation between SOC and AGB (Liu et al., 2022; Oldfield et al., 2022; Zhao et al., 2023), the relationship between AGB and SOC may be mutually causal (i.e., in both directions). An increase in AGB could lead to an increase in SOC due to an increase in residue inputs (Oldfield et al., 2020, Zhao et al., 2023), which in turn may affect soil health (Lal, 2020).

3.5.5. Implications of crop rotation design for soil health

After four growing seasons, crop rotation had no significant effects on SOC and TN concentrations, however, alternative rotations had similar SOC and TN concentrations under reduced N-fertilizer compared to the conventional rotations at the three sites. This suggests that replacing fallow with pulses or having a high frequency of pulses [chickpea (*Cicer arietinum*), soybean, faba bean (*Vicia faba* L.), lentil (*Lens culinaris* L.), and pea (*Pisum sativum*)] or oilseed crops [flax (*Linum usitatissimum*) and canola] in continuous rotations, such as in the pulse/oilseed intensified, diversified, high-risk and high-reward, and soil health-enhanced rotations could lead to SOC and TN concentrations across the three sites while reducing the negative impacts of N-fertilization to the environment. A previous study by van der Pol et al. (2022) found that incorporating legumes into continuous cropping systems increased soil C sequestration capacity. However, a high frequency of pulses may result in lower crop residue-C input (Liu et al., 2020). One way to enhance SOC is to increase the amount of crop residue returned to the soil (Ardenti et al., 2023). Therefore, the inclusion of perennial forage legumes in these rotations while limiting the frequency of annual pulse or oilseed crops may be one approach to increase the amount of biomass returned to the soil. This approach can help increase the quantity, quality, and chemical diversity of crop residue, thus sustaining and increasing SOC and soil fertility (Tiemann et al., 2015).

Furthermore, the inclusion of pulses in rotation, such as in the diversified, high-risk and high-reward, and soil health-enhanced rotations improved AS compared to the conventional rotations at both Lethbridge and Swift Current. Generally, pulse biomass (whether residue from a cash crop or soil incorporated as green manure) tends to be efficiently stabilized in the soil due to its higher quality (i.e., lower C/N ratios) (Johnson et al., 2007; Yan et al., 2022) and increased microbial substrate use efficiency (Castellano et al., 2015; Cotrufo et al., 2013). This may promote increased microbial biomass and activity due to the diverse crop residue and substrate inputs, with varying biochemical characteristics under these rotations (Gartner and Cardon, 2004; King and Hofmockel, 2017; Zhou et al., 2020) and thus, promote aggregate formation and stability observed in our study (Gartner and Cardon, 2004; Zhou et al., 2020). Therefore, it may be possible for growers to replace fallow or increase the frequency of pulses in the conventional cereal- and oilseed-dominated rotations without compromising soil health (van der Pol et al., 2022), while also promoting other ecosystem services, in particular when economic returns and N management options are considered. However, it should also be noted that there could be a possibility of root rot (*Aphanomyces euteiches*) and other pulse diseases that may occur with increased frequency of pulses in rotation, especially under higher precipitation as projected for 2031−2050 in western Canada (Cohen et al., 2019).

3.6. Conclusions

The 4-year field experiments indicate that relative to conventional rotations, the inclusion of annual pulse crops, whether as a harvested crop or green manure, or simply replacing fallow with pulses or green manure enhanced AS and stabilized SOC. Also, low precipitation during the study period resulted in low straw production, which also slowed down the stabilization of straw into SOC. Overall, the study showed that the crop species, frequency, and site-specific conditions also played key roles in SOC sequestration and AS. Future research should focus on the long-term effects of these cropping practices on SOC dynamics and AS, as well as aggregate-associated C in deeper soil layers, with the aim of better understanding SOC and AS accrual and function in resilient agroecosystems.

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Table 3.1. Baseline soil characteristics from 0−15 cm soil depth increment before study establishment at Lethbridge, Alberta and Swift Current and Scott, Saskatchewan, spring 2018.

Soil attributes [a]	Lethbridge	Swift Current	Scott
Classification [b]	Dark Brown Chernozem	Brown Chernozem	Dark Brown Chernozem
Chemical property			
SOC, g kg^{-1}	18.7	14.9	15.9
TN, g kg^{-1}	2.30	1.71	2.15
pH	7.26	6.97	6.80
EC, dS m^{-1}	0.64	0.77	0.55
Particulate organic matter (POM)			
POM-C, g kg^{-1}	7.12	3.35	3.33
POM-N, g kg^{-1}	0.47	0.22	0.24
POM-C/N	15.1	15.3	13.8
Mineral-associated organic matter (MAOM)			
MAOM-C, g kg^{-1}	11.58	11.55	12.57
MAOM-N, g kg^{-1}	1.83	1.49	1.91
MAOM-C/N	6.33	7.73	6.59
Physical property			
Texture	Clay	Loam	Loam
Sand, g kg^{-1}	220	290	370
Silt, g kg^{-1}	260	450	400
Clay, g kg^{-1}	520	260	230
AS, %	46	10	23

[a] SOC, soil organic carbon; TN, total nitrogen; EC, electrical conductivity; C, carbon; N, nitrogen; AS, aggregate stability. pH was determined using 1:2 soil-water ratio.
[b] Soil classification adopted from Larney et al., (2004).

Table 3.2. Crop rotations, sequences, and N management strategy at Lethbridge, Alberta and Swift Current, Saskatchewan.

Rotation	Crop sequence	Starting phase	Rotation history [a]				N management strategy
			2018	2019	2020	2021	
Conventional (control)	F−DW−B−DW	1	F	DW	B	DW	Based on crop N removal.
		2	DW	B	DW	F	Wheat: 84−150 kg ha^{-1} yr^{-1}; barley: 51−127 kg ha^{-1} yr^{-1}; and
		3	B	DW	F	DW	fallow: zero N across sites.
		4	DW	F	DW	B	
Pulse/oilseed intensified	L−DW−CP−DW	1	L	DW	CP	DW	Recommended N based on soil testing.
		2	DW	CP	DW	L	Wheat: 51−150 kg ha^{-1} yr^{-1}; and pulses: 13−20 kg ha^{-1} yr^{-1}
		3	CP	DW	L	DW	across sites.
		4	DW	L	DW	CP	
Diversified	L−Cn−P−DW	1	L	Cn	P	DW	Recommended N based on soil testing – N credits from previous crop residues.
		2	Cn	P	DW	L	
		3	P	DW	L	Cn	Wheat 20−69 kg ha^{-1} yr^{-1}; canola: 36−71 kg ha^{-1} yr^{-1}; and pulses: 13−20.2 kg ha^{-1} yr^{-1} across sites
		4	DW	L	Cn	P	
Market-driven	Cn−SW(Fl)[b]−SW(L)[b]−B	n/a	Cn(Fl)	SW	SW(L)	B	1.2 × crop N removal. Canola: 101 kg ha^{-1}; wheat: 19−101 kg ha^{-1} yr^{-1}; barley: 75−84 kg ha^{-1}; flax: 101 kg ha^{-1}; and lentil: 13 kg ha^{-1} across sites
High-risk and high-reward	S−C(CS)[c]−FB−DW	1	S	C(CS)	FB	DW	Recommended N based on soil testing.
		2	C(CS)	FB	DW	S	Corn:19−54 kg ha^{-1} yr^{-1}; wheat: 49−103 kg ha^{-1} yr^{-1}; pulses:
		3	FB	DW	S	C(CS)	0−20 kg ha^{-1} yr^{-1}; and canary seed: 64–75 kg ha^{-1} yr^{-1} across
		4	DW	S	C(CS)	FB	sites.
Soil health-enhanced	FP−B/P−FB/B−DW	1	FP	B/P	FB/B	DW	Recommended N based on soil testing.
		2	B/P	FB/B	DW	FP	Wheat: 64−103 kg ha^{-1} yr^{-1}; Intercrops: 13−20 kg ha^{-1} yr^{-1}
		3	FB/B	DW	FP	B/P	across sites.
		4	DW	FP	B/P	FB/B	

[a] B, barley (*Hordeum vulgare* L.); C, corn; Cn, canola; CP, chickpea; CS, canary seed (*Phalaris canariensis* L.); DW, durum wheat; F, fallow; FB, faba bean; Fl, flax; FP, forage pea (green manure); L, lentil; P, pea; S, soybean; SW, spring wheat (*Triticum astivum* L.); B/P, barley/pea intercrop; FB/B, faba bean/barley intercrop; and n/a, not applicable.

[b] Canola and spring wheat were grown at Lethbridge, while flax and lentil at Swift Current.

[c] Corn was grown at Lethbridge, while canary seed at Swift Current.

Note: Blanket applications of phosphorus: 17−44 kg P ha^{-1} yr^{-1} and sulphur: 10−23 kg S ha^{-1} yr^{-1} across sites.

Table 3.3. Crop rotations, sequences, and N management strategy at Scott, Saskatchewan.

Rotation	Crop sequence	Starting phase	Rotation history [a]				N management strategy
			2018	2019	2020	2021	
Conventional (control)	Cn−SW−P−SW	1	Cn	SW	P	SW	Based on crop N removal. Canola: 83−89 kg ha^{-1} yr^{-1}; wheat: 83−87 kg ha^{-1} yr^{-1}; and pulses: 3−4 kg ha^{-1} yr^{-1}.
		2	SW	P	SW	Cn	
		3	P	SW	Cn	SW	
		4	SW	Cn	SW	P	
Pulse/oilseed intensified	SW−Cn−SW−Cn	1	SW	Cn	SW	Cn	Recommended N based on soil testing. Wheat: 29−85 kg ha^{-1} yr^{-1}; and canola: 3.3−66 kg ha^{-1} yr^{-1}.
		2	Cn	SW	Cn	SW	
Diversified	P−SW−FB−Cn	1	P	SW	FB	Cn	Recommended N based on soil testing – N credits from previous crop residues. Wheat: 19−43 kg ha^{-1} yr^{-1}; canola: 3−87 kg ha^{-1} yr^{-1}; and pulses: 3−4 kg ha^{-1} yr^{-1}.
		2	SW	FB	Cn	P	
		3	FB	Cn	P	SW	
		4	Cn	P	SW	FB	
Market-driven	Cn−Cn−GP−Cn	n/a	Cn	Cn	GP	Cn	1.2 × crop N removal. Canola:100−104 kg ha^{-1} yr^{-1}; and green pea: 4 kg ha^{-1}.
High-risk and high-reward	Fl−S−DW−Cn	1	Fl	S	DW	Cn	Recommended N based on soil testing. Wheat: 19−66 kg ha^{-1} yr^{-1}; flax: 3−87 kg ha^{-1} yr^{-1}; soybean: 3−4 kg ha^{-1} yr^{-1}; and canola: 3−66 kg ha^{-1} yr^{-1}.
		2	S	DW	Cn	Fl	
		3	DW	Cn	Fl	S	
		4	Cn	Fl	S	DW	
Soil health-enhanced	FP−SW−FB−Cn	1	FP	SW	FB	Cn	Recommended N based on soil testing. Wheat: 4−64 kg ha^{-1} yr^{-1}; canola: 3−66 kg ha^{-1} yr^{-1}; and pulses: 3−4 kg ha^{-1} yr^{-1}.
		2	SW	FB	Cn	FP	
		3	FB	Cn	FP	SW	
		4	Cn	FP	SW	FB	

[a] Cn, canola; DW, durum wheat; FB, faba bean; Fl, flax; FP, forage pea (green manure); GP, green pea; P, pea; S, soybean; SW, spring wheat; and n/a, not applicable.

Note: Blanket applications of phosphorus: 16−18 kg P ha^{-1} yr^{-1}; potassium: 32−45 kg K ha^{-1} yr^{-1}; and sulphur: 10−15 kg S ha^{-1} yr^{-1} (excluding flax in 2021).

Table 3.4. Effect of crop rotations on soil organic matter pool in the 0−7.5 cm soil depth increment after 4 years at Lethbridge, Alberta.

Soil quality [a]	Crop rotations							
	Conventional (control)	Pulse/oilseed intensified	Diversified	Market-driven	High-risk and high-reward	Soil health-enhanced	Site mean	P-value
SOC, g kg^{-1}	27.12	27.12	27.28	27.56	26.37	27.03	27.08	0.82^{ns}
TN, g kg^{-1}	2.53	2.52	2.55	2.57	2.48	2.56	2.54	0.75^{ns}
SOC/TN	10.72	10.76	10.70	10.72	10.63	10.56	10.67	0.74^{ns}
POM-C, g kg^{-1}	6.68	6.88	6.98	6.68	6.36	6.50	6.68	0.42^{ns}
POM-N, g kg^{-1}	0.45	0.46	0.47	0.45	0.44	0.45	0.45	0.57^{ns}
POM-C/N	14.84	14.96	14.85	14.87	14.79	14.77	14.85	0.67^{ns}
POM-C/SOC, %	25	25	26	24	24	24	25	0.42^{ns}
POM-NTN, %	18	18	18	18	17	17	18	0.14^{ns}
MAOM-C, g kg^{-1}	20.44	20.24	20.30	20.87	20.01	20.53	20.40	0.83^{ns}
MAOM-N, g kg^{-1}	2.08	2.06	2.08	2.12	2.05	2.12	2.09	0.57^{ns}
MAOM-C/N	9.82	9.80	9.78	9.79	9.78	9.70	9.78	0.97^{ns}
MAOM-C/SOC, %	75	75	74	76	76	76	75	0.38^{ns}
MAOM-N/TN, %	82	82	82	82	83	83	82	0.14^{ns}

[a] SOC, soil organic carbon; TN, total nitrogen; POM, particulate organic matter; MAOM, mineral-associated organic matter; C, carbon; N, nitrogen; ns, not significant ($P > 0.05$).

Table 3.5. Effect of crop rotations on soil organic matter pool in the 0−7.5 cm soil depth increment after 4 years at Swift Current, Saskatchewan.

Soil quality [a]	Crop rotation							
	Conventional (control)	Pulse/oilseed intensified	Diversified	Market-driven	High-risk and high-reward	Soil health-enhanced	Site mean	P-value
SOC, g kg^{-1}	19.06	19.60	19.52	20.44	19.41	19.43	19.58	0.14^{ns}
TN, g kg^{-1}	1.75	1.81	1.78	1.87	1.78	1.79	1.80	0.23^{ns}
SOC/TN	10.89	10.77	10.97	10.93	10.90	10.85	10.89	0.41^{ns}
POM-C, g kg^{-1}	3.36	3.60	3.60	3.63	3.50	3.53	3.54	0.28^{ns}
POM-N, g kg^{-1}	0.24	0.26	0.25	0.26	0.25	0.25	0.25	0.68^{ns}
POM-C/N	14.0	13.85	14.40	14.0	14.0	14.12	14.13	0.67^{ns}
POM-C/SOC, %	18	18	18	18	18	18	18	0.28^{ns}
POM-N/TN, %	14	14	14	14	14	14	14	0.49^{ns}
MAOM-C, g kg^{-1}	15.70	16.0	15.92	16.84	15.91	15.90	16.04	0.20^{ns}
MAOM-N, g kg^{-1}	1.52	1.56	1.52	1.61	1.53	1.54	1.55	0.34^{ns}
MAOM-C/N	10.40	10.26	10.41	10.41	10.40	10.32	10.36	0.93^{ns}
MAOM-C/SOC, %	82	82	82	82	82	82	82	0.53^{ns}
MAOM-N/TN, %	86	86	86	86	86	86	86	0.49^{ns}

[a] SOC, soil organic carbon; TN, total nitrogen; POM, particulate organic matter; MAOM, mineral-associated organic matter; C, carbon; N, nitrogen; ns, not significant ($P > 0.05$).

Table 3.6. Effect of crop rotations on soil organic matter pool in the 0−7.5 cm soil depth increment after 4 years at Scott, Saskatchewan.

Soil quality [a]	Crop rotation							
	Conventional (control)	Pulse/oilseed intensified	Diversified	Market-driven	High-risk and high-reward	Soil health-enhanced	Site mean	P-value
SOC, g kg^{-1}	23.85	23.60	22.99	23.27	23.87	24.28	23.64	0.76^{ns}
TN, g kg^{-1}	2.23	2.19	2.15	2.15	2.18	2.28	2.20	0.47^{ns}
SOC/TN	10.70	10.78	10.69	10.82	10.95	10.65	10.76	0.65^{ns}
POM-C, g kg^{-1}	4.71	4.55	4.58	4.34	4.68	4.91	4.63	0.16^{ns}
POM-N, g kg^{-1}	0.33	0.32	0.33	0.32	0.33	0.35	0.33	0.10^{ns}
POM-C/N	14.27	14.22	13.88	13.56	14.18	14.03	14.09	0.73^{ns}
POM-C/SOC, %	20	19	20	19	20	20	20	0.73^{ns}
POM-N/TN, %	15	15	15	15	15	15	15	0.83^{ns}
MAOM-C, g kg^{-1}	19.14	19.05	18.41	18.93	19.19	19.37	19.02	0.92^{ns}
MAOM-N, g kg^{-1}	1.90	1.87	1.82	1.83	1.85	1.93	1.87	0.67^{ns}
MAOM-C/N	10.07	10.19	10.12	10.34	10.37	10.04	10.17	0.27^{ns}
MAOM-C/SOC, %	80	81	80	81	80	80	80	0.73^{ns}
MAOM-N/TN, %	85	85	85	85	85	85	85	0.83^{ns}

[a] SOC, soil organic carbon; TN, total nitrogen; POM, particulate organic matter; MAOM, mineral-associated organic matter; C, carbon; N, nitrogen; ns, not significant ($P < 0.05$).

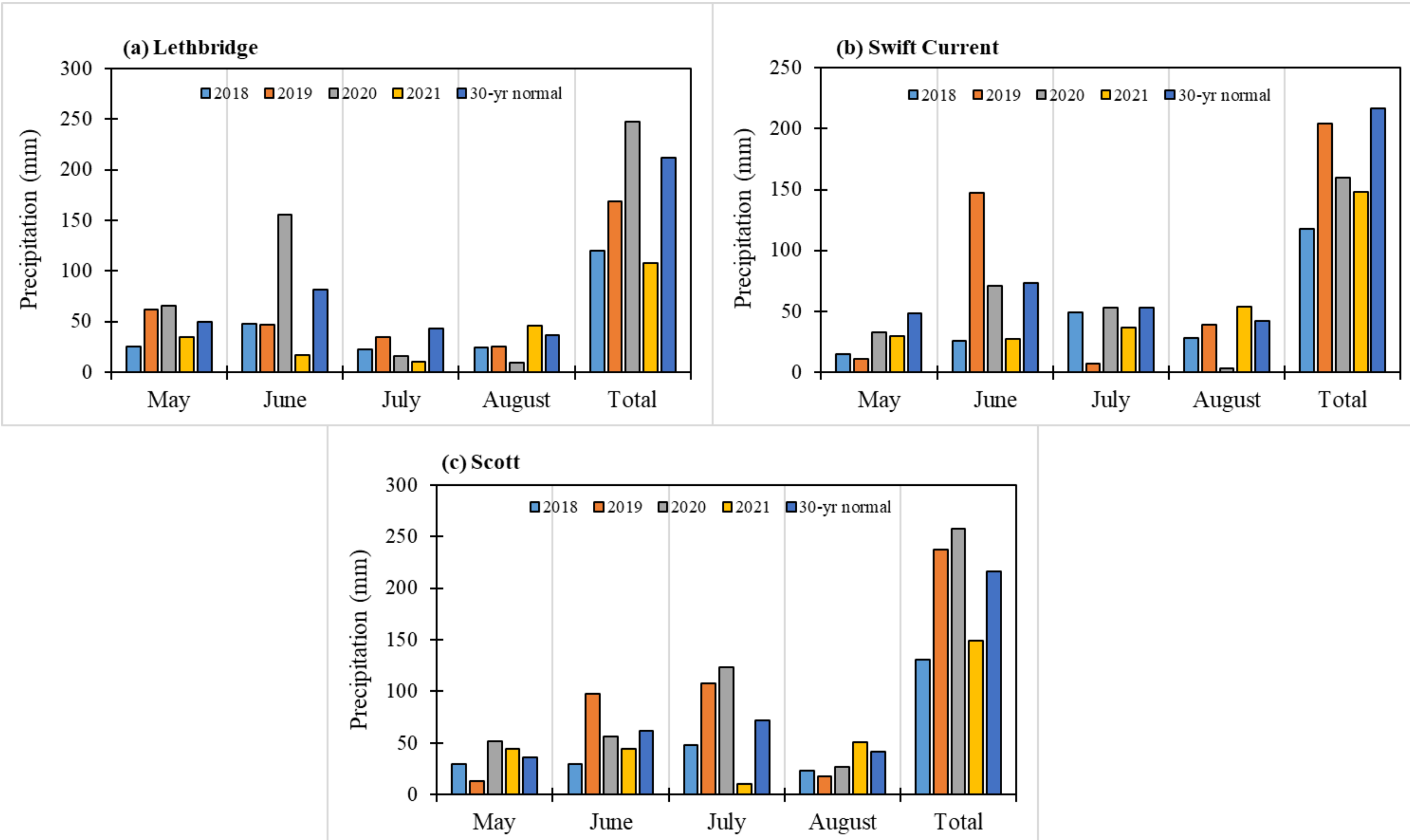

Figure 3.1. Growing season precipitation (May 1 to August 31) and 30-year normals (1981–2010) at (a) Lethbridge, Alberta and (b) Swift Current and (c) Scott, Saskatchewan.

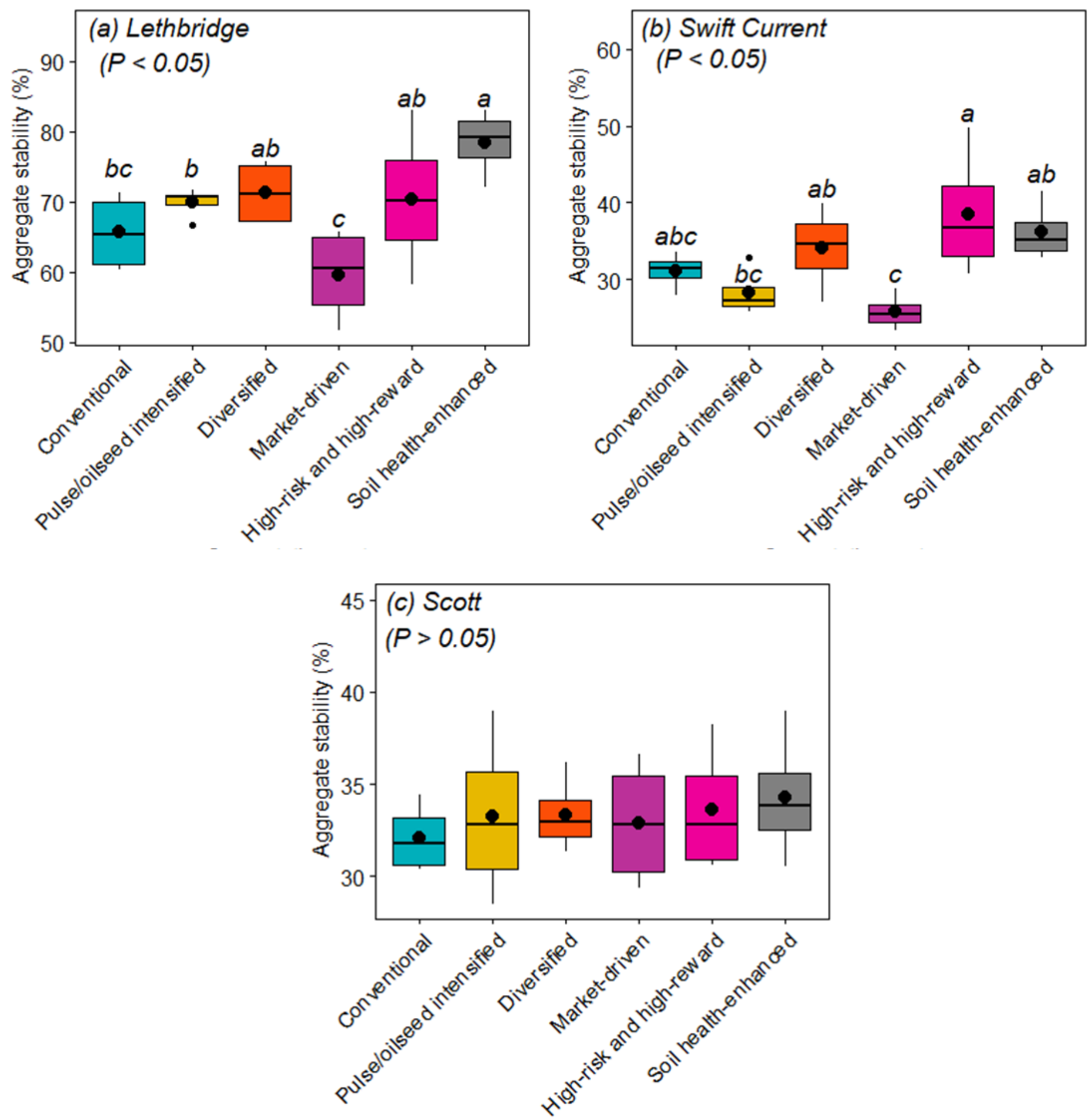

Figure 3.2. Aggregate stability (0−7.5 cm soil depth increment) as influenced by crop rotations at (a) Lethbridge, Alberta and (b) Swift Current and (c) Scott, Sasketchewan. The black dots within and outside the boxplot indicate mean value and outliers, respectively. Box plots followed by the same letter are not significant at $P < 0.05$.

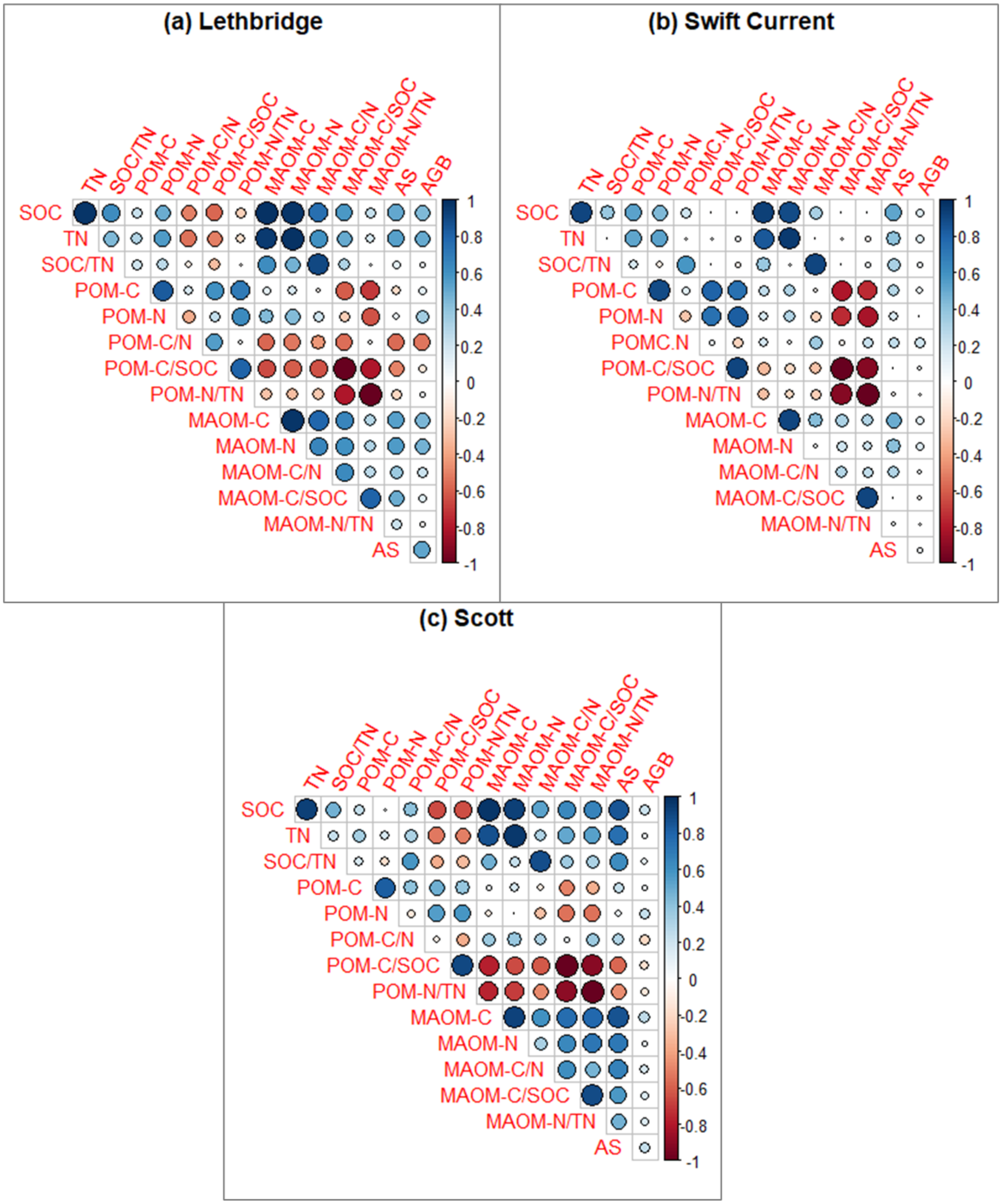

Figure 3.3. Spearman correlations between measured soil quality attributes (0−7.5 cm soil depth increment) at (a) Lethbridge, Alberta and (b) Swift Current and (c) Scott, Saskatchewan. The size and color of the circle represent *P*-values and correlation coefficients. Note: SOC, soil organic carbon; TN, total nitrogen; POM, particulate organic matter; MAOM, mineral-associated organic matter; C, carbon; N, nitrogen; AS, aggregate stability (determined by wet-sieving method), and AGB; above-ground straw biomass.

4. Crop Rotations Influence Soil Hydraulic and Physical Quality under No-till on the Canadian Prairies

Iheshiulo, E.M.-A., Larney, F.J., Hernandez-Ramirez, G., St. Luce, M., Chau, H.W., Lui, K., 2024. Crop rotations influence soil hydraulic and physical quality under no-till crop rotations on the Canadian prairies. Agric. Ecosyst. Environ., 442, 116777. https://doi.org/10.1016/j.agee.2023.108820.

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4.1. Highlights

- Crop rotations did not affect bulk density or total porosity in the short term.
- Legume inclusion in cereal-dominated rotations enhanced pore size distribution.
- Diverse rotations affected soil water content and hydraulic conductivity.
- Rotations with higher crop diversity improved soil physical quality metric.
- Magnitude of rotation effects depends on prevailing climate and soil conditions.

4.2. Synopsis

Cropping system sustainability is dependent on the conservation of soil hydraulic and physical quality over time. This study examined the effects of crop rotations on soil hydraulic and physical quality on the Canadian prairies, emphasizing choices of crop species and sequence to preserve or improve soil quality under no-till management. Field experiments were initiated in spring 2018 at three sites: Lethbridge (Alberta), and Swift Current and Scott (Saskatchewan) to evaluate six crop rotations, consisting of (i) conventional (control), (ii) pulse/oilseed intensified, (iii) diversified, (iv) market-driven, (v) high-risk and high-reward, and (vi) soil health-enhanced. Undisturbed soil cores were collected from 5–10 and 15–20 cm soil depth increments in 2021 after crop harvest, to determine bulk density (BD), total (TP) and effective porosity (EP), pore size distribution, soil water retention, and unsaturated hydraulic conductivity. Results revealed that crop rotations did not significantly impact BD, TP, or EP in the 5–10 and 15–20 cm soil depth increments across the three sites. Depending on the site and soil layer, the pulse/oilseed intensified, diversified, high-risk and high-reward, and soil health-enhanced rotations improved macroporosity by 13−127% and mesoporosity by 1−36% compared to the conventional rotation, resulting in concomitant increases in large and medium unsaturated hydraulic conductivities. At Lethbridge, both conventional and high-risk and high-reward rotations resulted in increased water content at field capacity (FC) by 12-14%, permanent wilting point (PWP) by 7−12%, and plant available water capacity (PAWC) by 16−17%, accompanied by significant increases in microporosity (8%) and residual porosity (16%) in the 5−10 cm depth compared to the soil health-enhanced rotation. However, no significant differences were found at Swift Current or Scott in the 5−10 cm depth. The pulse/oilseed intensified rotation significantly improved FC by 22% and PAWC by 19% compared to the market-driven rotation. This rotation also showed an 18% increase in FC and a 32% increase

in PWP when compared to the diversified rotation at Scott in the 15−20 cm depth, but did not differ significantly at Lethbridge or Swift Current. Overall, crop rotations with legumes and increased functional diversity have the potential to improve soil physical quality and plant available water but may require a period longer than the present study's duration to become evident.

Keywords: crop rotation; soil hydraulic-physical health; soil water retention; crop diversification

4.3. Introduction

Concerns about soil quality deterioration, long-term agroecosystem sustainability, and the risks posed by accelerating climate change call for the development and adoption of more resilient cropping system practices that can deliver high productivity, economic profitability, and environmental benefits (Bowles et al., 2020; Degani et al., 2019; Gan et al., 2015; Gaudin et al., 2015; Liu et al., 2020, 2019; St. Luce et al., 2020). As an ecologically-oriented strategy, crop rotation can help improve and preserve soil hydraulic and physical properties (Feng et al., 2011; Iheshiulo et al., 2023; Kiani et al., 2017; Larney and Lindwall, 1995; Nunes et al., 2018; Renwick et al., 2021), as well as increase crop yield (Degani et al., 2019; Gan et al., 2015; Gaudin et al., 2015; St. Luce et al., 2020). Increasing plant species diversity with varying biochemical characteristics can further enhance the benefits of crop rotation for soil hydraulic and physical quality (Alhameid et al., 2020; Nouri et al., 2019; Nunes et al., 2018) due to accelerated carbon (C) sequestration rates and increased biological activity and diversity (Soares et al., 2019), which in turn improve aggregate stability, water retention, and water transmission (Alhameid et al., 2017; Kumar et al., 2012a). Moreover, incorporating various crop species with different rooting patterns may improve the number and network of macropores and micropores (Kumar et al., 2012b), and consequently, enhance water availability and infiltration (Kemper et al., 2011; Alhameid et al., 2020; Renwick et al., 2021).

Crop rotation and no-till (NT) combined may further enhance soil hydraulic and physical properties by reducing aggregate disintegration, conserving soil organic carbon, and supporting soil biological health (Kumar et al., 2012a; Nunes et al., 2018). However, the extent of these benefits under NT on soil hydraulic and physical properties depends on the variability and sensitivity of the properties measured. Some properties, such as bulk density (BD), pore size distribution, and soil water retention (Hernandez-Ramirez et al., 2014; Guenette et al., 2019; Alhameid et al., 2020; Daly et al., 2023) are known to respond to agricultural management. Yet, the effects of crop rotation under NT on these properties are not consistent across different studies due to combined interactions of crop species, soil and climate conditions, and duration of the study (Abdallah et al., 2021; Blanco-Canqui and Ruis, 2018; Iheshiulo et al., 2023). For instance, a meta-analysis by Iheshiulo et al. (2023) found that adding legumes to cereal-based rotations reduced BD, improved porosity, and enhanced hydraulic conductivity, but did not affect infiltration rate under medium-textured soils in long-term studies. Similarly, Blanco-Canqui and Ruis (2018) reported that water infiltration, saturated hydraulic conductivity, and water retention were more likely to change under different management options for medium- and fine-textured soils than for coarse-textured soils.

Previous crop rotation research on the Canadian prairies has predominantly focused on crop yield and quality, and soil chemical, or biological properties, with limited attention given to the importance of soil hydraulic and physical quality. For instance, Campbell et al. (1990) provided a comprehensive summary of crop rotation studies, highlighting crop yield and soil fertility. More recently, Lafond and Harker (2012) updated long-term cropping system research results on the Canadian prairies, again with a focus on crop yield and soil fertility. Additionally, most published research on the impacts of crop rotation on soil hydraulic and physical quality is from the northern Great Plains of the US rather than the Canadian prairies (Iheshiulo et al., 2023).

As soils can respond differently to agronomic practices across different environments, more research is needed to fully understand the impact of crop rotation on soil hydraulic and physical properties on the Canadian prairies. The current study was part of a larger 4-year (2018−21) crop rotation project (Liu et al. 2023) established in 2018 at seven sites across the

Canadian prairies (three in Alberta, three in Saskatchewan, and one in Manitoba). Overall study objectives were to (i) increase crop yield and improve whole-farm economic outcomes; (ii) enhance system resiliency; (iii) improve soil nutrient supplying power and soil health; and (iv) decrease the environmental footprint. The present specific study fell under the soil health objective and aimed to (i) quantify the effects of six contrasting crop rotations on soil hydraulic and physical quality and (ii) identify sensitive parameters that may provide robust metrics of soil hydraulic and physical quality.

4.4. Materials and Methods

4.4.1. Study site description

The study was conducted at three of the seven project sites: Lethbridge, Alberta (49º 41’ N, 112º 46’ W); Swift Current, Saskatchewan (50º 17’ N, 107º 47’ W); and Scott, Saskatchewan (52º 21’ N, 108º 50’ W). Soil from the 0−15 cm soil depth at Lethbridge had a clay texture, with 0.22 kg kg^{-1} sand, 0.26 kg kg^{-1} silt, and 0.52 kg kg^{-1} clay, and classified as a Dark Brown Chernozem. Soils at Swift Current (Brown Chernozem) and Scott (Dark Brown Chernozem) from the 0−15 cm soil depth had a loam texture, with 0.29 kg kg^{-1} sand, 0.45 kg kg^{-1} silt, and 0.26 kg kg^{-1} clay at Swift Current and 0.37 kg kg^{-1} sand, 0.40 kg kg^{-1} silt, 0.23 kg kg^{-1} clay at Scott (Iheshiulo et al., 2024a). Precipitation data during the study, as well as 30-year normal values were obtained from the nearest Environment Canada weather station to each site.

4.4.2. Experimental design and management

A randomized complete block design experiment was conducted with four replications and six crop rotations at each site (Table 4.1). The six rotations had a unified treatment typology across ecosites while their components (crop phases) varied to reflect local site-specific conditions. In that regard, crop choices at Lethbridge and Swift Current were similar [e.g., predominantly durum wheat (*Triticum turgidum* L. var. *durum*)], with Scott somewhat different [predominantly canola (*Brassica napus* L.)]. The six rotations were (i) conventional (control), (ii) pulse/oilseed intensified, (iii) diversified, (iv) market-driven, (v) high-risk and high-reward, and (vi) soil health-enhanced (Table 1). All rotations were 4-year, with the exception of the 2-year [spring wheat (*Triticum astivum* L.)–canola] pulse/oilseed intensified rotation at Scott. It should be noted that at Lethbridge and Swift Current, five of the six rotations (market-driven excepted) were fully phased, i.e., each crop phase of each rotation appeared in each year, i.e., (5 rotations × 4 crop phases) + (1 rotation × 1 crop phase) = 21 crop phases × 4 replicates = 84 plots. At Scott, five of the six rotations (except market-driven) were also fully phased i.e., (4 rotations × 4 crop phases) + (1 rotation × 2 crop phases) + (1 rotation × 1 crop phase) = 19 crop phases × 4 replicates = 76 plots.

At Lethbridge and Scott, a NT seeder (Model CP 129A, Conserva Pak, Indian Head, SK, Canada) with a 23-cm row spacing was used for all crops, except corn at Lethbridge (76-cm row spacing corn planter). At Swift Current, a NT hoe-drill seeder (Fabro Manufacturing, Swift Current, SK, Canada) with a 23-cm row spacing was used for seeding all crops.

4.4.3. Soil core sampling

Prior to treatment allocation in spring 2018, five undisturbed soil cores were collected per experimental replicate at two soil depth increments (5–10 and 15–20 cm) at the three sites (5 cores × 4 replicates × 2 depths × 3 sites, $n = 120$). Soil samples were subsequently collected after a 4-year study period following the crop harvest in fall 2021, on subsets of the 84 plots at Lethbridge and Swift Current and the 76 plots at Scott. The rotation sequences (outlined in Table 4.1) were sampled in fall 2021, i.e., where a common durum wheat phase was present at Lethbridge and Swift Current (market-driven excepted), and a common canola phase at Scott. Two cores were collected at the 5–10 cm depth increment (these two cores were averaged as pseudo-replicates), and one core was collected at the 15–20 cm depth (n = 216). Stainless-steel cores with a volume of 250 cm^3 (8 cm internal diameter, 5 cm height) were used to collect the samples from the center of each plot to minimize edge effects. It is important to note that the selected soil depth only provides a representative indication of soil properties since the soil profile is not continuous from 0−20 cm. To avoid interference from plant material, undecomposed organic matter and surface crust, the top 5 cm was excluded from the samples (Daly et al. 2023; Hebb et al., 2017; Kiani et al. 2017). The cores were carefully excavated, leveled, and sealed with plastic covers to prevent soil loss and drying, and subsequently stored at 4 °C until analysis.

4.4.4. Soil hydraulic-physical properties and calculations

Soil water retention curves (SWRC) were generated by a simple evaporation method using the HYPROP® device (UMS GmbH, Munich, Germany) and the WP4® potentiometer dewpoint method (Decagon Devices, Pullman, WA, USA) (Daly et al., 2023; Guenette et al., 2019; Hebb et al., 2017; Schindler et al., 2010). The process involved auguring two holes into the saturated soil cores, to depths of 3.75 cm and 1.25 cm, and inserting ceramic-tipped tensiometers attached to a pressure transducer base. This allowed the matric potential to be recorded from 0 to –100 kPa at the two depths within the saturated soil cores. Tension measurements were recorded at 10-minute intervals using a computer interface, while the gravimetric water content of the samples was recorded twice daily for a duration of up to 14 days. After completing the HYPROP® measurements, the soil cores were oven-dried at 105 °C for 24 hours, weighed, and subsamples were processed using the WP4 dewpoint tensiometer following the methods described by Daly et al. (2023) and Kiani et al. (2017).

The measured data values from HYPROP and WP4 were fitted to the constrained van Genuchten model (van Genuchten 1980) for the SWRC. The fitting process was conducted using the HYPROP-FIT® software. The van Genuchten model is represented by Eq. (4.1):

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha h)^n]^m} \qquad (4.1)$$

where θ represents the 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 represents the inverse of the air entry potential (kPa^{-1}), h is the matric potential (kPa), and n and m are shape parameters. To evaluate the quality of the fitted curves, the goodness of fit (R^2) and the root mean square error (RMSE) were used as guides. The curves with the highest R^2 values and the lowest RMSE values were selected.

Pore volume fractions were determined based on the tension values of the SWRC and their corresponding pore diameters. The following pore categories were quantified: macropore (0 to –5 kPa, >60 µm diameter), mesopore (–5 to –33 kPa, 60–9 µm), micropore (–33 to –50 kPa, 9–6 µm), and residual pore (< –50 kPa, <6 µm) (Daly et al., 2023; Guenette et al., 2019; Hernandez-Ramirez et al., 2014). The saturated water content at 0 kPa was interpreted as effective porosity (EP), which represents the volume of pores occupied by water at 0 kPa while excluding occluded pores (Daly et al., 2023). Field capacity (FC) was determined at –33 kPa, and the permanent wilting point (PWP) was estimated at –1500 kPa from the SWRC. The plant-available water capacity (PAWC) was calculated as the difference in volumetric water content between FC and PWP, which was derived from the fitted van Genuchten models (Eq. (4.1)). The unsaturated hydraulic conductivity (UHC; cm d^{-1}) was analyzed using a similar approach. Three UHC classes were considered: large

(–1 to –10 kPa), medium (–10 to –20 kPa), and small (–20 to –30 kPa) (Daly et al., 2023; Guenette et al., 2019; Hernandez-Ramirez et al., 2014).

The S-index, an indicator of general soil physical quality, was estimated based on the slope of the SWRC at its inflection point (Daly et al., 2023; Dexter, 2004) from the fitted van Genuchten θ(h) function (Eq. (4.1)), and the calculation for the S-index is given by Eq. (4.2):

$$S = -n(\theta_s - \theta_r)\left(\frac{2n-1}{n-1}\right)^{\left(\frac{1}{n}-2\right)} \quad (4.2)$$

In Eq. (4.2), values < 0.035 represented "poor", while values > 0.035 represented "good" soil physical quality. The dry BD was estimated from the mass of soil in the stainless-steel cores after oven-drying at 105 °C for 48 hours, while TP was estimated using the BD values, assuming a soil particle density of 2.65 g cm^{-3}.

4.4.5. Statistical analysis

Data analyses were conducted using R software version 4.2.3 (R Core Team, 2023). An α level of 0.10 was used for significance testing. Normality assumptions were checked using the Shapiro-Wilk test, and homoscedasticity assumptions were assessed using the Levene test. The analyses were performed separately for each site and soil depth increment. One-way analyses of variance (ANOVA) with mixed models were employed, using the "*nlme*" package (Pingeiro et al., 2013) to examine differences among crop rotations as the fixed effect, while replications were treated as a random source of variation. Post hoc analysis was conducted using Tukey's Honest Significant Difference test in the "*Agricolae*" (ver. 1.3-5) package (de Mendiburu, 2021) to compare means and identify grouping structures, specifically following significant ($P < 0.10$) ANOVA models. Furthermore, due to insignificant effects on selected properties at Swift Current, principal component analysis (PCA) and linear regression analyses were only conducted on the pooled dataset from Lethbridge and Scott to assess associations among measured soil hydraulic and physical properties. The PCA was conducted using “*FactoMineR*” (ver. 2.8) R package (Lê et al., 2008) while the regression analysis was conducted with “*ggbiplot*” (ver. 0.55) package (Wickham, 2016). In all comparisons, an α level of 0.10 was chosen, rather than the conventional α of 0.05, as explained by Pennock (2004) for conservation-related research.

4.5. Results

4.5.1. Environmental conditions

The average 30-year (1981−2010) growing season (May 1 to August 31) normal precipitation ranged between 212 and 217 mm across the sites (Table 4.2). During the study (2018−21), precipitation deficits were experienced in three of four growing seasons at Lethbridge (51−80% of normal) and at Swift Current (54−94% of normal) throughout the 4-year duration (Table 2). On the other hand, the Scott site had two growing seasons with precipitation deficits (61−69%) and two close to long-term normal values (Table 4.2).

4.5.2. Initial soil properties in 2018

Baseline SOC and hydraulic and physical properties of the soil in 2018 varied among the three sites (Table 4.3). Bulk SOC concentrations from the 0−15 cm soil depth ranged between 14.9 and 18.7 g C kg^{-1}, with Lethbridge soil having the highest SOC concentration. Lethbridge and Swift Current soils had lower BD and higher TP in the 5–10 cm soil depth compared to the soil at Scott. However, the TP in the 15–20 cm soil depth was similar across all three sites. Soil water content at PWP was consistently lower at Lethbridge compared to Swift Current and Scott. On the other hand, PAWC was higher at Swift Current. The baseline soil physical quality was classified as degraded at all three sites. However, soils at Lethbridge were found to be more degraded than those at Swift Current and Scott, as indicated by S-index values falling below the soil physical quality threshold of 0.035 proposed by Dexter (2004). One-way ANOVA was performed at each site (Table 4.3) and percentages/significant differences were outlined below.

4.5.3. Effects of crop rotation on soil properties after 4 years

4.5.3.1. Bulk density, total porosity, and effective porosity

No significant differences were found in BD and associated TP in the 5–10 and 15–20 cm soil depths among the crop rotations at any of the three sites ($P > 0.10$; Tables 4.4, 4.5, and 4.6). However, consistently across the sites, the pulse/oilseed intensified, diversified, and soil health-enhanced rotations tended to decrease BD and hence higher TP compared to the conventional rotations (Tables 4.4, 4.5, and 4.6). For instance, the soil health-enhanced rotation tended to reduce BD and a concomitant increase in TP by approximately 6–7% at Lethbridge, 2–6% at Swift Current, and 3–7% at Scott compared to other crop rotations.

Interestingly, significant differences were only observed in EP at the 15–20 cm soil depth at Swift Current ($P > 0.10$; Table 4.5). The pulse/oilseed intensified, diversified, and soil health-enhanced rotations exhibited notably higher EP compared to the high-risk and high-reward rotation at Swift Current. However, these differences were not statistically significant compared to the conventional and market-driven rotations ($P > 0.10$; Table 4.5). Across the three sites, the soil health-enhanced rotations showed slightly higher EP at the 5–10 cm soil depth compared to other crop rotations, but again the differences were non-significant ($P > 0.10$; Tables 4.4, 4.5, and 4.6).

4.5.3.2. Soil water retention characteristics

The characteristics of the SWRC were significantly influenced by crop rotations, with variations observed across sites and soil depths (Tables 4.4, 4.5, and 4.6; Figs. 4.1a–f). The SWRC showed distinct differences among crop rotations; the high-risk and high-reward rotation tended to produce flatter curves for both soil layers, while the soil health-enhanced rotation exhibited steeper slopes at Lethbridge (Figs. 4.1a and 4.1b). However, the opposite trend was observed at Swift Current and Scott (Figs. 4.1c and 4.1f). At Lethbridge, both the conventional and high-risk and high-reward rotation had significantly higher FC (12−14%), PWP (7−12%), and PAWC (16−17%) compared to the soil health-enhanced rotation but was similar to other rotations (Table 4.4). At Swift Current, no significant effects of crop rotation were observed in FC, PWP, or PAWC for either of the soil layers (Table 4.5). At Scott, the pulse/oilseed intensified rotation displayed significantly higher FC, but not PWP or PAWC, compared to the diversified rotation in the 5–10 cm soil depth ($P < 0.05$; Table 4.6). However, at the 15–20 cm depth, the pulse/oilseed intensified rotation exhibited significantly higher FC (18−22%), PWP (32%), and PAWC (19%) compared to the diversified or market-driven rotations ($P < 0.05$; Table 4.6), but did not differ significantly from the conventional, high-risk and high-reward, or soil health-enhanced rotations.

4.5.3.3. S-index – soil physical quality metrics

At Lethbridge, S-index values ranged from 0.025 to 0.028 across crop rotations at both the 5–10 and 15–20 cm soil depths. However, there were no significant differences observed among crop rotations (Table 4.4). Additionally, all S-index values were below the threshold for "good physical quality" at both soil depths ($S < 0.035$; Table 4.4; Fig. 4.2). At Swift Current, significant changes in the S-index were only observed in the 15–20 cm soil depth (Table 4.5). Crop rotations at Swift Current were ranked as follows: pulse/oilseed intensified > diversified > market-driven > soil health-enhanced > conventional > high-risk and high-reward rotations. The pulse/oilseed intensified and diversified rotations had S-index values at or above the threshold for "good soil quality" in the 15–20 cm depth increment, while the soil health-enhanced rotation had an S-index value at the threshold in the 5–10 cm soil depth at Swift Current. However, no significant differences were found at Scott, where the S-index values ranged from 0.030 to 0.033. The S-index values at Scott were higher and closer to the boundary limit compared to those in Lethbridge at both soil depths (Table 4.6).

4.5.3.4. Pore volume fraction and distribution

Pore size distribution (PSD) exhibited significant differences among crop rotations at all three sites (Tables 4.4, 4.5, and 4.6; Figs. 4.1a–f). At Lethbridge, significant changes in mesoporosity, microporosity, and residual porosity were observed among rotations at the 5–10 cm soil depth (Table 4.4). The conventional and high-risk and high-reward rotations resulted in significant increases in microporosity (7−8%) compared to the pulse/oilseed intensified and soil health-enhanced rotations, while residual porosity (16%) was significantly greater under the conventional and high-risk and high-reward rotations compared to the soil health-enhanced rotation ($P < 0.05$; Table 4.4). However, no significant changes were observed among crop rotations for PSD at the 15–20 cm depth (Table 4.4).

At Swift Current, significant changes in PSD were only observed for microporosity at the 15–20 cm soil depth (Table 4.5; Fig. 4.1d), where the pulse/oilseed intensified rotation showed 28% higher microporosity compared to the high-risk and high-reward rotation. At Scott, significant differences in macroporosity were observed at both the 5–10 and 15–20 cm soil depths

(P < 0.05; Table 4.6). More specifically, the diversified rotation at Scott exhibited 92% greater macroporosity than the pulse/oilseed intensified rotation at the 5–10 cm depth. Furthermore, the diversified, market-driven, and soil health-enhanced rotations at Scott displayed 50−60% higher macroporosity than the high-risk and high-reward rotation at the 15–20 cm soil depth. Residual porosity in the 15–20 cm soil depth was generally higher in the pulse/oilseed intensified rotation compared to the diversified and market-driven rotations at Scott (Table 4.5).

4.5.3.5. Unsaturated hydraulic conductivity

At Lethbridge, significant crop rotation effects were observed in the large and medium UHC at the 5–10 cm soil depth (P < 0.05; Table 4.4). The soil health-enhanced rotation had higher large UHC compared to the conventional and diversified rotations. Similarly, the medium UHC was 124−166% higher in the soil health-enhanced rotation compared to the diversified and market-driven rotations, but no significant differences were found among other crop rotations. There were no significant differences in UHC classes at the 15–20 cm depth (P > 0.10; Table 4.4). At Swift Current differences in UHC classes were non-significant at both soil depths (P > 0.10; Table 4.5). At Scott, a significantly higher difference was observed in the large UHC at the 5–10 cm soil depth, where the soil health-enhanced (643%) and diversified (596%) rotations were higher compared to the pulse/oilseed intensified rotation (P = 0.024; Table 4.5).

4.5.4. Principal component and linear regression analyses

At Lethbridge, the first and second principal components (PC) explained 44% and 17%, respectively of the total variance in measured soil hydraulic and physical parameters (Fig. 4.3a). The first PC showed a positive correlation with S-index, TP, EP, macroporosity, and mesoporosity, indicating that these variables increased together. Conversely, these variables were negatively associated with BD, PAWC, FC, microporosity and residual porosity. The negative correlations were evident in the linear regression analyses, such as the significant relationships between BD and macroporosity (r^2 between 0.66 and 0.69; $P < 0.05$; Fig. 4.4a) and large UHC (r^2 between 0.12 and 0.38; $P < 0.05$; Fig. 4.4e).

At Scott, the first and second PCs accounted for 35% and 22% of the total variance, respectively (Fig. 4.3b). The first PC increased with increasing BD, PAWC, FC, PWP, microporosity and residual porosity. On the other hand, the second PC showed negative correlations between BD and EP, TP, macroporosity, and large UHC. This indicates that as BD increased, EP, TP, and macroporosity decreased, as expected. The linear regression analyses also supported these relationships, such as the significant correlations between BD and macroporosity (r^2 between 0.41 and 0.45; $P < 0.05$; Fig. 4.4b) as well as large UHC (r^2 between 0.21 and 0.30; $P < 0.05$; Fig. 4.4f).

4.6. Discussion

4.6.1. Rotation effects on bulk density and total porosity

Soil compaction, as indicated by BD, has considerable impact on porosity, water infiltration, and water storage capacity (Ouda et al., 2018). The present findings indicated that alternative crop rotations did not have significant impacts on BD or TP in the 5–10 and 15–20 cm soil depths compared to conventional rotations (Tables 4.4, 4.5, and 4.6). This lack of change in BD or TP in the depths considered could be attributed to the limited duration of the study (4 year) and site-specific conditions, such as below-normal precipitation (Table 4.2). It is known that changes in BD or TP under NT rely on underlying biological activity and surface residue accumulation, and therefore, may have been slower to manifest under the dry conditions during this study (Nouri et al., 2019). Long-term studies demonstrated that crop rotations with legumes and higher crop diversity significantly decrease BD compared to simpler rotations. This reduction in BD subsequently affected TP and EP due to the diverse root structures and characteristics that contributed to improve soil structure and aggregation (Alhameid et al., 2020; Iheshiulo et al., 2023; Riedell et al., 2013). A recent meta-analysis also highlighted that longer study durations are needed to detect significant decreases in BD or increases in TP, particularly in NT systems (Iheshiulo et al., 2023). Additionally, soil texture and climate have been identified as factors that can contribute to the lack of change in these soil properties (Grant and Lafond, 1993; Iheshiulo et al., 2023). Furthermore, SOC concentration did not differ among rotations after 4year period in the same experiment (Iheshiulo et al., in review), which may explain the absence of improved BD or TP. Périe and Ouimet (2008) and Robinson et al. (2022) found that higher SOC resulted in lower BD, which in turn improve soil hydraulic and physical properties.

However, decreasing trends were observed in BD. The diversified and soil health-enhanced rotations consistently exhibited lower BD and hence, higher TP in the 5–10 and 15–20 cm soil depths across all three sites (Tables 4.4, 4.5, and 4.6). These rotations, including the pulse/oilseed intensified rotation, had higher functional crop diversity compared to other rotations, which may have contributed to improving trends in BD and TP. The diverse root structures, such as fibrous and tap root systems, along with associated root exudates and microbial activity resulting in possibly better soil conditions, could be responsible for these outcomes (Alhameid et al., 2020; Chen et al., 2021; Lupwayi et al., 1998). Additionally, in a related study, emerging from the same experiment, revealed that crop rotations such as the pulse/oilseed intensified, diversified, and soil health-enhanced supported higher soil aggregate stability, which might have further contributed to the numerical increases in TP and EP (Iheshiulo et al., 2024a).

4.6.2. Rotation effects on soil water retention characteristics

A plant's ability to access and absorb soil water depends on various soil factors, such as porosity, FC, lower limit of plant available water, PAWC, macroporosity, and the plant root distribution and depth (Reynolds et al., 2002). In this study, the impact of crop rotations on soil water retention characteristics varied among sites (Tables 4.4, 4.5, and 4.6). Significant effects were observed in the 5–10 cm soil depth increment at both Lethbridge and Scott. However, the effects were not consistent across crop rotations. At Lethbridge, the conventional and high-risk and high-reward rotations significantly increased FC, PWP, and PAWC compared to the soil health-enhanced rotation in the 5–10 cm soil depth (Table 4.4). Similarly, at Scott, the pulse/oilseed intensified rotation significantly enhanced FC, PWP, and PAWC compared to the diversified rotation in the 5–10 cm soil depth and the market-driven rotation in the 15–20 cm soil depth (Table 4.6). These differences in outcomes could be attributed to changes in the volume fractions of different pore sizes. Decreased macropores and mesopores and increased micropores and residual pores may have led to a greater availability of soil water (Abdallah et al., 2021; Alhameid et al., 2020; Dexter et al., 2001). However, the inconsistent effects of crop rotations on soil moisture retention capacity may be due to factors such as insufficient production of plant residue (due to drier-than-normal growing season precipitation) and site-specific pedological factors, which can affect water drainage and soil surface characteristics (Nouri et al., 2019).

In contrast, crop rotation did not affect soil water retention characteristics at Swift Current (Table 4.5). Although crop rotations with legumes and higher crop diversity showed numerically higher FC, PWP, and lower PAWC, the differences were not statistically significant, supporting previous findings by Renwick et al. (2021). Results from the same experiment showed no difference in SOC (Iheshiulo et al., 2024a), which in turn may explain the absence of change in SWRC. Rawls et al. (2003) have reported that an increase in SOC leads to an increase in water retention. In general, the variations in SOC and soil texture and structure may explain the differences in EP, FC, and PWP, as well as the PSD observed at the three sites (Tables 4.4, 4.5, and 4.6) (Iheshiulo et al., 2024a). For instance, finer-textured soils, such as at Lethbridge, which mainly consist of micropores and residual pores, typically have moderate PAWC. On the other hand, loamy-textured soils, such as those at Swift Current and Scott have a wider range of PSD, resulting in a higher PAWC due to an ideal combination of mesopores and micropores (O'Green, 2013). These findings highlight the importance of considering soil texture, structure, and site-specific conditions when assessing the impact of cropping systems on soil water retention characteristics.

4.6.3. Rotation effects on S-index – soil physical quality metric

The S-index has been widely recognized as a reliable measure of soil physical quality and has been used to evaluate soil classifications and management practices (Dexter, 2004; Guenette et al., 2019; Hebb et al., 2017; Kiani et al., 2017). Dexter (2004) proposed a threshold value of 0.035 for the S-index, distinguishing between "good" and "poor" soil quality. In this study, the pulse/oilseed intensified rotation at Swift Current displayed a higher S-index value (0.037) at the 15–20 cm soil depth compared to the conventional and high-risk and high-reward rotations. On the other hand, the soil health-enhanced rotation at the 5–10 cm depth and the diversified rotation at the 15-20 cm depth fell at the acceptable range for good soil quality (Table 4.5). The positive outcomes observed in the pulse/oilseed intensified, diversified, and soil health-enhanced rotations could be attributed, in part, to increased macroporosity and mesoporosity, as well as a slight reduction in BD in the corresponding soil layers (Table 4.5; Fig. 4.1d). These changes indicate an improved soil structure and the abundant presence of structural pores, which are known to enhance soil quality (Dexter, 2004; Guenette et al., 2019). The strong and significant inverse regressions between BD and macroporosity further support these inferences (Figs. 4.4a and 4.4b).

In general, the soils evaluated under the different crop rotations across all three sites exhibited low soil physical quality, except for the soil health-enhanced rotation (S = 0.035) in the 5−10 cm depth and the pulse/oilseed intensified (S = 0.037) and diversified (S = 0.035) rotations in the 15−20 cm soil depth at Swift Current. This is a common characteristic of soils that have previously undergone frequent tillage and have been cropped with shallow-rooted crops over an extended period (Daly et al., 2023; Dexter, 2004; Hebb et al., 2017). These findings highlight the potential of the pulse/oilseed intensified, diversified, and soil health-enhanced rotations (all rotations included legumes) to improve soil physical quality, and provide insights into how crop rotations can be designed for enhancing soil health in agricultural systems.

4.6.4. Rotation effects on soil pore size distribution

The composition of pores in the soil has a significant impact on soil drainage and its ability to retain water within its pores (Abdallah et al., 2021; Alhameid et al., 2020). This study showed significant variations in PSD despite crop rotations not having significant effects on BD or TP across the three sites (Tables 4.4, 4.5, and 4.6). This is consistent with previous findings which reported that TP may remain unaffected by changes in PSD due to the regulatory activities of plant root growth (Chen et al., 2021; Daly et al., 2023; Daynes et al., 2013; Hebb et al., 2017) and microbial diversity (Soares et al., 2019; Lupwayi et al., 1998). At Scott, the diversified and soil health-enhanced rotations had significantly greater fraction of macropores compared to the pulse/oilseed intensified rotation in the 5–10 cm soil depth and high-risk and high-reward rotation in the 15–20 cm soil depth (Table 4.6). This increase in macroporosity could facilitate faster drainage and improve water infiltration, as supported by previous studies (Alhameid et al., 2020; Fan et al., 2017; Kemper et al., 2011; Kumar et al., 2012b; Talukder et al., 2023). As observed under these crop rotations, the presence of diverse plant rooting patterns and structures may be contributing to the increased macroporosity by recurrently developing and using soil biopores (Bodner et al., 2014; Chen et al., 2021; Daly et al., 2023).

Mesopores can play a crucial role in regulating and improving PAWC in soils (Abdallah et al., 2021; Daly et al., 2023; Hebb et al., 2017). At Lethbridge, in the 5–10 cm soil depth increment, the soil health-enhanced rotation had a significantly higher volume fraction of mesopores (i.e., water conducting pores) compared to the market-driven rotation (Table 4.4). Moreover, this study found that the pulse/oilseed intensified, diversified, and soil health-enhanced rotations tended to increase mesoporosity by 9 to 43% compared to the conventional rotations at Lethbridge (15–20 cm depth) and Swift Current (both soil depths) (Tables 4.4 and 4.5). This increase in mesopores may further facilitate both aeration and drainage (Alhameid et al., 2020; Talukder et al., 2023). Additionally, the conventional and high-risk and high-reward rotations at Lethbridge had a higher proportion of micropores and residual pores in the 5–10 cm soil depth, enabling these rotations to retain more water and potentially improve water use efficiency and drought resilience (Alhameid et al., 2020). Moreover, increased volume of mesopores and micropores also resulted in higher PAWC under the pulse/oilseed intensified and diversified rotations at Swift Current in the 15–20 cm soil depth (Table 4.5), possibly due to better soil structure as supported by S-index values at that soil layer (Fig. 4.2) (O'Green, 2013).

The lack of significant changes in PSD and moisture retention at Swift Current may be attributed to factors such as the duration of the study, soil texture, and management practices (Abdallah et al., 2021; Bacq-Labreuil et al., 2018; O'Green, 2013). Long-term studies have shown that at least 15 years or more of crop rotation under NT are required to consistently increase soil TP, macroporosity, and bio-porosity (Blanco-Canqui and Ruis, 2018; Dıaz-Zorita et al., 2004; Galdos et al., 2019; Kay and VandenBygaart, 2002; Lal et al., 1994). While enhanced macroporosity may increase water infiltration, it may also come at the expense of a reduction in water-holding pores, pore continuity, and moisture retention capacity in the long term (Abdallah et al., 2021). Furthermore, the variations in response among these soils were expected due to differences in initial SOC, soil texture, and cultivation histories (Strudley et al., 2008; Talukder et al., 2023). Additionally, it is worth noting that the clay content at Lethbridge was higher (0.52 kg kg^{-1}) compared to Swift Current and Scott (0.23−0.26 g kg^{-1}), which may inherently enhance agrégations, stability (Iheshiulo et al., 2024a), and pore size re-arrangement more efficiently due to increased reactive surfaces that promote the formation of organo-mineral complexes and macroaggregates (Bach et al., 2010). Previous soil management practices can also have legacy effects on soil quality for several years (Keller et al., 2021; Or et al., 2021).

4.6.5. Rotation effects on soil hydraulic conductivity

At Lethbridge and Scott, the primary differences in UHC among crop rotations were observed in the 5–10 cm soil depth increment (Tables 4.4 and 4.6). The soil health-enhanced rotation exhibited greater large and medium UHC compared to the conventional or diversified rotations (Table 4.4). Similarly, at Scott, the soil health-enhanced and diversified rotations had the highest large UHC (Table 4.6). Furthermore, although not statistically significant at Swift Current, there were noticeable increasing trends in large and medium UHC under the pulse/oilseed intensified, high-risk and high-reward, and soil health-enhanced rotations. These crop rotations appear to promote water movement through large continuous pores. These pores are likely formed by diverse root systems as root channels which are predominantly vertical biopores in orientation, also displaying high connectivity (Bodner et al., 2014; Chen et al., 2021; Daly et al., 2023; Dexter et al., 2001; Talukder et al., 2023). Likewise, the inclusion of legumes in rotations was also reported to lead to significant increases in earthworm populations, which can also improve water transmission and availability by modifying the soil pore structure and conductivity (Ashworth et al., 2017; Pelosi et al., 2017). Additionally, the inclusion of both shallow- and tap-rooted crops in the pulse/oilseed intensified, diversified, and soil health-enhanced rotations may have resulted in the creation of connected, stable pores as roots grew and decayed, thereby increasing UHC (Fuentes et al., 2004; Mitchell et al., 1995; Zhang et al., 2018).

4.7. Conclusions

The impact of crop rotations on soil hydraulic and physical properties varied across the three sites after the 4-year experiment. While diversifying rotations did show certain improvements in soil physical quality, there was still underlying variability in site-specific and inherent soil conditions that may have prevented consistently-evident study-wide improvement. Nonetheless, pulse/oilseed intensified, diversified, and soil health-enhanced rotations led to noticeable trends such as decreased BD and increased EP. Overall, the S-index, which measures soil physical quality, indicated good soil quality under the soil health-enhanced rotation in the 5–10 cm depth increment and under pulse/oilseed intensified and diversified rotations in the 15–20 cm depth increment. Depending on the study site and soil layer, rotations also affected FC, PWP, PAWC, macroporosity and mesoporosity, as well as large and medium UHC. These findings suggest that crop rotations can have a positive impact on soil hydraulic and physical properties, even after a single 4-year cycle, but detection of more significant changes may require further cycles over longer time periods, e.g., 8 years (two full cycles) or 12 years (three full cycles). In conclusion, no single crop rotation improved all soil hydraulic and physical attributes across the three sites. The wide range in soil conditions in the study and the complex interactions between crop species, underlying soil properties, seasonal weather, and management practices contributed to the observed variations. Future studies should consider the potential long-term effects as well as the plant rooting patterns and architectures in relation to gradual developments in soil physical properties over time.

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Table 4.1. Description of crop sequences in rotations at Lethbridge, Alberta, and Swift Current and Scott, Saskatchewan.

Rotation	Site	Crop sequence
Conventional (control)	Lethbridge and Swift Current	Fallow−durum wheat−barley (*Hordeum vulgare* L.)−durum wheat
	Scott	Canola−spring wheat−pea (*Pisum sativum* L.)−spring wheat
Pulse/oilseed intensified	Lethbridge and Swift Current	Lentil (*Lens culinaris*)−durum wheat−chickpea (*Cicer arietinum*)−durum wheat
	Scott	Spring wheat−canola−spring wheat−canola
Diversified	Lethbridge and Swift Current	Lentil−canola−pea−durum wheat
	Scott	Pea−winter wheat−faba bean (*Vicia faba* L.)−canola
Market-driven	Lethbridge and Swift Current	Canola[Flax (*Linum usitatissimum*)][a]−spring wheat (*Triticum aestivum* L.)−spring wheat (lentil)[a]−barley
	Scott	Canola−canola−green pea−canola
High-risk and high-reward	Lethbridge and Swift Current	Soybean (*Glycine max [L.] Merr.*)−corn (*Zea mays* L.)[canary seed (*Phalaris canariensis* L.)][b]−faba bean−durum wheat
	Scott	Flax−soybean−durum wheat−canola
Soil health-enhanced	Lethbridge and Swift Current	Forage pea (*Pisum sativum* L. Var. *arvense*) (GM)[c]−barley/pea intercrop−faba bean/barley intercrop−durum wheat
	Scott	Forage pea (GM)−winter wheat−faba bean−canola

[a] Canola and spring wheat were grown at Lethbridge, while flax and lentil at Swift Current in the market-driven rotation

[b] Corn were grown at Lethbridge, while canary seed at Swift Current in the high-risk and high-reward rotation

[c] GM, green manure.

Table 4.2. Growing season precipitation (GSP) and 30-year average (1981−2010) precipitation from May 1 to August 31 at Lethbridge, Alberta, and Swift Current and Scott, Saskatchewan.

Study site and month	Growing season precipitation (mm)				
	2018	2019	2020	2021	30-year average
Lethbridge					
May	25	62	66	35	50
June	48	47	156	17	82
July	23	35	16	10	43
August	24	25	9	46	37
Total	120	169	247	108	212
GSP, % of normal	57	80	116	51	
Swift Current					
May	15	11	33	30	49
June	26	147	71	27	73
July	49	7	53	37	53
August	28	39	3	54	42
Total	118	204	160	148	217
GSP, % of normal	54	94	74	68	
Scott					
May	30	13	52	44	36
June	30	98	56	44	62
July	48	108	123	10	72
August	23	18	27	51	46
Total	131	237	258	149	216
GSP, % of normal	61	110	119	69	

Table 4.3. Selected baseline soil hydraulic and physical properties in the 5−10 and 15−20 cm soil depth increment prior to study establishment at Lethbridge, Alberta, and Swift Current and Scott, Saskatchewan, spring 2018.

Soil quality	Lethbridge	Swift Current	Scott	Lethbridge	Swift Current	Scott
SOC, g kg^{-1} (0−15 cm)	18.70	14.90	15.90			
		5−10 cm			**15−20 cm**	
BD[a], g cm^{-3}	1.21	1.22	1.41	1.35	1.35	1.36
TP, %	54.00	54.00	47.00	49.00	49.00	49.00
EP, %	50.75	57.56	42.66	46.20	42.90	43.49
FC, %	28.33	36.82	27.25	30.24	24.03	22.77
PWP, %	15.43	12.23	10.53	15.98	8.40	8.82
PAWC, %	12.90	24.60	16.72	14.26	15.63	14.56
S-index, unitless	0.023	0.032	0.027	0.021	0.033	0.032
Pore volume fraction (PVF)						
Macro, cm^3 cm^{-3}	0.099	0.029	0.028	0.058	0.002	0.083
Meso, cm^3 cm^{-3}	0.080	0.121	0.074	0.047	0.111	0.070
Micro, cm^3 cm^{-3}	0.068	0.078	0.083	0.065	0.082	0.086
Residual, cm^3 cm^{-3}	0.177	0.143	0.196	0.199	0.170	0.148
Unsaturated hydraulic conductivity (UHC)						
Large, cm d^{-1}	12.28	9.88	9.66	4.04	43.26	88.75
Medium, cm d^{-1}	0.306	0.749	0.193	0.015	2.603	0.545
Small, cm d^{-1}	0.001	0.0065	0.006	0.001	0.008	0.006
Root means square error (RMSE)						
RMSE θ, cm^3 cm^{-3}	0.015	0.022	0.015	0.019	0.010	0.014
RMSE K, cm d^{-1}	0.250	0.283	0.266	0.291	0.162	0.202

[a]BD, bulk density; TP, total porosity; EP, effective porosity (θ at 0 kPa); FC, field capacity at –33 kPa; PWP, permanent wilting point at –1500 kPa; PAWC, plant available water capacity; Macro, PVF diameters >60 μm; Meso, PVF diameters between 9 and 60 μm; Micro, PVF diameters between 6 and 9 μm; Residual, PVF diameters <6 μm; Large, UHC between –1 and –10 kPa; Medium, UHC between –10 and –20 kPa; Small, UHC between –20 and –33 kPa; RMSE for modeled θ and K. Hydraulic and physical properties were derived from raw data fitted to the van Guentchen model, while BD and TP were directly measured from dry weights.

Table 4.4. Effect of crop rotations on soil hydraulic and physical properties at Lethbridge, Alberta after harvest, fall 2021.

Soil depth and crop rotation	Physical property			Soil water retention characteristic				Pore volume fraction (PVF)				Unsaturated hydraulic conductivity (UHC)			Root mean square error (RMSE)	
	BD [a], g cm^{-3}	TP, %	EP, %	FC, %	PWP, %	PAWC, %	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}	RMSE θ, cm^3 cm^{-3}	RMSE K, cm d^{-1}
5−10 cm																
Conventional (control)	1.32	50.75	49.11	31.20 a	14.50 ab	16.71 a	0.026	0.037	0.095 ab	0.079 a	0.219 a	0.471 b	0.027 abc	0.001	0.01	0.38
Pulse/ oilseed intensified	1.34	50.00	47.33	29.07 ab	14.20 ab	14.87 ab	0.025	0.051	0.098 ab	0.071 b	0.199 ab	2.673 ab	0.037 abc	0.001	0.01	0.28
Diversified	1.27	52.50	50.47	29.19 ab	13.85 ab	15.34 ab	0.028	0.068	0.110 ab	0.076 ab	0.200 ab	0.780 b	0.021 c	0.001	0.01	0.44
Market-driven	1.34	50.00	47.52	29.30 ab	13.89 ab	15.41 ab	0.025	0.041	0.094 b	0.077 ab	0.203 ab	0.924 ab	0.025 bc	0.001	0.01	0.38
High-risk and high-reward	1.33	50.00	49.45	31.75 a	15.18 a	16.57 a	0.025	0.044	0.100 ab	0.078 a	0.219 a	2.771 ab	0.048 ab	0.001	0.01	0.29
Soil health-enhanced	1.24	53.75	51.12	27.80 b	13.50 b	14.30 b	0.027	0.084	0.116 a	0.073 ab	0.189 b	19.481 a	0.056 a	0.001	0.01	0.27
P-value	0.46	0.40	0.28	**0.026***	**0.063***	**0.051***	0.21	0.24	**0.089***	**0.027***	**0.026***	**0.040***	**0.012***	0.37		
15−20 cm																
Conventional (control)	1.38	47.75	47.53	32.25	14.72	17.52	0.026	0.023	0.081	0.0766	0.229	0.421	0.028	0.001	0.01	0.28
Pulse/oilseed intensified	1.37	48.25	47.83	30.76	14.35	16.41	0.026	0.033	0.101	0.0754	0.215	0.898	0.038	0.001	0.01	0.28
Diversified	1.37	48.25	47.67	30.81	13.18	17.64	0.028	0.026	0.097	0.0819	0.220	0.400	0.034	0.001	0.01	0.38
Market-driven	1.39	48.00	47.79	31.36	14.60	16.77	0.026	0.030	0.097	0.0779	0.219	0.260	0.025	0.001	0.01	0.35
High-risk and high-reward	1.32	50.50	50.95	32.58	15.10	17.48	0.028	0.034	0.096	0.0784	0.219	1.624	0.049	0.001	0.01	0.28
Soil health-enhanced	1.30	51.00	48.43	28.24	13.62	14.61	0.026	0.055	0.110	0.0714	0.192	2.474	0.058	0.001	0.01	0.36
P-value	0.77	0.68	0.47	0.27	0.38	0.45	0.63	0.54	0.36	0.23	0.36	0.36	0.44	0.15		

[a] BD, bulk density; TP, total porosity; EP, effective porosity (θ at 0 kPa); FC, field capacity at –33 kPa; PWP, permanent wilting point at –1500 kPa; PAWC, plant available water capacity; Macro, PVF diameters >60 µm; Meso, PVF diameters between 9 and 60 µm; Micro, PVF diameters between 6 and 9 µm; Residual, PVF diameters <6 µm; Large, UHC between –1 and –10 kPa; Medium, UHC between –10 and –20 kPa; Small, UHC between –20 and –33 kPa; RMSE for modeled θ and K. Physical and hydrologic properties were derived from raw data fitted to the van Guentchen model, while BD and TP were directly measured from dry weights. Means followed by the different letters within columns for each depth increment are significantly different from each other ($P < 0.10$).

Table 4.5. Effect of crop rotations on soil hydraulic and physical properties at Swift Current, Saskatchewan after harvest, fall 2021.

Soil depth and crop rotation	Physical property			Soil water retention characteristic				Pore volume fraction (PVF)				Unsaturated hydraulic conductivity (UHC)			Root means square error (RMSE)	
	BD [a], g cm^{-3}	TP, %	EP, %	FC, %	PWP, %	PAWC, %	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}	RMSE θ, cm^3 cm^{-3}	RMSE K, cm d^{-1}
5−10 cm																
Conventional (control)	1.39	47.75	42.78	25.52	8.19	17.33	0.033	0.023	0.108	0.093	0.180	10.24	0.586	0.006	0.01	0.27
Pulse/oilseed intensified	1.32	50.50	44.35	24.58	7.69	16.90	0.033	0.030	0.120	0.088	0.181	34.87	0.702	0.007	0.01	0.20
Diversified	1.36	49.50	44.92	25.60	8.15	17.45	0.034	0.030	0.121	0.095	0.180	29.58	0.615	0.005	0.01	0.29
Market-driven	1.38	48.25	43.46	25.68	8.21	17.47	0.033	0.027	0.118	0.094	0.183	23.55	0.742	0.005	0.01	0.24
High-risk and high-reward	1.38	48.25	43.86	26.03	7.92	18.10	0.034	0.023	0.112	0.095	0.185	7.16	0.528	0.005	0.01	0.28
Soil health-enhanced	1.32	50.50	45.15	25.08	8.10	16.98	0.035	0.030	0.126	0.095	0.171	39.19	0.778	0.005	0.01	0.27
P-value	0.45	0.36	0.37	0.77	0.83	0.76	0.95	0.66	0.73	0.92	0.83	0.53	0.29	0.56		
15−20 cm																
Conventional (control)	1.36	48.75	42.10 ab	26.03	8.25	17.78	0.030 bc	0.022	0.099	0.088 ab	0.191	14.06	0.524	0.006	0.01	0.22
Pulse/oilseed intensified	1.32	50.33	44.83 a	25.56	7.40	18.11	0.037 a	0.024	0.120	0.105 a	0.168	17.79	0.701	0.009	0.01	0.32
Diversified	1.33	49.75	43.66 a	26.43	7.83	18.60	0.035 abc	0.020	0.108	0.101 ab	0.184	16.76	1.019	0.010	0.01	0.25
Market-driven	1.33	50.00	43.24 ab	25.68	8.15	17.53	0.034 ab	0.022	0.110	0.098 ab	0.173	12.64	0.523	0.007	0.01	0.26
High-risk and high-reward	1.36	48.75	40.25 b	24.09	8.23	15.86	0.029 c	0.024	0.100	0.082 b	0.173	33.65	0.724	0.005	0.01	0.21
Soil health-enhanced	1.34	49.75	43.47 a	26.22	8.98	17.25	0.031 abc	0.026	0.110	0.089 ab	0.188	30.08	0.899	0.005	0.01	0.21
P-value	0.95	0.93	**0.018***	0.66	0.37	0.38	**0.014***	0.73	0.20	**0.042***	0.62	0.64	0.11	0.19		

[a] BD, bulk density; TP, total porosity; EP, effective porosity (θ at 0 kPa); FC, field capacity at –33 kPa; PWP, permanent wilting point at –1500 kPa; PAWC, plant available water capacity; Macro, PVF diameters >60 µm; Meso, PVF diameters between 9 and 60 µm; Micro, PVF diameters between 6 and 9 µm; Residual, PVF diameters <6 µm; Large, UHC between –1 and –10 kPa; Medium, UHC between –10 and –20 kPa; Small, UHC between –20 and –33 kPa; RMSE for modeled θ and K. Physical and hydrologic properties were derived from raw data fitted to the van Guentchen model, while BD and TP were directly measured from dry weights. Means followed by the different letters within columns for each depth increment are significantly different from each other ($P < 0.10$).

Table 4.6. Effect of crop rotations on soil hydraulic and physical properties at Scott, Saskatchewan after harvest, fall 2021.

Soil depth and crop rotation	Physical property			Soil water retention characteristic				Pore volume fraction				Unsaturated hydraulic conductivity			Root means square error	
	BD [a], g cm^{-3}	TP, %	EP, %	FC, %	PWP, %	PAWC, %	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}	RMSE θ, cm^3 cm^{-3}	RMSE K, cm d^{-1}
5−10 cm																
Conventional (control)	1.37	48.50	43.78	24.09 ab	7.50	16.60	0.032	0.035 ab	0.120	0.089	0.176	22.51 ab	0.549	0.006	0.01	0.24
Pulse/oilseed intensified	1.41	47.00	43.96	29.46 a	7.68	15.58	0.033	0.026 b	0.114	0.095	0.185	5.86 b	0.518	0.006	0.01	0.37
Diversified	1.33	49.75	44.80	22.93 b	7.39	15.55	0.033	0.050 a	0.136	0.081	0.170	40.79 a	0.482	0.005	0.01	0.17
Market-driven	1.41	47.00	44.28	24.82 ab	8.60	16.22	0.030	0.038 ab	0.118	0.085	0.180	22.79 ab	0.493	0.005	0.01	0.25
High-risk and high-reward	1.37	49.00	43.60	23.30 ab	7.51	15.79	0.031	0.041 ab	0.124	0.083	0.173	29.61 ab	0.593	0.006	0.01	0.23
Soil health-enhanced	1.33	50.00	44.82	23.80 ab	8.15	15.65	0.032	0.046 ab	0.130	0.082	0.173	43.58 a	0.583	0.006	0.01	0.19
P-value	0.10	0.13	0.78	**0.038***	0.19	0.97	0.49	**0.057***	0.17	0.11	0.52	**0.024***	0.66	0.58		
15−20 cm																
Conventional (control)	1.41	46.50	41.29	22.85 abc	6.55 ab	16.30 ab	0.033	0.023 ab	0.114	0.094	0.160 abc	8.13	0.534	0.004	0.01	0.26
Pulse/oilseed intensified	1.38	48.25	42.73	25.69 a	8.25 a	17.44 a	0.031	0.024 ab	0.107	0.091	0.189 a	5.80	0.422	0.004	0.01	0.17
Diversified	1.39	48.00	41.03	21.68 bc	6.23 b	15.46 ab	0.033	0.031 a	0.123	0.090	0.154 bc	29.40	0.967	0.005	0.01	0.25
Market-driven	1.35	49.25	41.38	21.00 c	6.40 ab	14.60 b	0.033	0.032 a	0.128	0.085	0.144 c	11.08	0.874	0.007	0.01	0.28
High-risk and high-reward	1.41	46.50	41.12	24.87 ab	7.58 ab	17.29 a	0.031	0.020 b	0.101	0.091	0.180 ab	8.25	0.532	0.005	0.01	0.22
Soil health-enhanced	1.33	50.00	42.55	23.88 abc	7.58 ab	16.31 ab	0.031	0.030 a	0.114	0.089	0.174 abc	18.07	0.665	0.004	0.01	0.22
P-value	0.17	0.18	0.75	**0.006***	**0.039***	**0.030***	0.75	**0.030***	0.13	0.64	**0.008***	0.85	0.15	0.84		

[a] BD, bulk density; TP, total porosity; EP, effective porosity (θ at 0 kPa); FC, field capacity at –33 kPa; PWP, permanent wilting point at –1500 kPa; PAWC, plant-available water capacity; Macro, PVF diameters >60 µm; Meso, PVF diameters between 9 and 60 µm; Micro, PVF diameters between 6 and 9 µm; Residual, PVF diameters <6 µm; Large, UHC between –1 and –10 kPa; Medium, UHC between –10 and –20 kPa; Small, UHC between –20 and –33 kPa; RMSE for modeled θ and K. Physical and hydrologic properties were derived from raw data fitted to the van Guentchen model, while bulk density and total porosity were directly measured from dry weights. Means followed by the different letters within columns for each depth increment are significantly different from each other ($P < 0.10$).

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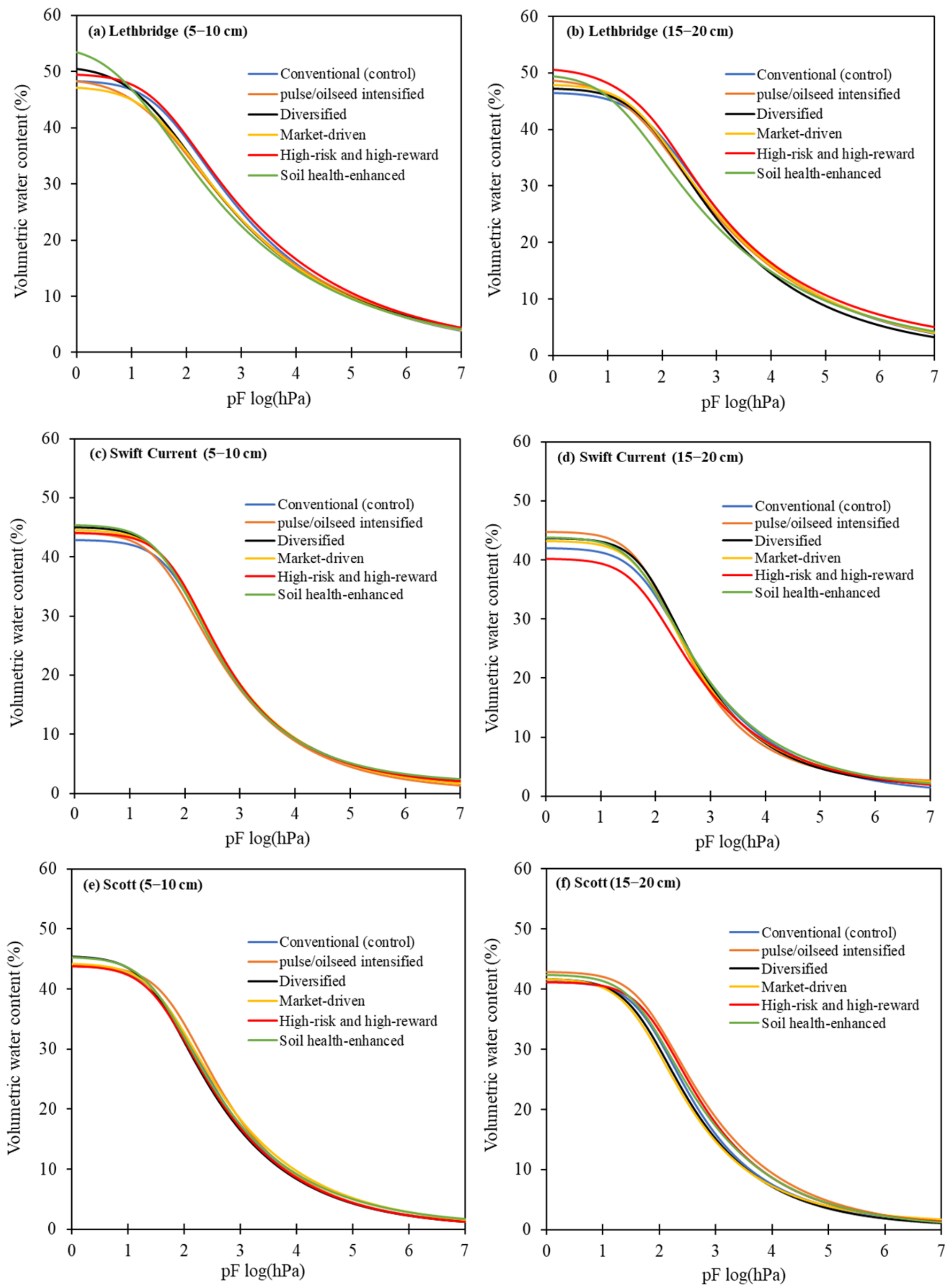

Figure 4.1. Soil water retention curves as influenced by crop rotations at Lethbridge, Alberta (a, b) and Swift Current (c, d) and Scott, Saskatchewan (e, f) for the 5−10 and 15−20 cm soil depth increments, fall 2021. Curves showed van Genuchten model on measured data for each crop rotation.

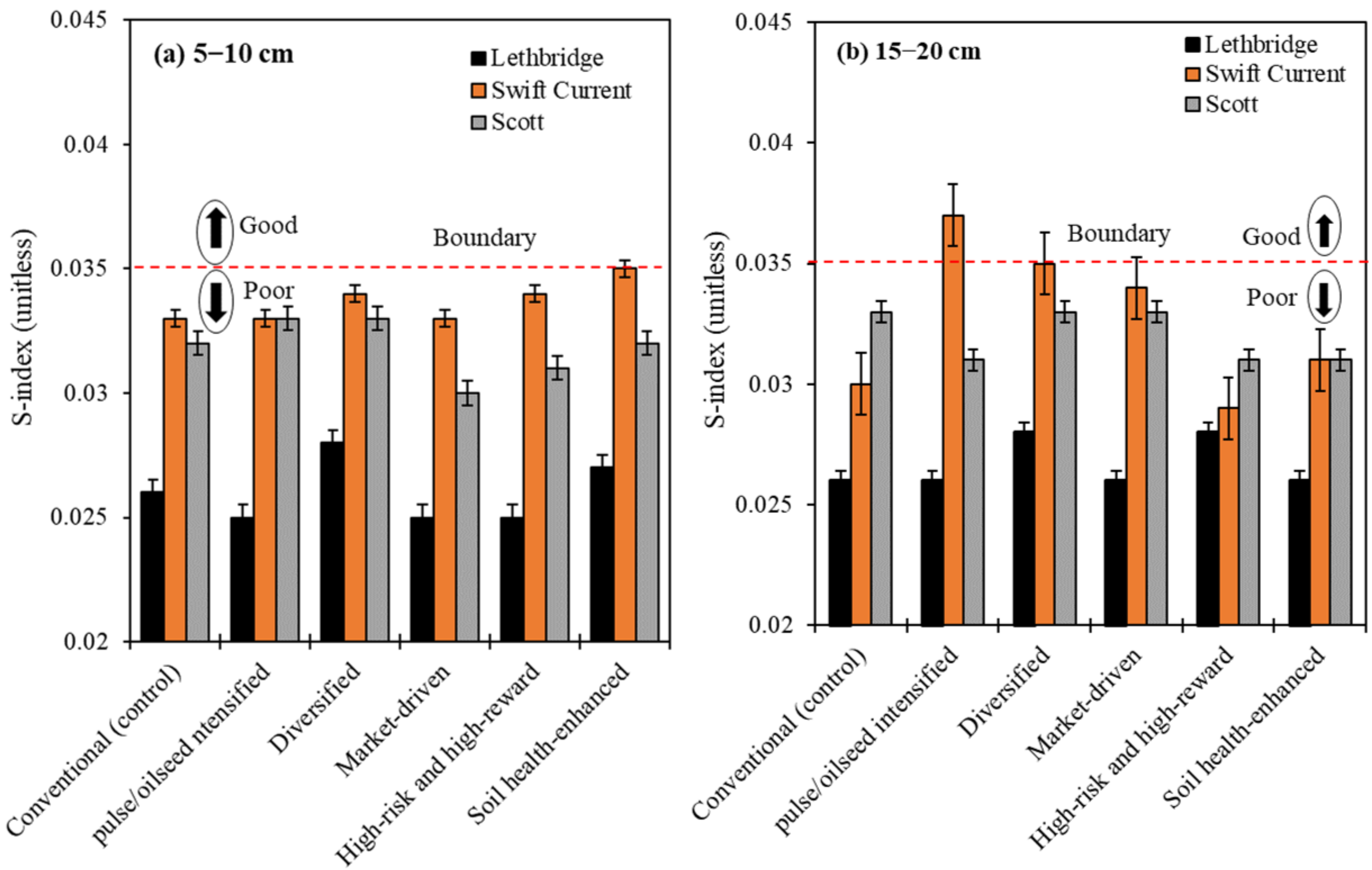

Figure 4.2. Soil physical quality as described by the S-index for (a) 5−10 and (b) 15−20 cm soil depth under different crop rotations at Lethbridge, Alberta and Swift Current and Scott, Saskatchewan, fall 2021. The boundary line (red broken horizontal line) indicates the threshold between good (S > 0.035) and poor (S < 0.035) soil physical quality according to Dexter (2004).

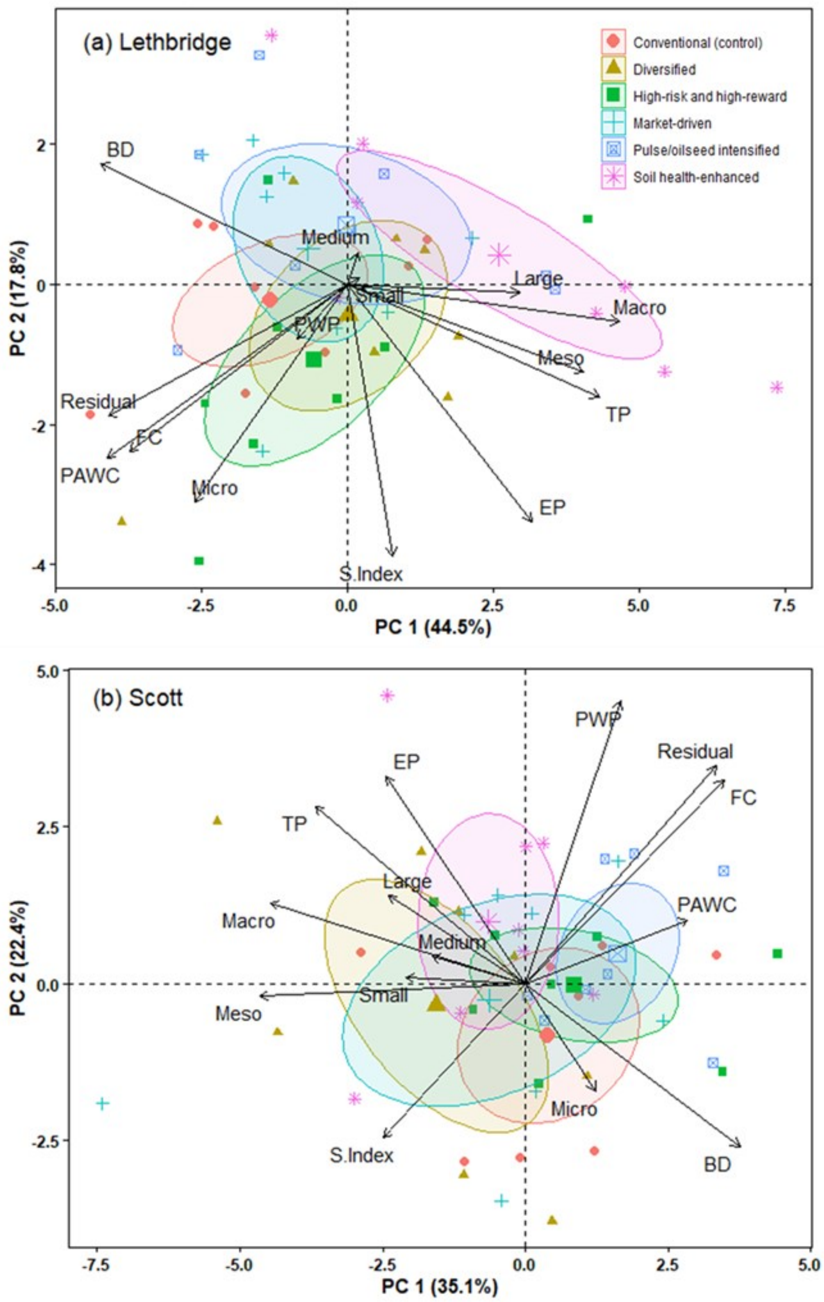

Figure 4.3. Principal component analysis (PCA) of measured soil hydraulic and physical properties across soil depths at (a) Lethbridge, Alberta and (b) Scott, Saskatchewan. The PCA differentiates the measured parameters based on crop rotations. BD, bulk density; TP, total porosity; EP, effective porosity; FC, field capacity; PWP, permanent wilting point; PAWC, plant-available water content capacity; Macro, pore volume diameters >60 µm; Meso, pore volume diameters between 9 and 60 µm; Micro, pore volume diameters between 6 and 9 µm; Residual, pore volume diameters <6 µm; Large, unsaturated hydraulic conductivity between –1 and –10 kPa; Medium, unsaturated hydraulic conductivity between –10 and –20 kPa; Small, unsaturated hydraulic conductivity between –20 and –33 kPa.

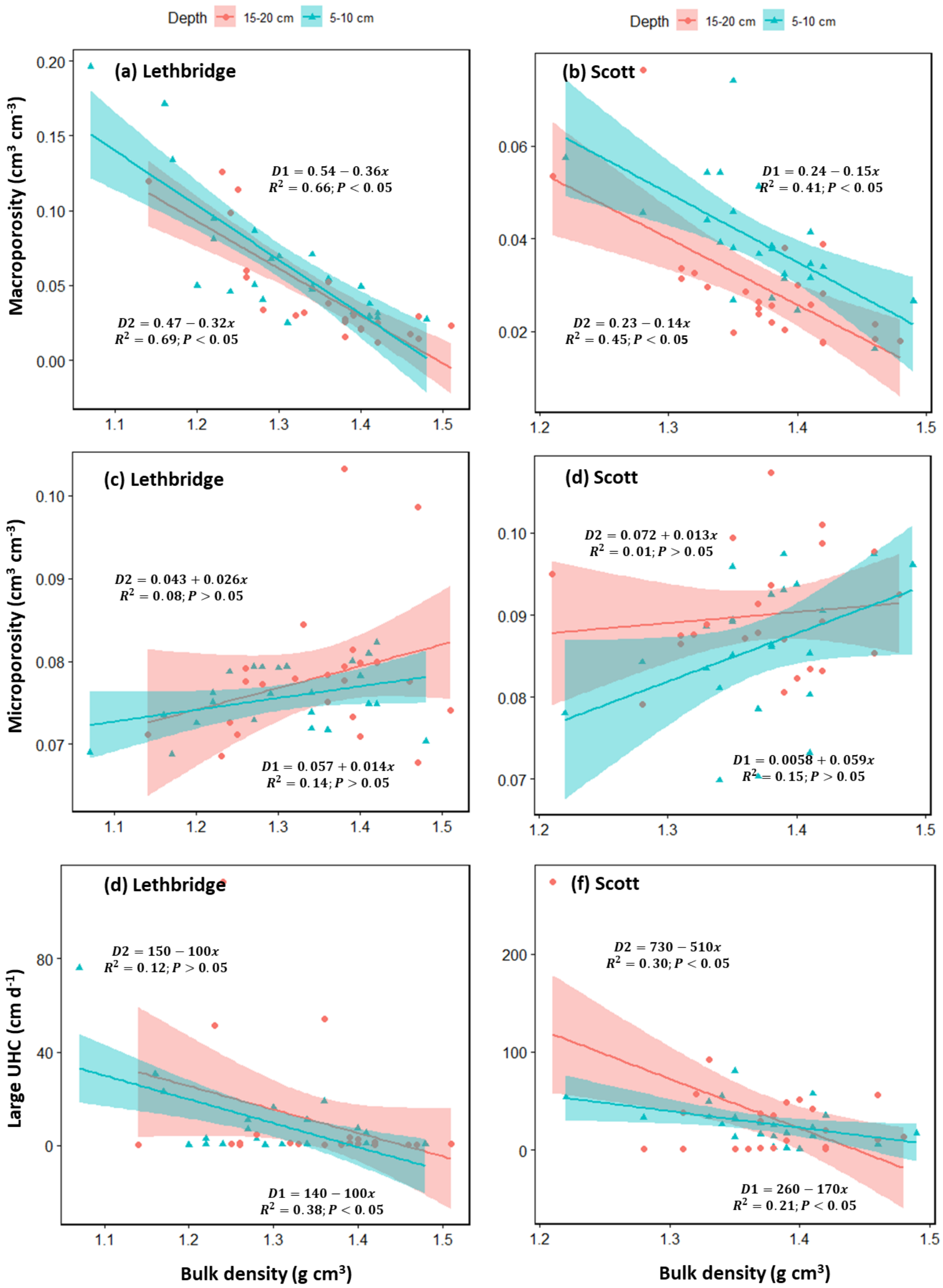

Figure 4.4. Linear regressions of macroporosity, microporosity, and large unsaturated hydraulic conductivity (UHC) across rotations measured in 5–10 (D1) and 15–20 (D2) cm soil depth increment as a function of bulk density at Lethbridge, Alberta (a, c, d) and Scott, Saskatchewan (b, d, f). The shaded area around the fitted lines shows a 95% confidence band of prediction. While macroporosity and large UHC showed statistically significant relationships with bulk density, microporosity was not significantly related.

5. Quantitative Evaluation of Soil Health Based on a Minimum Dataset Under Various Short-term Crop Rotations on the Canada Prairies

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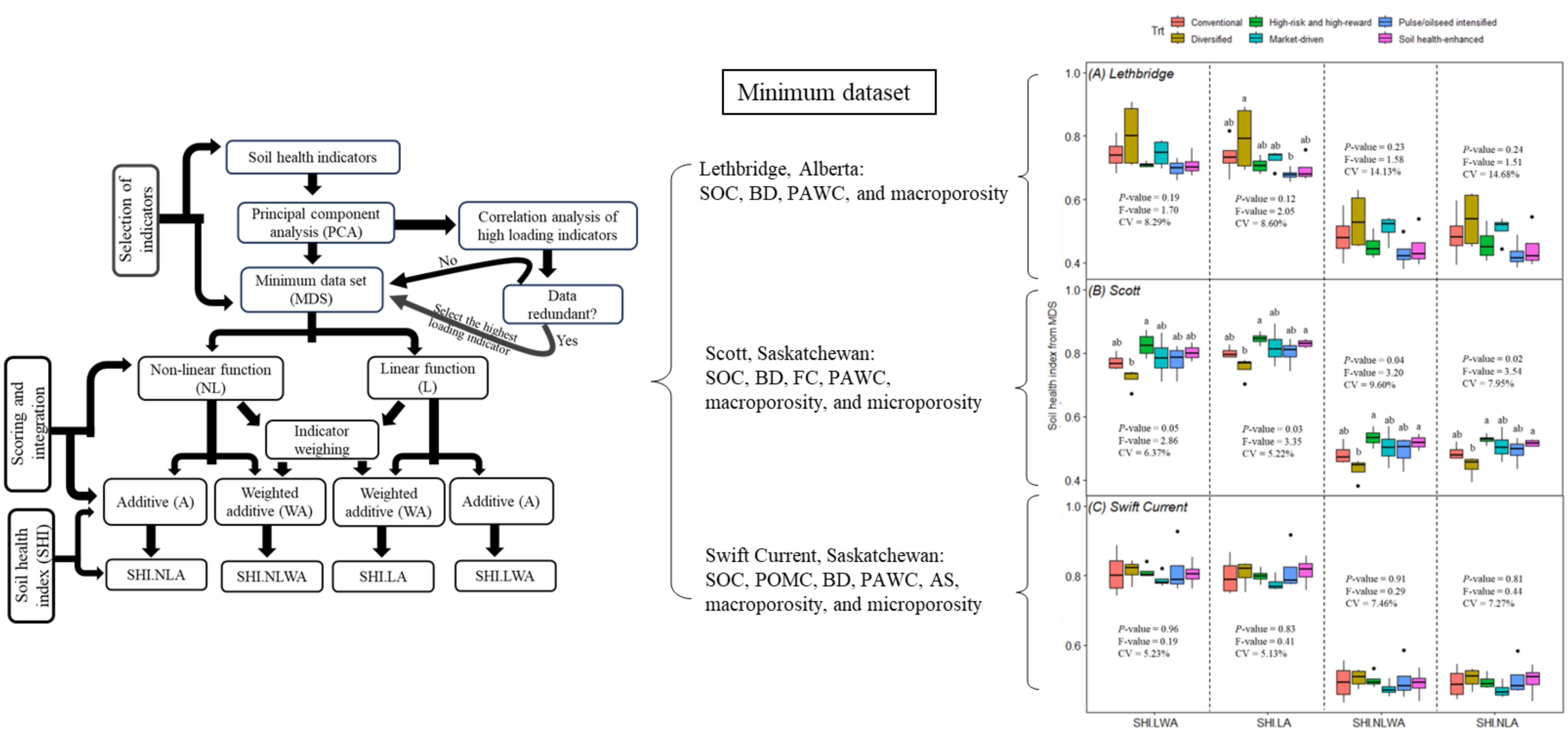
5.1. Highlights

- The number of indicators in the minimum dataset varied across sites.
- Common indicators across sites included SOC, BD, macroporosity, and PAWC.
- Non-linear weighted additive indexing is the most sensitive and effective method.
- Crop rotation impact on soil health (SH) depends on the site.
- Diversified rotation and high-risk and -reward rotation had the greatest SH index.

5.2. Graphic Abstract



5.3. Synopsis

Maintaining and improving soil health (SH) is essential for the long-term sustainability and productivity of agriculture, notably in the face of climate change. This study addressed the challenge of selecting appropriate soil indicators, scoring method, and indexing approaches for evaluation of SH under no-till crop rotations. This study aimed to develop minimum datasets (MDS) and assess SH in six crop rotations (conventional, diversified, high-risk and high-reward, market-driven, pulse-oilseed intensified, and soil health-enhanced rotations) at three experimental sites on the Canadian prairies. Fourteen soil indicators in the total dataset (TDS) were examined, encompassing both chemical (0−7.5 cm depth) and physical (5−10 cm depth) properties. Principal component analysis (PCA) identified MDSs from the TDS. Two scoring [linear (L) and non-linear (NL)] and two SH indexing approaches [additive (A) and weighted additive (WA)] were used to calculate the SH index (SHI). One-way ANOVA evaluated the SHI among crop rotations. The PCA revealed variations in the number of indicators in the MDS across sites, with soil organic carbon, bulk density, macroporosity, and plant-available water capacity as the common indicators for MDS across sites. Additionally, other indicators such as particulate organic matter carbon, aggregate stability, field capacity, and microporosity were also found to be important, depending on the site. The non-linear scoring weighted additive SH indexing (SHI.NLWA) method proved to be the most sensitive and effective for differentiating among crop rotations in the short-term across study sites. Overall, the diversified rotation at Lethbridge and Swift Current, along with the high-risk and high-reward rotation at Scott, exhibited the highest SHI compared to other rotations. Monitoring SHI over time and selecting crop rotations that improve SH can collectively enhance soil functions and agroecosystem productivity.

Keywords: Diverse crop rotations; Minimum dataset; Soil health index; Soil function; soil properties

5.4. Introduction

Soil health (SH) is crucial for long-term sustainable agriculture and environmental quality (Doran and Parkin, 1994; Nakajima et al., 2016, 2015). However, agricultural practices such as intensive cropping and inadequate soil management can lead to a significant decline in SH. Thus, it is essential to adopt sustainable soil management practices, and develop and implement criteria for evaluating SH (Amgain et al., 2022). Soil health refers to the ability of the soil to support crop production and maintain ecosystem services in both natural and managed agroecosystems (Andrew et al., 2002; Karlen et al., 1997; Lehmann et al., 2020). To develop sustainable agriculture systems that improve SH, understanding and evaluating cropping systems' influence on overall SH is crucial, as this may aid early detection of problems and provide warning signals of negative trends (Amgain et al., 2022; Bi et al., 2013; Doran and Zeiss, 2000; Nakajima et al., 2015). However, the selection, interpretation, and integration of soil indicators into a SH index (SHI) requires a reliable and accurate approach.

The Soil Management Assessment Framework (SMAF) is an important management tool for evaluating land use management and sustainability, comprising three essential steps: indicator selection, interpretation (indicator scoring), and integration into SHI (Andrews et al., 2004). The SMAF has been widely employed to identify sensitive soil indicators and develop SHI for assessing different land use management influences on SH (Amgain et al., 2022; Andrews et al., 2002; Andrews and Carroll, 2001; Jiang et al., 2020; Mesfin et al., 2023; Yu et al., 2018), including studies on crop rotation effects (Andrews et al. 2004; Karlen et al. 2006), different planting patterns and soil classification (Bi et al., 2013), and soil and irrigation types (Lu et al. 2024). The development of SHI may be based on soil intrinsic properties, proposed land use, and management goals (Andrews et al., 2004). Soil health assessment typically considers soil physical, chemical, and biological properties (Fine et al., 2017; Gauthier et al., 2023), with various soil indicators utilized in previous studies for comparing agronomic practices related to soil productivity (Aziz et al., 2013; Karlen et al., 2006). However, establishing a robust set of soil indicators remains challenging.

In the first step of SMAF, soil indicators may be selected based on expert opinion (Andrews et al., 2002; Nosrati and Collins, 2019; Sánchez-Navarro et al., 2015; Vasu et al., 2016), statistical methods (Lima et al. 2008; Vasu et al., 2016; Zuber et al., 2017), or a combination of strategies (Bi et al., 2013; Lenka et al., 2022; Lima et al., 2008), leading to the creation of a minimum dataset (MDS) from the total dataset (TDS). The second step involves interpreting the selected MDS through scoring (or transformation) using a linear or non-linear function (Andrews and Carroll, 2001; Masto et al., 2008). Scoring methods are developed based on the relationship between soil indicators and relevant soil functions, and indicator scores are adjusted for environmental conditions, land management, and soil properties (Andrews et al., 2004). The linear scoring approach is a simple method not requiring indicator thresholds to determine the variance of indicators (Masto et al., 2008; Raiesi, 2017; Yu et al., 2018). On the other hand, the non-linear scoring method requires the understanding of soil function and considers thresholds and base values from previous studies or specific regions (Guo et al., 2017; Yu et al., 2018). The third step integrates soil indicator scores into an overall SHI by summing the soil indicators to create a single SH score (Andrews et al., 2004).

Several soil indicators have been identified for SH assessment using the three step approach stated in SMAF (Amgain et al., 2022; Lu et al., 2024; Yu et al., 2018); however, the influence of management on soil indicators is site- or system-specific (i.e., cropping system, soil texture and soil classification) and cannot be generalized due to variability and complexity in inherent soil properties, proposed land use, environmental conditions, and management goals (Andrews et al., 2004; Lima et al., 2008). Therefore, selecting suitable soil indicators for a MDS to evaluate SH should consider soil functions and management goals (Andrews et al., 2004; Karlen et al., 1997; Lima et al., 2008), which are both site- and soil-specific. Our study objectives were to (i) determine a MDS for evaluating SH under various no-till (NT) crop rotations, (ii) develop a site-specific SH diagnosis model for determining the SH status under different crop rotations and (iii) quantify the current SH by comparing selected soil indicator values among the different crop rotations at three sites on the Canadian prairies. Therefore, we hypothesized that increased diversity in crop rotations (e.g., diversified, high-risk and high-reward, and soil health-enhanced rotations) would have greater SHI score (i.e., better SH and soil health promoting management) compared to conventional cereal-based and less diverse crop rotations (e.g., conventional, pulse/oilseed intensified, and market-driven rotations). By identifying the crop rotation that best enhances SH in the short-term, growers will have the opportunity to strategically plan their management accordingly. Also, it will provide a scientific SH monitoring system to ensure, improve, or maintain quality grain production, soil, and environmental quality.

5.5. Materials and Methods

5.5.1. Site description and experimental treatments

The three sites in this study were part of the seven research sites across three Canadian prairie provinces to evaluate the impact of diverse crop rotations on crop yield and whole-farm economics, system resilience, soil health, and environmental footprint. For this present study, the site description, experimental design, and field management for the three sites are detailed in Iheshiulo et al. (2024a, 2024b), hence, only a brief description is presented here. The soils were clay-textured (Dark Brown Chernozem; 220 g sand kg^{-1}; 260 g silt kg^{-1}; and 520 g clay kg^{-1}) at Lethbridge, Alberta (49º 41'N, 112º 46'W) and loam-textured at Scott (Dark Brown Chernozem; 370 g sand kg^{-1}, 400 g silt kg^{-1}, 230 g clay kg^{-1}; 52º 21' N, 108º 50' W), and Swift Current (Brown Chernozem; 290 g sand kg^{-1}, 450 g silt kg^{-1}, 260 g clay kg^{-1}; 50º 17' N, 107º 47' W), Saskatchewan, based on samples collected from the top 0-15 cm depth prior to study establishment in spring of 2018.

Six crop rotations, arranged in a randomized complete block design with four replications, were implemented at each site. The rotations maintained consistent treatment types across the three sites, adapting their crops to local conditions. The rotations were as follows:

(i) Conventional (control): fallow–durum wheat (*Triticum turgidum* L. var. durum)–barley (*Hordeum vulgare* L.)–durum wheat at Lethbridge and Swift Current; and canola (*Brassica napus* L.)–spring wheat (*Triticum astivum* L.)–pea (*Pisum sativum* L.)–spring wheat at Scott.

(ii) Pulse/oilseed intensified: lentil (*Lens culinaris*)–durum wheat–chickpea (*Cicer arietinum*)–durum wheat at Lethbridge and Swift Current; and spring wheat–canola–spring wheat–canola at Scott.

(iii) Diversified: lentil–canola–pea–durum wheat at Lethbridge and Swift Current; and pea–winter wheat–faba bean (*Vicia faba* L.)–canola at Scott.

(iv) Market-driven: canola [flax (*Linum usitatissimum*) at Swift Current]–spring wheat–spring wheat (lentil at Swift Current)–barley at Lethbridge and Swift Current; and canola–canola–green pea–canola at Scott.

(v) High-risk and high- reward: soybean (*Glycine max* [L.] Merr.)–corn (*Zea mays* L.) [canary seed (*Phalaris canariensis* L.)]–faba bean–durum wheat at Lethbridge and Swift Current; and flax–canola–durum wheat–canola at Scott.

(vi) Soil health-enhanced: forage pea (as green manure; *Pisum sativum* L. Var. arvense)–barley/pea intercrop–faba bean/barley intercrop–durum wheat at Lethbridge and Swift Current; and forage pea (as green manure)–winter wheat–faba bean–canola at Scott.

All the rotations were 4-year, except for the 2-year pulse/oilseed intensified rotation at Scott. Further details on these rotations can be found in Iheshiulo et al. (2024b, 2024a).

5.5.2. Soil sampling and analysis

In fall 2021 (4 years after establishment), composite soil samples were collected from each of the three sites. Comprehensive descriptions of the soil/core sampling and laboratory analysis can be found in Iheshiulo et al. (2024b, 2024a). Specifically, soil chemical properties [total carbon (TC), soil organic carbon (SOC), and total nitrogen (TN)] were determined from 0−7.5 cm soil depth by dry combustion method, as described in Iheshiulo et al. (2024a). Also, soil organic matter fractions [particulate organic matter carbon (POMC) and nitrogen (POMN)] were determined through the particle-size fractionation method as reported in Iheshiulo et al. (2024a). Soil physical properties, including bulk density (BD), total porosity (TP), field capacity (FC), plant available water capacity (PAWC), macroporosity, mesoporosity, and microporosity, were assessed by a simple evaporation method (Schindler et al., 2010) using undisturbed soil cores collected from 5–10 cm depth, following the procedures described in Iheshiulo et al. (2024b) and Daly et al. (2023). Aggregate stability (AS) was determined by a modified wet-sieving method (Kemper and Rosenau, 1986), with 4 g of 1−4 mm air-dried soil aggregates, collected from the 0−7.5 cm depth

5.5.3. Soil health index assessment

This present study employed the SMAF developed by Andrews et al., (2004) to calculate SHI. The process involved three key steps: (i) selecting an MDS, (ii) interpreting the MDS indicators through scoring, and (iii) integrating the scored MDS indicators into an overarching SHI (Fig. 5.1).

5.5.3.1. Selection of MDS indicators

Fourteen soil indicators in the TDS were considered for the development of the SHI (Table 5.1). Recognizing the impracticality of regularly assessing these indicators, the MDSs were therefore selected to serve as representative proxies. To select the MDS for each site, principal component analysis (PCA) was performed separately for each site and on the combined dataset (Andrews et al. 2002; Bi et al. 2013; Doran and Parkin, 1994; Lima et al. 2013). Principal components (PCs) with eigenvalues ≥1.0 and high factor loadings were chosen as best representations of the system attributes (Askari and Holden, 2014; Armenise et al., 2013; Yu et al., 2018). Within each PC, only highly weighted indicators within 10% of the highest weighted indicator were retained for the MDS (Amgain et al., 2022; Andrews and Carroll, 2001; Yu et al., 2018). Following the determination of highly weighted loading indicators, correlation analysis was performed to identify redundancy (Fig. 5.1), with indicators showing a correlation coefficient of ≥0.70 considered redundant and subsequently eliminated from the dataset. Conversely, highly weighted uncorrelated indicators were retained in the MDS (Andrews et al., 2002, 2004,; Andrews and Carroll, 2001). Weights for MDS and TDS indicators were assigned according to PCA results' variance and communality. The MDS indicators were weighted based on the explained variance of each PC. Weighted values were calculated as the ratio of the variation of each PC to the cumulative variation of PCs. While the TDS weighted values were determined by the ratio of each indicator's communality to the total communalities. These weighted values for MDS and TDS were employed in the development of the SHI.

5.5.3.2. Transformation of soil indicators

Measured values for indicators in both TDS and MDS were transformed into unitless scores within the range of 0 and 1, utilizing both linear (L) and non-linear (NL) scoring methods, as depicted in Fig. 5.1 (Amgain et al., 2022; Andrews et al., 2004, 2002; Yu et al., 2018). In this study, two linear scoring methods were applied: the "more is better" and "less is better" approaches (Andrews et al., 2004; Jiang et al., 2020; Lu et al., 2024; Mesfin et al., 2023). The "more is better" scoring was employed when higher levels of indicators corresponded to improved SH. Conversely, the "less is better" scoring was applied to indicators where an increase had a negative impact on SH (Andrews et al., 2004; Jiang et al., 2020; Mesfin et al., 2023). The linear scoring methods, "more is better" (Eq. (5.1)) and "less is better" (Eq. (5.2)) were utilized as follows:

$$S_L = \left(X_i / X_{i,max.}\right) \quad (5.1)$$

$$S_L = \left(X_{i,min.} / X_i\right) \quad (5.2)$$

where S_L is the linear score for the i^{th} indicator between 0 and 1; X_i is the measured value of the i^{th} indicator; $X_{i,min.}$ and $X_{i,max.}$ is the minimum and maximum value of the i^{th} indicator (Askari and Holden, 2014; Lu et al., 2024; Yu et al., 2018). Furthermore, the non-linear scoring involved the application of the sigmoidal function (Eq. (5.3)) to standardize and score each indicator in the TDS and MDS (Amgain et al., 2022; Lu et al., 2024; Yu et al., 2018).

$$S_{NL} = \frac{1}{1 + (X/X_m)^b} \quad (5.3)$$

where S_{NL} is the non-linear score for the i^{th} indicator between 0 an 1, X is the measured i^{th} indicator value, X_m is the mean value of the i^{th} indicator, and b is the slope of the equation, sets as −2.5 for "more is better" and +2.5 for "less is better" (Amgain et al., 2022; Andrews et al., 2002; Askari and Holden, 2014; Lu et al., 2024; Yu et al., 2018).

5.5.3.3. Integration of indicators into SHI

All transformed scores for indicators in the TDS and MDS were amalgamated to generate a comparative SHI, using both the additive (A) (Eq. (5.4)) and weighted additive (WA) (Eq. (5.5)) methods as illustrated in Fig. 5.1 (Amgain et al., 2022; Lu et al., 2024; Yu et al., 2018).

$$SHI_A = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{S_i} / n \qquad (5.4)$$

$$SHI_{WA} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{W_i} \times \mathrm{S_I} \qquad (5.5)$$

where SHI_A and SHI_{WA} are the additive and weighted additive soil health indices, respectively; S_i is the linear or non-linear indicator score, n is the number of indicators in the MDS; and W_i is the weighting value of the indicators, determined by the variation of each respective PC.

Scoring functions for TC, SOC, POMC, AS, PAWC, macroporosity, and mesoporosity employed the "more is better" approach, based on their role in water partitioning, structural ability, soil fertility, nutrient availability, microbial activity, and plant productivity (Andrews et al., 2004). For instance, increased macroporosity and mesoporosity promoted enhanced water infiltration rates and water storage capacity, facilitating improved plant growth and increased crop productivity. On the other hand, BD and microporosity utilize the "less is better" curves as increased BD can impede root growth and soil porosity, negatively impacting SH.

5.5.4. Statistical analysis

All datasets were analyzed using RStudio software (ver. 4.2.3) (R Core Team, 2023). Principal component analysis was performed for each site separately, and for the combined dataset of all three sites using the "*FactoMineR*" package (ver. 2.8) (Lê et al. 2008) to select the MDS. To assess redundancy among highly weighted indicators, correlation analyses were performed using the "*heatmaply*" package (ver. 1.4.2). All standardized datasets were tested for normality and homogeneity of variance using the Shapiro-Wilk and Levene test, respectively. Quantitative analysis of the differences in SHI influenced by various crop rotations was carried out through a one-way ANOVA separately for each site and the combined dataset. The linear mixed-effect model in the "*nlme*" package (Pinheiro et al. 2013) was applied, treating crop rotation as a fixed effect and replicates as a random effect. Significance was set at $\alpha = 0.10$, and pairwise comparisons were executed using Tukey's HSD post-hoc test with the "*Agricolae*" package (ver. 1.3-5) (de Mendiburu, 2021). An alpha critical level of 0.10 was chosen, following the recommendation of Pennock (2004) for conservation-related research.

5.6. Results

5.6.1. Descriptive statistics of soil health indicators

Fourteen soil indicators within the TDS encompassing both chemical and physical properties (Table 5.1) were considered as potential indicators associated with different crop rotations' influence on SH. Across the sites, TC ranged from 26.0 to 31.1 g kg^{-1}, SOC from 23.1 to 30.5 g kg^{-1}, and TN varied between 2.25 and 2.78 g kg^{-1}. The AS ranged from 52 to 83%, BD varied between 1.07 and 1.48 g cm^{-3}, and TP fluctuated between 45 and 60% (Table 5.1). The skewness of the majority of the measured soil indicators fell within the range of −0.5 and +0.5, indicating a moderately symmetrical distribution. At Lethbridge and Scott, TN, POMC, POMN, AS, BD, and PAWC were negatively skewed, but not TC, SOC, and mesoporosity (Table 5.1). At Swift Current, most of the indicators showed negative skewness (Table 5.1). Further details on the descriptive statistics of the indicators can be found in Table 5.1.

5.6.2. Total and minimum datasets

5.6.2.1. Lethbridge, Alberta

The PCA results at Lethbridge indicated that the first three PCs collectively explained 77.6% of the total variance in the TDS, with eigenvalues ≥1.0 (Table 5.2). PC1, accounting for 36.0% of the variance, exhibited highly weighted indicators such as TC, SOC, and TN. These high-loading indicators were well-correlated ($r \geq 0.92$; $P < 0.001$; Fig. 5.2a). Hence, the choice to retain or eliminate high-loading indicators was based on practicality (Andrews et al., 2002). Consequently, only SOC, with the highest loading value, was retained for MDS. PC2 accounted for 22.4% of the variance and had BD, TP, and PAWC as the high-loading indicators. However, BD and TP were highly correlated ($r = -0.99$; $P < 0.001$), while their correlation with PAWC was not strong ($r \leq 0.57$; Fig. 5.2a). Thus, BD and PAWC were chosen for MDS under PC2, with BD preferred over TP due to its ease of measurement and its ability to serve as a proxy for TP. PC3, explaining 19.1% of the variance, had macroporosity as the sole highly weighted indicator. Consequently, macroporosity was retained for MDS under PC3 (Table 5.2). In summary, the MDS comprising SOC, BD, PAWC, and macroporosity, was utilized to calculate the SHI at Lethbridge.

5.6.2.2. Scott, Saskatchewan

The first four PCs accounted for 80.9 % of the total variance in the TDS at Scott (Table 5.3). PC1 accounting for 32.1% of the variance, had highly weighted indicators particularly TC, SOC, and TN. Given their significant correlations ($r \geq 0.84$, $P < 0.001$; Fig. 5.2b), only SOC with the highest loading value, was retained for MDS. PC2 explained 21.8% of the variance, with BD, TP, FC, and microporosity within 10% of the highest loading indicator. Although BD and TP were strongly correlated with each other as anticipated ($r = -0.99$; $P < 0.001$), neither was correlated with FC ($r = 0.30$) or microporosity ($r = -0.42$). Hence, BD, FC, and microporosity were retained for MDS under PC2 (Table 5.3). Additionally, PC3 and PC4 accounted for 16.7 and 9.9% of the total variance, respectively. Macroporosity and mesoporosity were the two high-loading indicators in PC3 and were highly correlated ($r = 0.82$; $P < 0.001$; Fig. 5.2b). Consequently, only macroporosity with the highest loading value, was retained for MDS under PC3. Meanwhile, PAWC was retained under PC4 as the only high-loading indicator for MDS (Table 5.3). In summary, the MDS used for computing the SHI at Scott included SOC, BD, FC, PAWC, macroporosity, and microporosity.

5.6.2.3. Swift Current, Saskatchewan

Five PCs collectively accounted for 85.1% of the total variance at Swift Current (Table 5.4). PC1 accounted for 28.6% of the variance and had five high-loading indicators: TC, SOC, TN, POMC, BD, and TP, within 10% of the highest loading indicator. Among these indicators, TC, SOC, and TN were highly correlated ($r \geq 0.83$; $P < 0.001$) but were not well-correlated with POMC ($r \leq 0.40$), BD ($r \leq 0.26$), or TP ($r \leq -0.24$). Additionally, BD and TP were strongly correlated (r = −0.99). Considering these significant correlations (Fig. 5.2c), SOC, POMC, and BD were retained for MDS under PC1. Furthermore, PAWC under PC2, macroporosity under PC3, microporosity under PC4, and AS under PC5 were retained as high-loading indicators for MDS (Table 5.4). Therefore, the selected MDS indicators for calculating the SHI at Swift Current included SOC, POMC, BD, PAWC, AS, macroporosity, and microporosity.

5.6.2.4. Combined dataset

In the combined dataset, the first four PCs explained 89.6% of the total variance (Supplementary Table S5.1). PC1 accounted for 55.4% of the variance and had six highly weighted indicators: TC, SOC, TN, POMC, POMN, and AS. These indicators were significantly and well-correlated with each other ($r \geq 0.78$; $P < 0.001$), except for the correlation between TC and AS ($r = 0.69$; Fig. 5.2d). Thus, TC and AS were selected for MDS under PC1. PC2 explained 15.3% of the variance and had two highly weighted indicators: BD and TP. However, due to the significant correlation between BD and TP ($r = -0.99$; $P < 0.001$; Fig. 5.2d), only BD was chosen for the MDS for PC2. Mesoporosity was the only high-loading indicator under PC3 and was retained for MDS. Moreover, under PC4 (explaining 8.9% of the variance), PAWC and macroporosity were the two highly weighted indicators. Since these indicators were not well-correlated ($r = -0.18$), both were retained for MDS (Supplementary Table S5.1). In summary, TC, AS, BD, PAWC, macroporosity, and mesoporosity were chosen as the MDS for calculating the SHI for the combined dataset.

5.6.3. Calculation of soil health index

Soil indicators in both the MDS and TDS were scored or transformed using linear and non-linear scoring functions. The weights of each indicator in the MDS and TDS at each site, including for the combined dataset, along with the parameters used in the linear and non-linear scoring functions, are outlined in Table 5.5 and Supplementary Table S5.1. In the MDS, soil indicator weights varied from 0.25 to 0.46 at Lethbridge, 0.11 to 0.40 at Scott, 0.09 to 0.36 at Swift Current, and 0.10 to 0.62 for the combined dataset. SOC at Lethbridge and Scott, PAWC at Swift Current, and TOC and BD for the combined dataset had the highest weightings, contributing highest towards the SHI. In the TDS, indicator weights ranged from 0.052 to 0.105 at Lethbridge, 0.06 to 0.112 at Scott, 0.044 to 0.130 at Swift Current, and 0.03 to 0.139 for the combined dataset (Table 5.5; Supplementary Table S5.1). PAWC at Lethbridge, macroporosity at Scott, and microporosity at Swift Current, had the highest weighting, contributing the most towards the SHI (Table 5.5).

5.6.4. Linear and non-linear scoring functions

Compared to non-linear SHIs across datasets in both the MDS and TDS, the linear scoring function had higher SHI values in both additive and weighted additive approaches. However, the F and coefficient of variation (CV) values of the non-linear SHI were higher than those of the linear SHI in most cases (Figs. 5.3 and 5.4; Supplementary Fig. S5.1), indicating a greater sensitivity to crop rotations. Also, in most cases, for both linear and non-linear scoring methods, the SHI values of the weighted additive approach were greater than those of the additive SHI approach (Fig. 5.3). Across sites, Pearson correlation analysis revealed significant correlations among SHIs with each other ($P < 0.001$; $r \geq 0.75$; Supplementary Table S5.2). The average correlation coefficients of SHIs for the weighted additive approach, for both linear and non-linear methods in both the MDS and TDS, were higher than those of the additive approach. Additionally, the non-linear additive and weighted additive approaches in both the MDS and TDS had a higher correlation sum compared to the linear additive and weighted additive approaches (Supplementary Table S5.2; Supplementary Fig. S5.2).

5.6.5. Soil health indexing method

After transforming and weighting, eight SHIs were developed, comprising four for the MDS and four for the TDS at each site (Figs. 5.3 and 5.4; Supplementary Fig. S5.1). Across crop rotations and sites, including for the combined dataset, the SHI values ranged from 0.66 to 0.83 for the linear weighted additive SHI (SHI.LWA), 0.64 to 0.84 for the linear additive SHI (SHI.LA), 0.43 to 0.53 for the non-linear weighted additive SHI (SHI.NLWA), and 0.43 to 0.54 for the non-linear additive SHI (SHI.NLA) for the MDS. For the TDS, the SHI values ranged from 0.69 to 0.86 for SHI.LWA, 0.70 to 0.86 for SHI.LA, 0.46 to 0.53 for SHI.NLWA, and 0.47 to 0.52 for SHI.NLA (Figs. 5.3 and 5.4; Supplementary Fig. S5.1). In the MDS, at Lethbridge, the linear additive method was able to capture significant differences among crop rotations (Fig. 5.3A), whereas at Scott, significant differences were captured in both linear and non-linear additive as well as weighted additive methods (Fig. 5.3B). However, no significant differences were observed at Swift Current (Fig. 5.3C) and for the combined dataset (Supplementary Fig. S5.1B). In the TDS, the linear additive and weighted additive approaches captured significant differences at Lethbridge (Fig. 5.4A). In contrast, both linear and non-linear scoring methods captured significant differences in both additive and weighted additive approaches at Scott (Fig. 5.4B). Similar to Swift Current MDS (Fig. 5.3C), no significance was observed using the TDS at Swift Current (Fig. 5.4C).

5.6.6. Crop rotation influence on soil health

Higher SHI values were considered indicative of better soil function and sustainability, reflecting a positive influence of crop rotations. Depending on the scoring function and indexing methods at Lethbridge, the diversified rotation (0.79−0.87) exhibited significantly better SH compared to the pulse/oilseed intensified rotation (0.68−0.80). However, it did not differ from conventional (0.74−0.83), high-risk and high-reward (0.71−0.81), market-driven (0.71−0.82), or soil health-enhanced (0.69−0.82) rotations in both the MDS and TDS ($P < 0.10$; Figs. 5.3A and 5.4A). On the other hand, at Scott in both the MDS and TDS, the high-risk and high-reward rotation had significantly better SH compared to the diversified rotation but did not differ significantly from conventional, market-driven, soil health-enhanced or pulse/oilseed intensified rotations ($P < 0.10$; Figs. 5.3B and 5.4B). At Swift Current, no significant differences ($P > 0.10$) were found in either the MDS or TDS; however, the diversified rotation tended to have better SH than other rotations (Figs. 5.3C and 5.4C). In addition, although still not significant ($P > 0.10$), the soil health-enhanced and diversified rotations tended to have overall better SH than other rotations across sites for the combined dataset, both in MDS and TDS (Supplementary Fig. S51).

5.7. Discussion

5.7.1. Minimum and total datasets for soil health evaluation

The evaluation of SH in response to agricultural land use management using either or both of the MDS and TDS concepts is well-documented in the literature (Amgain et al., 2022; Choudhury and Mandal, 2021; Lenka et al., 2022; Lu et al., 2024; Yu et al., 2018). In our study, the MDSs were selected through PCA and included indicators such as SOC, BD, PAWC, and macroporosity at Lethbridge (Table 5.2); SOC, BD, FC, PAWC, macroporosity, and microporosity at Scott (Table 5.3); and SOC, POMC, AS, BD, PAWC, macroporosity, and microporosity at Swift Current (Table 5.4). These PCA-selected indicators can serve as proxies for evaluating short-term SH under crop rotations in these sites (Amgain et al., 2022; Lu et al., 2024). Common PCA-selected MDS indicators across sites included SOC, BD, PAWC, and macroporosity. Although FC, PAWC, macroporosity, and microporosity are not commonly reported as MDS indicators, their inclusion in the study suggests their importance in short-term SH evaluation under crop rotations, influencing nutrient and water retention capacity, and subsequently impacting crop productivity (Iheshiulo et al., 2024b). Soil indicators such as SOC, BD, and AS have been previously reported as MDSs for SH evaluation under various land use management (Bagnall et al., 2023, 2022; Lenka et al., 2022; Lima et al., 2008; Liptzin et al., 2022; Lu et al., 2024; Rieke et al., 2022). In addition, the variability in the number of MDS indicators (ranging from four to seven) highlights the potential need for site-specific MDSs for SH assessment, as reported by Zhao et al., (2021).

On the other hand, the TDS approach considered all 14 measured soil indicators in calculating the SHI (Table 5.1). While this method may provide more comprehensive results (Amgain et al., 2022; Askari and Holden, 2014; Lu et al., 2024), the practicality of regularly measuring all these indicators for SH evaluation is limited due to the associated cost and time requirements (Askari and Holden, 2015; Lu et al., 2024; Yang et al., 2023; Yu et al., 2018). Therefore, the PCA-selected MDSs at the three sites may function as practical proxies for other soil indicators, offering a cost-effective and time-efficient approach for SH evaluation (Amgain et al., 2022; Bünemann et al., 2018; Vasu et al., 2021). This approach provides the necessary information needed for SH evaluation through properly selected soil indicators (Andrews et al., 2004; Askari and Holden, 2015, 2014; Lu et al., 2024).

5.7.2. Comparing soil health indexing approaches

The choice between linear and non-linear scoring approaches for SHI development involves trade-offs in simplicity, prior knowledge requirements, and sensitivity to system variations. The linear scoring approach, being simpler and relying on observed values, requires less prior knowledge of the system. However, it can be influenced by the variance of the specific attributes measured and may be biased by extreme outliers. On the other hand, the non-linear scoring approach, which assumes normal distribution and depends on non-linear response patterns, requires in-depth knowledge of each indicator's behavior (Amgain et al., 2022; Andrews et al., 2002; Guo et al., 2017; Masto et al., 2008; Raiesi, 2017; Rinot et al., 2019). In our study, four SHIs, employing distinct scoring and weighting methods were compared for accuracy and practicability. The SH evaluation results (Figs. 5.3 and 5.4) and strong positive correlations (Supplementary Table S5.2) among the four SHIs demonstrated consistent SH assessments. This is further supported by the higher R^2 values observed with linear regression analysis (Supplementary Figs. S5.2, S5.3, and S5.4). This consistency suggests that these SHIs are representative of system function and equally effective in quantifying the effects of crop rotations on SH in terms of both sensitivity and accuracy (Lu et al., 2024; Yu et al. 2018).

In our study, the non-linear approach had higher CV, F-values, and correlation coefficients in most cases (Figs. 5.3 and 5.4; Supplementary Table S5.2) and thus, could be considered a suitable method for SH indexing. Previous studies have suggested the non-linear scoring approach as the most suitable for indexing SH indicators (Andrews et al., 2002; Askari and Holden, 2014; Lu et al., 2024; Yu et al., 2018). While the non-linear method had higher CV, F-values, and correlation coefficients, the linear scoring approach yielded higher SHI values in both the additive and weighted additive methods for both the TDS and MDS (Figs. 5.2 and 5.3). This is consistent with previous studies (Andrews et al., 2002; Guo et al., 2017; Lu et al., 2024; Yu et al., 2018). However, a recent study by Amgain et al. (2022) reported higher SHI scores with the non-linear scoring function than all the other methods.

Furthermore, there was no variation in the SH ranking of crop rotations in both the TDS and MDS across sites, using the additive and weighted additive indexing methods (Figs. 5.3 and 5.4). This is consistent with previous studies that reported similar findings (Amgain et al., 2022; Lu et al., 2024; Yu et al., 2018). Moreover, the weighted additive approach tended to be more sensitive than the additive approach in evaluating the crop rotations based on the F-value, CV, and correlation coefficients at Scott and Swift Current (Figs. 5.3 and 5.4; Supplementary Table S5.2; Supplementary Figs. S5.2, S5.3, and S5.4). These findings were similar to those reported in previous studies conducted in Ireland (Askari and Holden, 2015) and China (Lu et al., 2024; Yu et al., 2018) under different land use, soil classification, and irrigation systems. In general, SHI-NLWA calculated using the non-linear scoring and weighted additive indexing method was the most sensitive and useful index for differentiating among crop rotations across the three sites in the short-term (Figs. 5.3 and 5.4). The SHI-NLWA concept is a useful tool that enables for an unbiased assessment of SH among different crop rotations and sites in the short-term. However, since soil systems are complex and diverse, it is important to carefully select the soil indicators in the MDSs when applying the SHI.NLWA techniques in other regions on large scale in the long-term (Lu et al., 2024; Yu et al., 2018). However, it is still unknown whether this method can effectively be utilized for all cropping systems and environments, and further testing and evaluation will be necessary to determine its efficacy.

5.7.3. Assessment of soil health under different crop rotations

Crop rotations had a significant impact on SHI at two of three NT sites in the short-term (Figs. 5.3 and 5.4). Depending on the dataset (MDS or TDS) and scoring method at Lethbridge, the diversified rotation showed significantly higher SHI values than the pulse/oilseed intensified rotation, indicating better-improved SH at that study site (Figs. 5.3A and 5.4A). Similarly, at Scott, the high-risk and high-reward rotation resulted in higher SHI values compared to the diversified rotation (Figs. 5.3B and 5.4B). Meanwhile, although not significant, the diversified rotation at Swift Current tended to have higher SHI values (Figs. 5.3C and 5.4C). The commonality between these rotations (diversified and high-risk and high-reward rotations) is the combination of cereal, pulse, and oilseed crops in rotation (Iheshiulo et al., 2024b, 2024a). The findings in this study provide further evidence to support previous studies which have shown that the use of diverse crops in rotation improved SH indicators (Alhameid et al., 2020, 2017; Iheshiulo et al., 2024b, 2024a, 2023; Maiga et al., 2019; McDaniel et al., 2014; Renwick et al., 2021; Riedell et al., 2013; Soares et al., 2019). The higher SHI values observed under the diversified and high-risk and high-reward rotations may be attributed to above- and below-ground residue diversity, as well as root architecture. This diversity directly increases both the quality and quantity of organic material input into the soil, thereby altering SOC and microbial composition and activity, promoting SH (Alhameid et al., 2020; McDaniel et al., 2014; Soares et al., 2019; Zuber et al., 2018). Furthermore, the inclusion of crops with diverse root architecture, rooting depths, C composition, and root exudates may promote soil structure and aggregation, which in turn improve permeability, and aeration, and thus, enhance SH and functions (Campbell et al., 1990). Although SH could be expected to gradually improve over time with crop rotations at these sites, different crop rotations have varying abilities to improve SH in the short term. Based on the SHI values, the diversified rotation at Lethbridge and high-risk and high-reward rotation at Scott seem to be best for improving SH in the short-term at these sites, while the diversified rotation at Swift Current also showed potential to improve SH in a short period.

Additionally, the combined dataset did not show significant differences in SH among crop rotations in both MDS and TDS (Supplementary Fig. S51). However, analyzing each site separately revealed significant influences on SH in both TDS and MDS at two of the three sites (Figs. 5.3 and 5.4). Concluding that crop rotations had no significant impact on short-term SH based solely on the combined dataset could be misleading. Although combining datasets could improve statistical power and the ability to compare outcomes across the three sites, it could also mask the short-term benefits from individual crop rotations at each site. Consistent with others, variations in crop species, soils, and climatic conditions across sites may contribute to the inconsistent results found in our study (Amgain et al., 2022; Iheshiulo et al., 2024b, 2024a, 2023; Jiang et al., 2020; Lima et al., 2008), in particular when significant impacts were not observed across sites. Thus, we emphasize the need for site-specific cropping systems and MDSs, as this will provide more accurate and reliable SH assessment.

5.7.4. Study limitation and future research

The primary goal of this study was to develop MDSs for assessing SH and to explore the impact of crop rotations on SH at three Canadian prairie sites over a short-term period (4 years). The MDSs in this study comprised one or two chemical indicators (SOC and POMC) and three to five physical indicators (AS, BD, FC, PAWC, macroporosity, and microporosity), depending on the site, to represent the TDS. According to Allen et al. (2011), MDSs should include soil physical, chemical, and biological properties responsive to management and linked to soil function. While the MDSs in this study are associated with key soil functions, the absence of soil biological properties may be a potential limitation. Although the results obtained are reliable, the exclusion of certain indicators (chemical, biological, or physical indicators) during selection may impact the accuracy and reliability of this study (Pulido et al., 2017). Future studies should expand the dataset by incorporating additional chemical (e.g., macro- and micro-nutrients) and biological properties (e.g., microbial biomass, community, and respiration) to enhance the accuracy, reliability, sensitivity, and discrimination ability of the SHI (Lu et al., 2024). However, it is noteworthy that some studies have also excluded either physical, chemical, or biological properties in the selection of MDSs (Amgain et al., 2022; Choudhury and Mandal, 2021; Jiang et al., 2020; Lu et al., 2024). Furthermore, there is need for validation with measurement of some tangible outcomes (such as plant growth, microbial activity, and greenhouse gas production) that may arise from improved SH.

5.8. Conclusion

This study aimed to assess SH of three Canadian prairie sites under short-term NT crop rotations, using two approaches, TDS and MDS, and four indexing methods (SHI.LA, SHI.LWA, SHI.NLA, and SHI.NLWA). Fourteen soil indicators, encompassing chemical and physical properties, were used in the TDS to develop MDS and evaluate SH under six crop rotations. Site-specific MDS indicators derived from PCA included SOC, BD, PAWC, and macroporosity at Lethbridge; SOC, BD, FC, PAWC, macroporosity, and microporosity at Scott; and SOC, POMC, AS, BD, PAWC, macroporosity, and microporosity at Swift Current. Consistent results across sites and positive correlations between scoring and indexing methods indicated that all four indices are equally effective in assessing the short-term impact of crop rotations on SH. The SHI.NLWA emerged as the most effective method based on the F-values, CV, and correlation and regression coefficients; and thus, recommended for future studies. In addition, the diversified rotation at Lethbridge and Swift Current, along with the high-risk and high-reward rotation at Scott, exhibited the highest SHI values compared to other rotations. To enhance sensitivity and discrimination ability of SHI, future studies should expand the dataset by including more soil chemical and biological properties.

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Table 5.1. Descriptive statistics of soil indicators in the total dataset at Lethbridge, Scott, and Swift Current.

Descriptive statistics	TC	SOC	TN	POMC	POMN	AS	BD	TP	FC	PAWC	Macroporosity	Mesoporosity	Microporosity
	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	%	g cm^{-3}	%	%	%	%	%	%
Lethbridge, Alberta													
Min.	26.01	23.10	2.25	5.56	0.37	51.68	1.07	45.0	25.44	13.04	2.47	8.08	6.88
Max.	31.12	30.49	2.78	7.64	0.52	83.05	1.48	60.0	33.66	18.41	19.63	12.92	8.23
Mean	28.04	27.08	2.54	6.68	0.45	69.19	1.31	51.17	29.72	15.53	6.53	10.25	7.56
Median	27.66	26.73	2.52	6.73	0.45	70.06	1.31	51.0	29.71	15.68	4.93	10.19	7.56
SD	1.49	1.79	0.14	0.45	0.03	8.06	0.10	0.04	2.03	1.35	4.47	1.25	0.38
Skewness	0.49	0.01	−0.0001	−0.20	−0.24	−0.18	−0.38	0.46	−0.01	−0.10	1.71		
Scott, Saskatchewan													
Min.	22.13	20.59	1.97	3.94	0.28	19.01	1.22	44.0	20.84	8.81	1.62	9.62	6.98
Max.	30.92	28.40	2.60	5.23	0.37	41.75	1.49	54.0	26.80	18.14	7.40	16.08	9.75
Mean	25.56	23.64	2.20	4.63	0.33	30.38	1.37	48.54	24.07	15.90	3.93	12.38	8.61
Median	25.21	23.41	2.18	4.66	0.33	30.32	1.38	48.50	24.16	16.09	3.16	12.32	8.62
SD	2.03	1.74	0.14	0.34	0.02	6.28	0.06	0.02	1.45	1.86	1.26	1.33	0.81
Skewness	0.74	1.05	1.01	−0.15	−0.47	−0.20	−0.45	0.31	−0.54	−2.33	0.74	0.68	−0.46
Swift Current, Saskatchewan													
Min.	18.78	17.81	1.64	3.06	0.21	21.82	1.23	45.0	21.50	14.85	1.46	9.75	6.94
Max.	21.79	21.21	1.96	4.08	0.29	40.39	1.48	54.0	28.06	19.50	6.08	15.73	12.41
Mean	20.23	19.58	1.80	3.54	0.25	31.79	1.36	49.12	25.41	17.37	2.93	11.74	9.35
Median	20.27	19.77	1.80	3.59	0.25	31.89	1.35	49.50	25.45	17.53	2.66	11.66	9.27
SD	0.81	0.83	0.07	0.23	0.02	5.07	0.06	0.02	1.43	1.14	1.10	1.60	1.06
Skewness	−0.07	−0.41	−0.003	−0.22	−0.27	−0.21	0.17	−0.07	−0.59	−0.39	1.72	0.82	0.41

Note: TC, total carbon; SOC, soil organic carbon; TN, total nitrogen; POMC, particulate organic matter carbon; POMN, particulate organic matter nitrogen; AS, aggregate stability; BD, bulk density; TP, total porosity; FC, field capacity; PAWC, plant-available water capacity; and SD, standard deviation.

Table 5.2. Result of principal component (PC) analysis of total dataset at Lethbridge, Alberta. Boldface factor loading values are considered highly weighted, while boldface and underlined loading values correspond to the indicator included in the minimum dataset (MDS) for the soil health index calculation.

Soil indicators [a]	Principal components			
	PC1	PC2	PC3	Communality
TC	**−0.414**	−0.039	0.036	0.174
SOC	**<u>−0.446</u>**	0.035	0.021	0.201
TN	**−0.442**	−0.038	0.058	0.200
POMC	−0.290	−0.175	−0.308	0.210
POMN	−0.365	−0.184	−0.243	0.226
AS	−0.249	−0.014	0.309	0.158
BD	−0.232	**<u>0.442</u>**	−0.147	0.271
TP	0.222	**−0.450**	0.163	0.278
FC	0.203	0.364	−0.316	0.274
PAWC	0.035	**<u>0.418</u>**	−0.372	0.314
Macroporosity	0.019	−0.335	**<u>−0.444</u>**	0.310
Mesoporosity	0.009	−0.290	−0.380	0.229
Microporosity	−0.092	0.172	0.342	0.155
PCs' parameter				
Eigenvalue	4.685	2.914	2.486	
Explained variance, %	36.038	22.413	19.122	
Cumulative variance, %	36.038	58.451	77.573	
		MDS		
Weight	0.463	0.289	0.246	

[a] TC, total carbon; SOC, soil organic carbon; TN, total nitrogen; POMC, particulate organic matter carbon; POMN, particulate organic matter nitrogen; AS, aggregate stability; BD, bulk density; TP, total porosity; FC, field capacity; and PAWC, plant-available water capacity.

Table 5.3. Result of principal component (PC) analysis of total dataset at Scott, Saskatchewan. Boldface factor loading values are considered highly weighted, while boldface and underlined loading values correspond to the indicator included in the minimum dataset (MDS) for the soil health index calculation.

Soil indicators [a]	Principal components				
	PC1	PC2	PC3	PC4	Communality
TC	**0.397**	−0.204	−0.058	−0.190	0.239
SOC	**<u>0.432</u>**	−0.230	−0.113	0.007	0.252
TN	**0.421**	−0.191	−0.094	−0.039	0.224
POMC	0.324	0.158	0.299	0.286	0.301
POMN	0.248	0.256	0.347	0.092	0.256
AS	0.356	−0.244	−0.243	0.151	0.268
BD	−0.268	**−<u>0.411</u>**	0.065	0.363	0.377
TP	0.246	**0.406**	−0.081	−0.385	0.380
FC	−0.013	**−<u>0.402</u>**	−0.139	−0.367	0.316
PAWC	−0.224	−0.124	−0.179	**−<u>0.459</u>**	0.308
Macroporosity	0.031	−0.223	**<u>0.557</u>**	−0.193	0.398
Mesoporosity	−0.020	−0.101	**0.525**	−0.403	0.449
Microporosity	−0.013	**<u>0.384</u>**	−0.240	−0.154	0.229
PCs' parameter					
Eigenvalue	4.176	2.830	2.335	1.171	
Explained variance, %	32.124	21.769	17.964	9.006	
Cumulative variance, %	32.124	53.893	71.858	80.864	
		MDS			
Weight	0.397	0.269	0.222	0.111	

[a] TC, total carbon; SOC, soil organic carbon; TN, total nitrogen; POMC, particulate organic matter carbon; POMN, particulate organic matter nitrogen; AS, aggregate stability; BD, bulk density; TP, total porosity; FC, field capacity; and PAWC, plant-available water capacity.

Table 5.4. Result of principal component (PC) analysis of total dataset at Swift Current, Saskatchewan. Boldface factor loading values are considered highly weighted, while boldface and underlined loading values correspond to the indicator included in the minimum dataset (MDS) for the soil health index calculation.

Soil indicators [a]	Principal component					
	PC1	PC2	PC3	PC4	PC5	Communality
TC	**0.354**	0.229	−0.320	0.276	−0.010	0.356
SOC	<u>**0.365**</u>	0.278	−0.295	0.213	−0.019	0.343
TN	**0.338**	0.298	−0.290	0.051	−0.068	0.294
POMC	<u>**0.337**</u>	0.151	0.308	−0.341	0.176	0.378
POMN	0.320	0.111	0.314	−0.452	0.198	0.457
AS	0.100	0.099	−0.071	−0.060	<u>**0.727**</u>	0.557
BD	<u>**0.341**</u>	−0.307	0.175	0.208	−0.068	0.289
TP	**−0.337**	0.322	−0.151	−0.217	0.074	0.293
FC	0.309	−0.369	0.099	0.098	0.039	0.253
PAWC	0.158	**−<u>0.440</u>**	−0.017	0.033	−0.001	0.220
Macroporosity	0.072	−0.314	**−<u>0.514</u>**	−0.358	0.070	0.501
Mesoporosity	−0.121	−0.331	−0.415	−0.130	0.306	0.407
Microporosity	−0.175	−0.001	0.167	<u>**0.551**</u>	0.535	0.648
PCs' parameter						
Eigenvalue	3.968	3.268	1.693	1.185	1.021	
Explained variance, %	30.523	25.136	13.023	9.116	7.855	
Cumulative variance, %	30.823	55.658	68.681	77.798	85.653	
			MDS			
Weight	0.356	0.293	0.152	0.106	0.092	

[a] TC, total carbon; SOC, soil organic carbon; TN, total nitrogen; POMC, particulate organic matter carbon; POMN, particulate organic matter nitrogen; AS, aggregate stability; BD, bulk density; TP, total porosity; FC, field capacity; and PAWC, plant-available water capacity.

Table 5.5. Scoring function, parameters of non-linear and linear equations, and calculated weights of the total (TDS) and minimum data set (MDS) at Lethbridge, Scott, and Swift Current.

Soil indicators [a]	Scoring curve	Non-linear function				Linear function						Weight					
		Mean (*X*m)			Slope (*b*)	Xmax			Xmin			TDS			MDS		
		LB [b]	Scott	SC		LB	Scott	SC	LB	Scott	SC	LB	Scott	SC	LB	Scott	SC
TC	More is better	28.04	25.56	20.23	−2.5	31.12	30.92	21.79	-	-	-	0.058	0.060	0.071	-	-	-
SOC	More is better	27.08	23.64	19.58	−2.5	27.08	28.40	21.21	-	-	-	0.067	0.063	0.069	0.463	0.397	0.119
TN	More is better	2.54	2.20	1.80	−2.5	2.78	2.60	1.96	-	-	-	0.067	0.056	0.059	-	-	-
POMC	More is better	6.68	4.63	3.54	−2.5	7.64	5.23	1.04	-	-	-	0.070	0.075	0.076	-	-	0.119
POMN	More is better	0.45	0.33	0.25	−2.5	0.52	0.37	0.29	-	-	-	0.075	0.064	0.091	-	-	-
AS	More is better	69.19	30.38	31.79	−2.5	83.05	41.75	40.39	-	-	-	0.053	0.067	0.111	-	-	0.092
BD	Less is better	1.31	1.37	1.36	2.5	-	-	-	1.07	1.22	1.23	0.090	0.094	0.058	0.144	0.090	0.119
TP	More is better	51.17	48.54	49.12	−2.5	60.0	54.0	54.0	-	-	-	0.093	0.095	0.059	-	-	-
FC	More is better	29.72	24.07	25.41	−2.5	33.66	26.80	28.06	-	-	-	0.091	0.079	0.051	-	0.090	-
PAWC	More is better	15.53	15.90	17.37	−2.5	18.41	18.14	19.50	-	-	-	0.105	0.077	0.044	0.144	0.111	0.293
Macroporosity	More is better	6.53	3.93	2.93	−2.5	19.63	7.40	6.08	-	-	-	0.076	0.112	0.100	0.246	0.222	0.152
Mesoporosity	More is better	10.25	12.58	11.74	−2.5	12.92	16.08	15.73	-	-	-	0.052	0.057	0.081	-	-	-
Microporosity	Less is better	7.56	8.61	9.35	2.5	-	-	-	6.88	6.98	6.94	0.058	0.060	0.130	-	0.090	0.106

[a] TC, total carbon; SOC, soil organic carbon; TN, total nitrogen; POMC, particulate organic matter carbon; POMN, particulate organic matter nitrogen; AS, aggregate stability; BD, bulk density; TP, total porosity; FC, field capacity; and PAWC, plant-available water capacity.
[b] LB, Lethbridge; and SC, Swift Current.

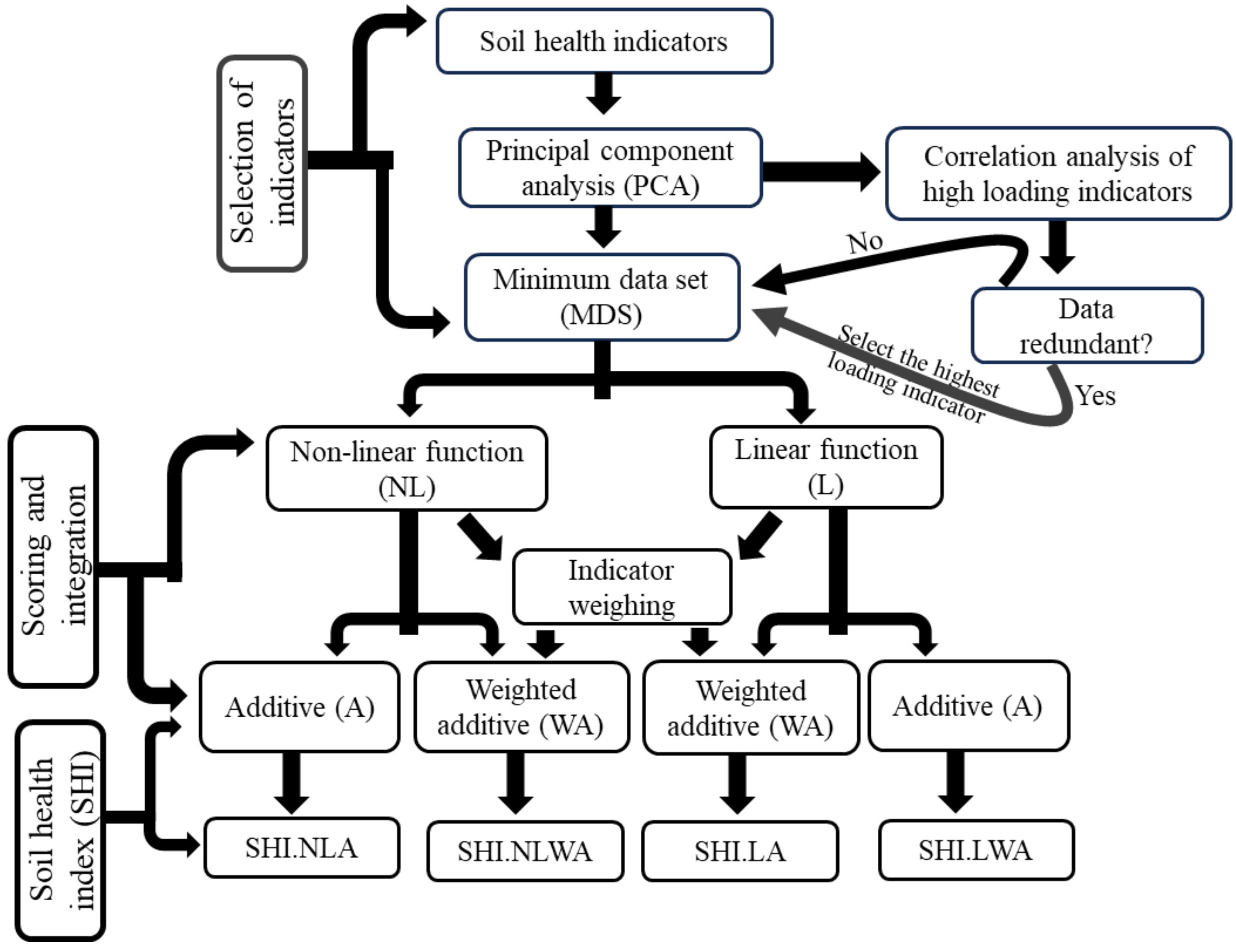

Figure 5.1. Schematic flow chart showing the soil health index (SHI) computation procedure. SHI.NLA, non-linear additive SHI; SHI.NLWA, non-linear weighted additive SHI; SHI.LWA, linear weighted additive SHI; and SHI.LA, linear additive SHI.

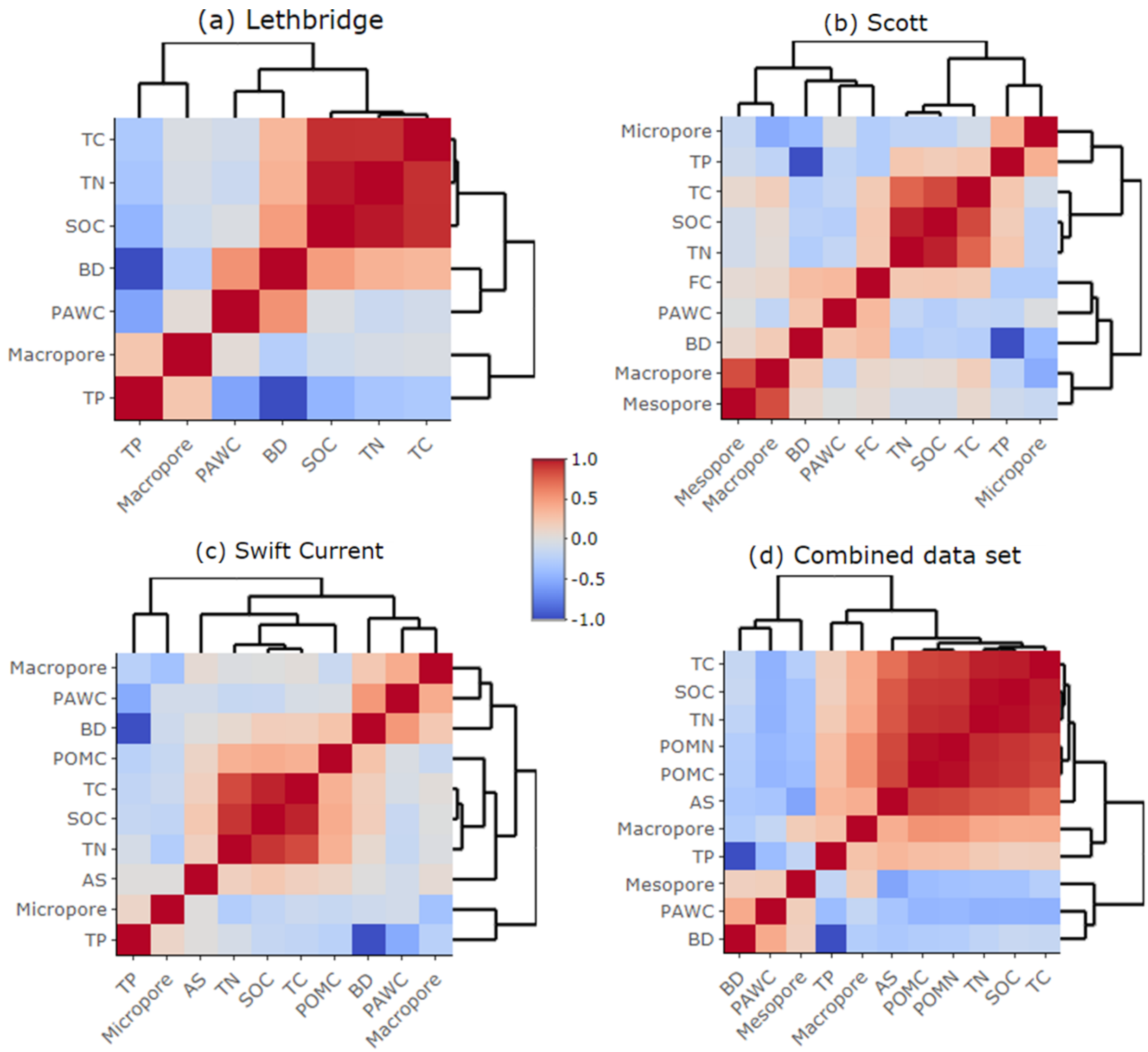

Figure 5.2. Cluster-Pearson correlation coefficient heat map among high-weighted variables at (a) Lethbridge, (b) Scott, (c) Swift Current, and (d) combined dataset. TC, total carbon; SOC, soil organic carbon; TN, total nitrogen; POMC, particulate organic matter carbon; POMN, particulate organic matter nitrogen; AS, aggregate stability; BD, bulk density; TP, total porosity; FC, field capacity; PAWC, plant-available water capacity; macropore, macroporosity; mesopore, mesoporosity; and micropore, microporosity.

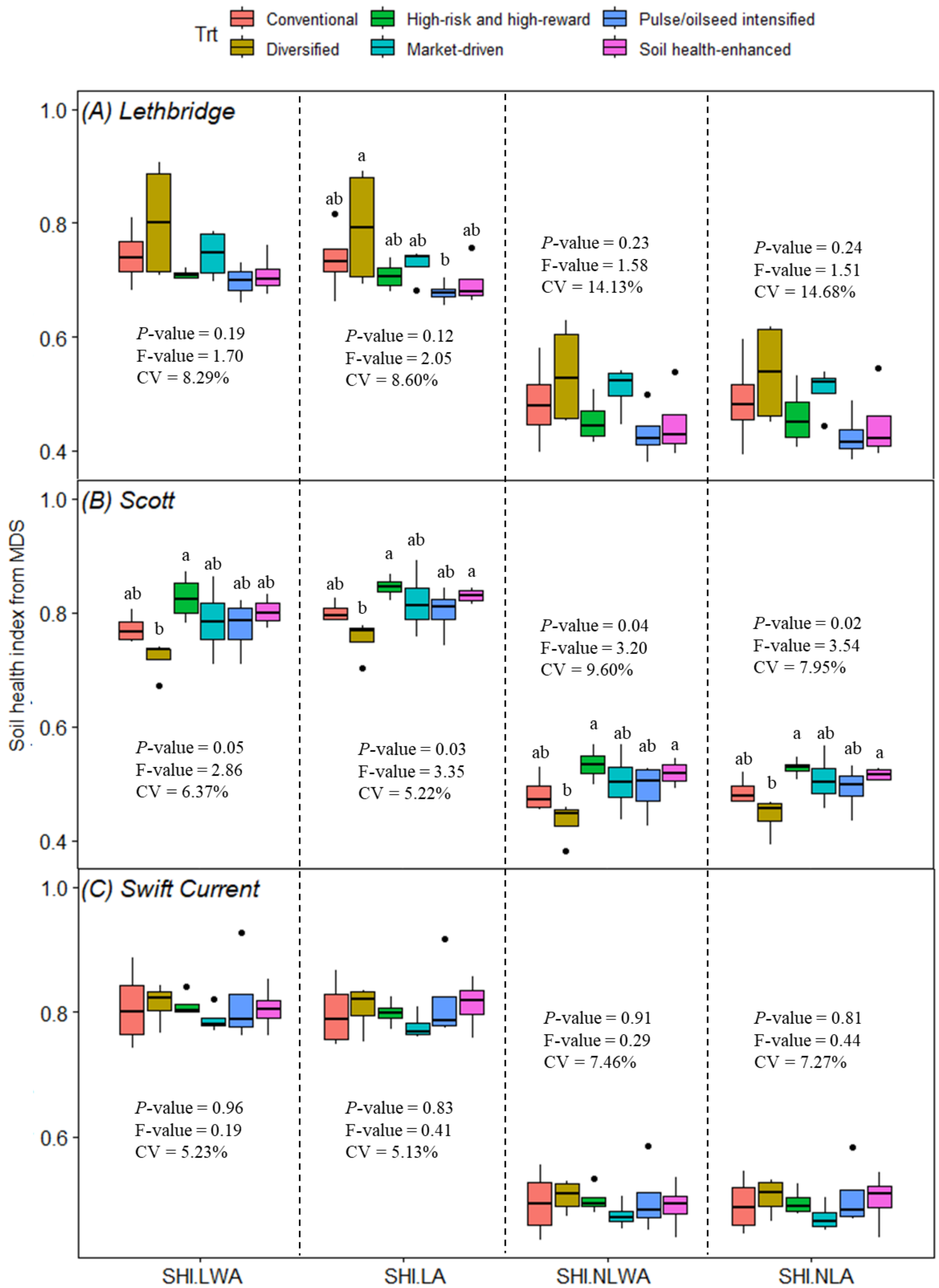

Figure 5.3. Soil health index (SHI) developed among different cropping systems at (A) Lethbridge, (B) Scott, and (C) Swift Current. SHI values were calculated using the PCA-selected minimum dataset (MDS). Mean SHI values with the same letter did not significantly differ (*P* > 0.10). SHI.LWA, linear weighted additive SHI; SHI.LA, linear additive SHI, SHI.NLWA, non-linear weighted additive SHI; SHI.NLA, non-linear additive SHI; and CV, coefficient of variance. The *P*- and F-values were the results of the ANOVA test, while the black dots outside the boxplots represent the outliers.

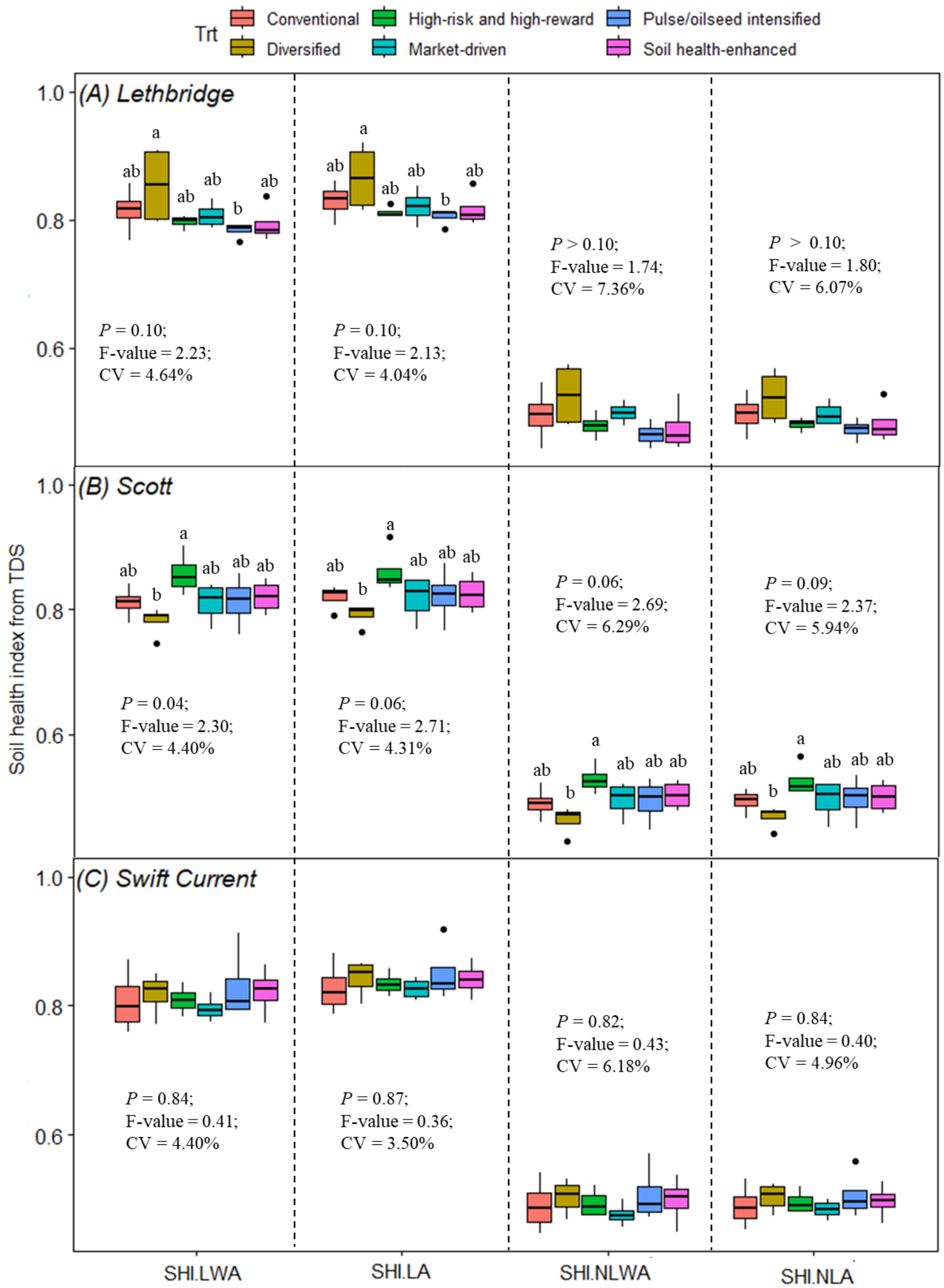

Figure 5.4. Soil health index (SHI) developed among different cropping systems at (A) Lethbridge, (B) Scott, and (C) Swift Current. SHI values were calculated using the total dataset (TDS). Mean SHI values with the same letter did not significantly differ ($P > 0.10$). SHI.LWA, linear weighted additive SHI; SHI.LA, linear additive SHI, SHI.NLWA, non-linear weighted additive SHI; SHI.NLA, non-linear additive SHI; and CV, coefficient of variance. The *P*- and F-values were the results of the ANOVA test, while the black dots outside each boxplot represent the outliers.

6. CONCLUSIONS

This dissertation contributes to the understanding of crop diversification in rotations and its impact on SH attributes. Including diverse crops in rotations presents an opportunity to enhance SH, improving soil functions and agroecosystem productivity. However, most supporting studies are from the US, necessitating an assessment of diverse crop rotations within the Canadian context, especially on soil physical and hydraulic attributes. Chapter 2 addressed the question of whether diversifying crops in rotations improves soil physical health, and revealed that increasing crop diversity, combined conservation tillage or pulses, enhances soil physical health, particularly in medium- and fine-textured soils with over 900 mm mean annual precipitation when managed for 5−10 years.

Building on Chapter 2, Chapter 3 explored the impact of diverse crop rotations on short-term SOM and AS dynamics. The inclusion of annual pulse crops, whether harvested or used as green manure, or simply replacing fallow with pulses or green manure, stabilized SOC and improved AS at two sites, with crop species, rotation frequency, and site-specific conditions influencing SOC sequestration and AS dynamics. Chapter 4 demonstrated that diverse crop rotations can improve soil hydraulic and physical properties after a single 4-year cycle, with a longer study period potentially yielding more significant changes. However, variability in site-specific conditions and complex interactions prevented uniform study-wide improvements, aligning with Chapter 2's conclusions.

Finally, Chapter 5 analyzed the impact of different crop rotations on overall SH using a minimum dataset, site-specific model, and SH index. Common indicators across sites included SOC, BD, macroporosity, and PAWC, while other indicators varied depending on the site. The non-linear scoring weighted additive indexing approach effectively differentiated short-term crop rotations. Based on the selected minimum dataset, the diversified rotations at Lethbridge and Swift Current, and the high-risk and high-reward rotation at Scott, showed greater potential for improving SH in the short-term. The study concluded that monitoring SH over time and selecting crop rotations that enhance SH can positively impact soil functions and agroecosystem productivity.

Based on the results, the dissertation suggests that diversifying crops in rotations has the potential to improve soil health and create opportunity for expanding crop type. However, several challenges within the Canadian context need attention. Chapter 2's meta-analysis highlighted a limited understanding of physical and hydraulic properties in Canada, with most research in this area originating from the US. The focus on simpler crop rotations with two or three crop species underscores the need for more comprehensive, well-replicated, and long-term studies, particularly in the face of climate change. Future research should explore interactions between improved soil physical health and other ecological benefits such as soil biological processes, nutrient cycling, and drought tolerance.

Chapters 3 and 4 revealed system- and site-specific results, emphasizing the need for considering long-term effects, plant rooting patterns, and architectures in future studies. Discrepancies in rotation performances across sites reveal the importance of gradual developments in soil properties over time. Also, Chapter 3's findings that including pulse or oilseed crops did not significantly increase SOM fractions suggests that there may be potential benefits of including perennial forage legumes or high residue cereals like rye and limiting annual pulse or oilseed crop frequency. This approach could enhance crop residue quantity, quality, and chemical diversity, thereby increasing SOM.

In summary, while diversifying crops in rotation shows promise for improving soil health, addressing geographic gaps, conducting more complex studies, and considering site-specific factors are crucial for advancing sustainable agriculture practices in the Canadian prairie.

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APPENDIX

Supplementary Materials

2. Do Diversified Crop Rotations Influence Soil Physical Health? A Meta-Analysis

Iheshiulo, E. M.-A., Larney, F. J., St. Luce, M., Lui, K., Chau, H. W., 2023. Do diversified crop rotations influence soil physical health? A meta-analysis. Soil Tillage Res., 233, 105781. https://doi.org/10.1016/j.still.2023.105781.

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Table S2.1. List of 148 studies used in the meta-analysis on crop diversity effects on soil bulk density and total porosity, including estimated bulk density and total porosity.

Study location	Study duration (yr)	Crops in control	Crops in rotation	Other treatment/management	Authors
Indian Head, SK	4	spring wheat and winter wheat	spring wheat, flax, winter wheat	zero-tillage, minimum tillage, and conventional tillage; fallow included in both control and treatment	Grant and Lafond, 1993
Elora, ON	30	corn	corn, soybean, wheat, barley, (red clover), oat	no-tilled and mouldboard plow	Munkholm et al., 2013
Hays, KS	33	wheat	wheat, sorghum	no-till; fallow included in both control and treatment	Blanco-Canqui et al., 2010b
Hesston, KS	8	sorghum	wheat, soybean, sorghum	no-till and stubble-mulch tilled	Blanco-Canqui et al., 2010a
Bushland, TX	9	wheat	wheat, soybean	no-till and stubble-mulch tilled; fallow included in both control and treatment	Baumhardt et al., 2012
Lafayette, IN	16	corn	corn, soybean, wheat	no-till, moldboard, and chisel plow	Diack and Stott, 2001
Akron, CO	7	wheat	wheat, corn, millet, sunflower	no-till; fallow included in the treatment	Benjamin et al., 2007
Akron, CO	15	wheat	wheat, corn	no-tilled	Benjamin et al., 2008
Crossville, AL	11	corn, wheat	soybean, wheat, and corn	conventional tillage	Edwards et al., 1992
Centralia, MO	14	corn, soybean	corn, soybean, wheat	mulch tillage, no-till	Jiang et al., 2007
Urbana, IL	5	corn, soybean	corn, soybean, rye, (vetch)	no-till; fallow included in the treatment	Villamil et al., 2006
Mandan, ND	28	wheat, barley, or oat	spring wheat, winter wheat, barley, oat, soybean, dry pea, sunflower, corn, buckwheat	conventional and conservation tillage	Liebig et al., 2014
Wooster, OH	29	corn	corn, soybean, oat, and meadow (alfalfa + red clover)	no-till, chisel plow, and mouldboard plow	Lal et al., 1994
Mandan, ND	8	spring wheat	spring wheat, winter wheat, sunflower, millet, rye, safflower	conventional and conservative tillage; fallow included in both control and treatment	Liebig et al., 2004
Mandan, ND	12	wheat	spring wheat, winter wheat, and sunflower	no-till, conventional tillage, and minimum tillage; fallow included in both control and treatment	Halvorson et al., 2002
Akron, CO	12	winter wheat	winter wheat, corn, spring wheat, soybean, sorghum, sunflower, oat, clover (as a cover crop), lentil, millet	no-till and conventional tillage; fallow included in the treatment	Pikul et al., 2007
Monmouth, IL	15	corn	corn, soybean, wheat	no-till and conventional tillage	Zuber et al., 2015
Piketon, OH	5	corn	corn, wheat, soybean	conventional till	Aziz et al., 2011
Sterling, CO	12	corn	corn, wheat	no-till; fallow included in both control and treatment	Shaver et al., 2002
Milan, TN	15	corn	corn, cotton, soybean	no-till	Nouri et al., 2019
Beresford, SD	27	corn, soybean	soybean, corn, oat, winter wheat, cover crop	no-till	Singh et al., 2020
Jefferson City, MO	3	corn	corn, soybean	conventional and conservation tillage	Haruna and Nkongolo, 2015
Ralston, WI	11	winter wheat	spring wheat, winter wheat, barley	chemical fallow, reduced tillage, and no-till. Fallow included in both control and treatment	Feng et al., 2011
Arlington, WI	18	corn	soybean, winter wheat, corn	no-till and conventional tillage	Jokela et al., 2011
Kanawha, IA	43	corn	corn, soybean, oat (manure), (meadow: alfalfa + red clover)	conventional tillage	Karlen et al., 2006
Beresford, SD	23	maize and soybean	maize, soybean, wheat, oat	conservation tillage	Alhameid et al., 2017
Nashua, IA	48	corn	corn, oat, (alfalfa)	conventional tillage	Russell et al., 2006
Arlington, WI	10	corn	corn, soybean, wheat	no-till and conventional tillage	Kazula et al., 2017
Bangladesh	4	wheat, rice	wheat, mung-bean, rice, dhaincha	zero-till, deep-till, and conventional till	Alam et al., 2017
Brazil	1.6	wheat, soybean, lupine	wheat, oat, turnip, soybean, lupine, pea	conservation tillage	Sustakowski et al., 2020
Ethiopia	3	maize	maize, wheat, faba-bean, pepper	conservation tillage	Degu et al., 2019
India	8	rice, wheat	rice, wheat, mung-bean,	Reduced tillage, conventional tillage, and no-till	Patra et al., 2019
India	7	maize	maize, chickpea, sesbania, wheat, mung-bean, mustard	conventional and conservation tillage	Parihar et al., 2016
Malawi	12	maize	maize, cowpea, pigeon pea, velvet bean	no-till	Eze et al., 2020
Poland	8	spring triticale	sugar beet, spring triticale, faba-bean, winter triticale, oat	conventional tillage	Głab et al., 2013
Romania	21	wheat	wheat, maize, and soybean	conventional till.	Şandor et al., 2012
South Africa	5	maize	maize, winter wheat, soybean	no-till and conventional till; fallow included in both control and treatment	Mtyobile et al., 2020
South Africa	3	maize	maize, wheat, and soybean	conventional and conservation tillage	Nebo et al., 2020
Vietnam	10	rice	rice, maize, mung-bean	conventional tillage	Linh et al., 2016
Vietnam	10	rice	rice, maize, mung-bean	conventional tillage	Linh et al., 2017

Table S2.2. List of studies used in the meta-analysis on crop diversity effects on aggregate stability (NA, not available).

Study location	Study duration (yr)	Crops in control	Crops in rotation	Other treatment/management	Authors
Indian Head, SK	39	wheat	wheat, hay, green manure	tillage and fertilizer included	Campbell et al., 2001
Multiple sites in ON	14	corn	soybean, corn, wheat, tobacco, rye, (red clover), (alfalfa), barley, oat,	conventional till and no-till	Congreves et al., 2015
Ontario, Canada	14	corn	soybean, winter wheat, corn	conventional and conservation tillage	Van Eerd et al., 2014
Bushland, TX	12	sorghum	wheat, sorghum	no-till	Alemu et al., 1997
Piketon, OH	5	corn	corn, soybean, wheat	conventional tillage	Aziz et al., 2011
Akron, CO	15	wheat	wheat, corn	no-till	Benjamin et al., 2008
Urbana, IL	5	corn	corn, soybean	no-till	Villamil et al., 2006
Wooster, OH	29	corn	corn, soybean, oat, (meadow: alfalfa + red clover)	no-till, chisel plow, and moldboard plow	Lal et al., 1994
Mandan, ND	17	spring wheat	spring wheat, winter wheat, sunflower	conventional tillage	Liebig et al., 2004
Brookings, SD	12	corn	corn, soybean, spring wheat, (alfalfa)	conventional tillage	Pikul et al., 2007
Monmouth, IL	15	corn	corn, wheat, soybean	no-till and conventional tillage	Zuber et al., 2015
Akron, CO	8	wheat	wheat, corn, millet	conventional tillage	Wright and Anderson, 2000
Bozeman, MT	8	wheat	pea, wheat, legume green manure	no-till	O'Dea et al., 2015
Multiple sites in CO	12	corn	wheat, corn	no-till	Shaver et al., 2002
Milan, TN	15	corn	cotton, soybean, corn	no-till	Nouri et al., 2019
Arlington, WI	18	corn	corn and soybean	conventional tillage	Jokela et al., 2011
Columbus, OH	7	corn	corn, soybean, wheat	various fertilization levels	Subbian et al., 2000
Multiple sites in OH	49	corn	corn, soybean	Zero-till, minimum till, plow-till	Kumar et al., 2012a
Multiple sites in IA	43	corn	corn, soybean, oat, (meadow: alfalfa + red clover)	Conventional tillage	Karlen et al., 2006
Beresford, SD	27	corn, soybean	corn, soybean, oat, wheat, cover crop	no-till; fallow included in the treatment	Singh et al., 2020
Beresford, SD	23	maize, soybean	maize, wheat, soybean, oat	NA	Alhameid et al., 2017
India	7	rice, wheat	rice, corn, mung-bean	conventional tillage	Kumar and Nath, 2019
India	13	rice, wheat	rice, corn, chickpea, and mung-bean	conventional tillage	Nath et al., 2019
India	7	maize, soybean	wheat, maize, mustard, soybean, corn, mung-bean	conventional and conservation tillage	Parihar et al., 2016
India	13	maize, pea, wheat	maize, wheat, mung-bean, corn	conventional tillage	Hazra et al., 2019
Romania	21	wheat	wheat, maize, soybean	conventional tillage	Şandor et al., 2012
Syria	12	wheat	wheat, corn, lentil, velvet bean	conservation tillage	Masri and Ryan, 2006
Zambia	2	maize	corn, maize, soybean	conservation tillage	Thierfelder and Wall, 2010

Table S2.3. List of studies used in the meta-analysis on crop diversity effects on water infiltration rates (NA, not available).

Study location	Study duration (yr)	Crops in control	Crops in rotation	Other treatment/management	Authors
Multiple sites in US and CA	12	winter wheat	winter wheat, soybean, sorghum, spring wheat, millet, alfalfa (as a cover crop), lentil, sunflower	conventional till and no-till; fallow included in both control and treatment	Pikul et al., 2006
Bushland, TX	12	wheat	wheat and sorghum	no-till and reduce tillage; fallow included in both control and treatment	Alemu et al., 1997
Hays, KS	33	wheat or sorghum	wheat, sorghum	no-till; fallow included in both control and treatment	Blanco-Canqui et al., 2010b
Hesston, KS	8	sorghum	sorghum, wheat, soybean	no-till trafficked and no-tilled non-trafficked	Blanco-Canqui et al., 2010a
Bushland, TX	24	wheat	wheat, soybean	no-till and stubble-mulch tilled; fallow included in both control and treatment	Baumhardt et al., 2012
Mandan, ND	28	wheat, barley, or oat	wheat, barley, oat, sunflower, spring wheat, winter wheat, dry pea, corn, soybean, buckwheat	NA	Liebig et al., 2014
Milan, TN	15	corn	corn, cotton, soybean	no-till	Nouri et al., 2019
Ralston, WI	11	winter wheat	winter wheat, and barley	reduced till and no-till; chemical fallow	Feng et al., 2011
Mandan, ND	17	spring wheat	spring wheat, winter wheat, sunflower	conventional tillage and no-till	Liebig et al., 2004
Aurora, NY	6	corn	corn, soybean, wheat, clover (as a cover crop)	conventional till, plow, and ridge-till	Katsvairo et al., 2002
Beresford, SD	27	corn, soybean	soybean, corn, oat, wheat	no-till	Singh et al., 2020
Wooster, OH	49	corn	corn, soybean	zero-till, minimum till, plow-till	Kumar et al., 2012b
Lafayette, IN	16	corn	corn, wheat, soybean	no-till, moldboard, and chisel plow	Diack and Stott, 2001
Australia	2	wheat	wheat, lucerne, annual medics, *Panicum coloratum* (as a cover crop)	no-till	Thomas et al., 2009
Bangladesh	4	wheat	wheat, rice, mung-bean, dhaincha	zero-till	Alam et al., 2017
Mexico	12	wheat	wheat, maize	conventional till and no-till	Govaerts et al., 2007
Mozambique	5	maize	maize, pigeon pea	no-till	Rusinamhodzi et al., 2012
Syria	12	wheat	wheat, chickpea, lentil, vetch (as a cover crop)	conservation tillage	Masri and Ryan, 2006
Zambia	2 - 4	maize	maize, cotton, sun-hemp	conventional tillage	Thierfelder and Wall, 2010

Table S2.4. List of studies used in the meta-analysis on crop diversity effects on saturated hydraulic conductivity.

Study location	Study duration (yr)	Crops in control	Crops in rotation	Other treatments and management	Author
Hesston, KS	8	sorghum	sorghum, wheat, soybean	no-till	Blanco-Canqui et al., 2010a
Hays, KS	33	wheat	wheat, sorghum	no-till and reduced till; fallow included in both control and treatment	Blanco-Canqui et al., 2010b
Wooster, OH	49	corn	corn and soybean	zero-till, minimum till, plow-till	Kumar et al. 2012a
Ames, IA	5	maize	maize, soybean, triticale, switchgrass (as a cover crop), aspen	no-till; fertilization based on soil test	Anwar et al. 2017
Akron, CO	7	wheat	wheat, corn, sunflower, millet	no-till; fallow included in both control and treatment	Benjamin et al., 2007
Akron, CO	15	wheat	wheat, corn	no-till; fallow included in both control and treatment	Benjamin et al., 2008
Newport, ME	3	potato	potato, alfalfa, vetch (as a cover crop), lupine, oat	conventional tillage	Honeycutt et al., 1995
Milan, TN	15	corn	corn, cotton, soybean	no-till	Nouri et al., 2019
Centralia, MO	14	corn, soybean	corn, soybean, wheat	mulch tillage; no-till	Jiang et al., 2007
Ralston, WI	11	winter wheat	winter wheat, barley, spring wheat	reduced till; fallow and chemical fallow	Feng et al., 2011
Argentina	15	corn	corn, wheat, soybean	no-till	Sasal et al., 2010
Australia	2	wheat	wheat, lucerne, annual medics, *Panicum coloratum*	no-till	Thomas et al., 2009
Germany	3	maize	mustard, maize, winter wheat, sugar beet	conservation tillage	Götze et al., 2016
India	8	rice, wheat	rice, wheat, maize, mung-bean	conventional tillage	Patra et al., 2019
India	7	maize, sesbania	maize, mustard, chickpea, mung-bean, wheat, sesbania	conventional and conservation tillage	Parihar et al., 2016
Malawi	10 - 12	maize	maize, cowpea, pigeon pea, velvet bean	no-till	Eze et al., 2020
Romania	21	wheat	wheat, maize, soybean	conventional tillage	Şandor et al., 2012
Syria	12	wheat	wheat, chickpea, lentil, vetch (as a cover crop)	conservation tillage	Masri and Ryan, 2006
Vietnam	10	rice	rice, maize, mung-bean	conventional tillage	Linh et al., 2017

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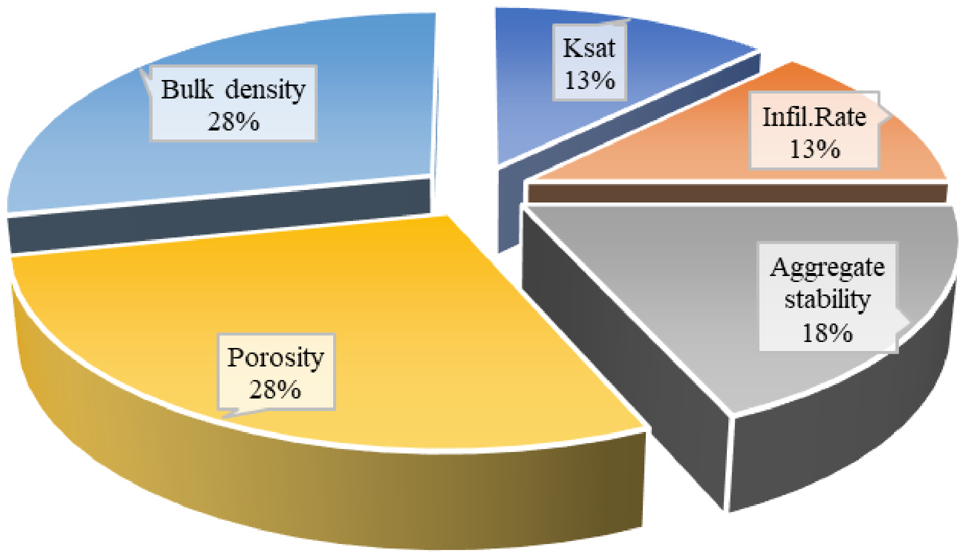

Figure S2.1. Proportion of soil physical health properties used in the meta-analysis. Ksat, saturated hydraulic conductivity and Infil.Rate, infiltration rate.

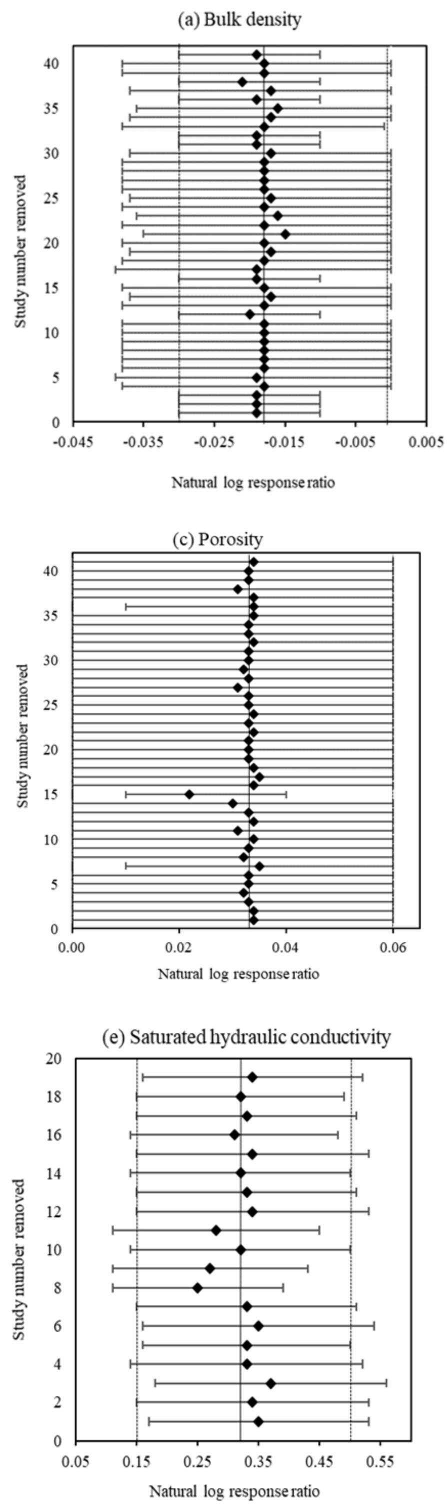

Figure S2.2. Jackknife analysis to determine the analysis's sensitivity to study inclusion. As individual studies were removed, the x-axis shows the change in mean effect size and revised 95% confidence intervals (CIs, y-axis). The solid line represents the original overall mean effect, while the dotted lines indicate the original 95% CIs.

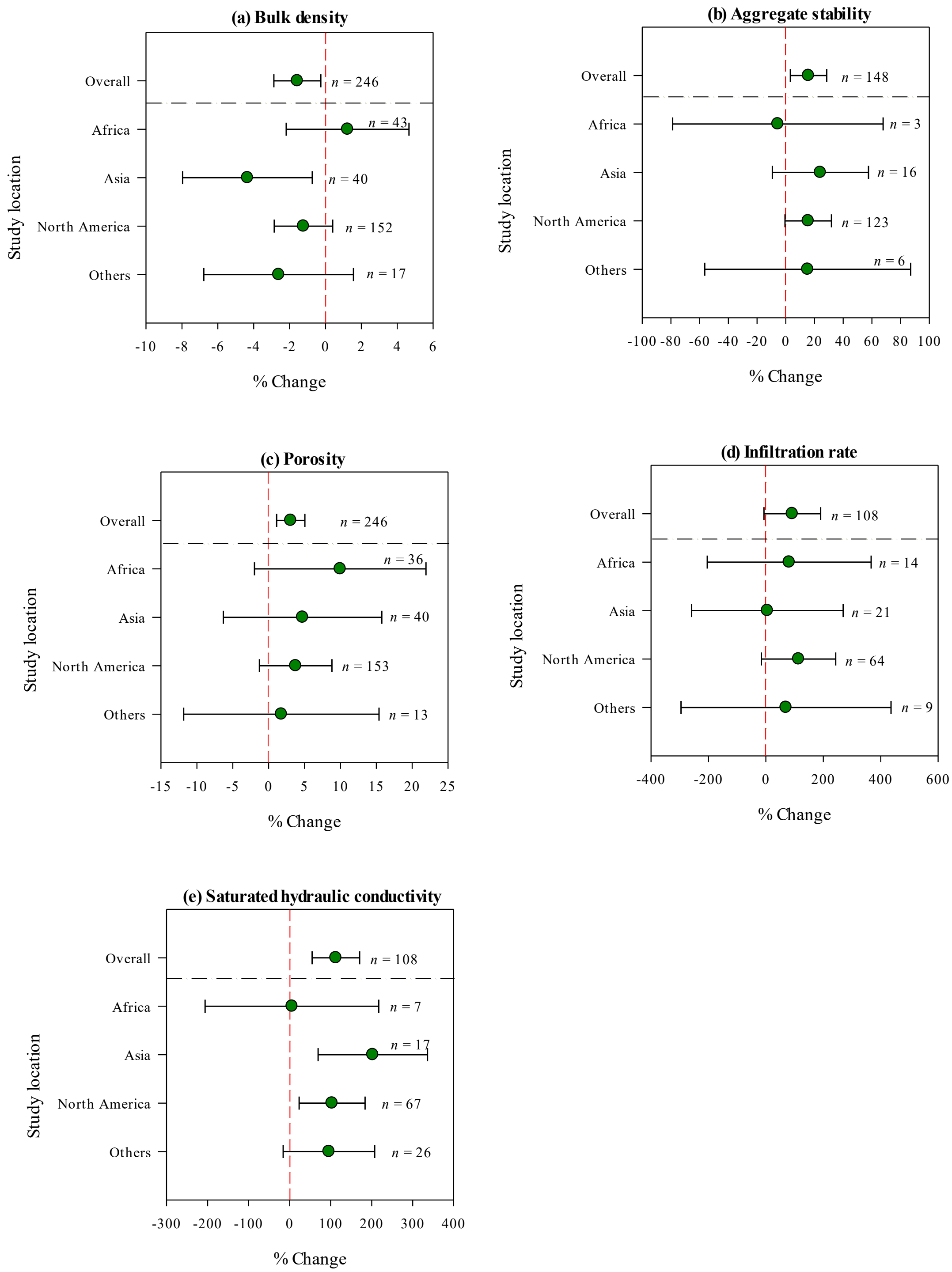

Figure S2.3. Crop diversity effect on soil physical health properties under different study regions. Means and confidence intervals (CI) are estimated using fixed effects for subgroups related to the region. Horizontal bars indicate the 95% CI, while error bars not overlapping zero (broken vertical line) indicate a significant decrease or increase at $P < 0.05$ (n = number of paired comparisons).

Supplementary Materials

3. Soil Organic Matter and Aggregate Stability Dynamics under Major No-till Crop Rotations on the Canadian Prairies

Iheshiulo, E.M.-A., Larney, F.J., St. Luce, M., Chau, H.W., Lui, K., 2024. Soil organic matter and aggregate stability dynamics under major no-till crop rotations on the Canadian prairies. *Geoderma*, 442, 116777.

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Table S3.1. Average above-ground biomass [dry matter weight (DM)] at Lethbridge, Swift Current, and Scott. The mean is the average of straw across the fully phased rotation for each year.

Site	Crop rotation	Above-ground straw biomass (kg DM ha^{-1})				
		2018	2019	2020	2021	Average
Lethbridge	Conventional	1421	2582	3001	391	1849 b
	Pulse/oilseed intensified	1182	1794	2668	367	1503 b
	Diversified	1969	2064	2539	964	1884 b
	Market-driven	2771	3586	3521	393	2568 ab
	High-risk and high-reward	1186	1755	4173	916	2008 ab
	Soil health-enhanced	2752	2624	3989	1473	2710 a
	Overall mean	1880 b	2401 b	3315 a	751 c	
	P-value					
	Rotation	0.0002				
	Year	<0.0001				
	Treatment × Year	0.131				
Swift Current	Conventional	1207	4153	3912	1898	2792 bc
	Pulse/oilseed intensified	1520	3664	3838	1184	2552 bc
	Diversified	2049	3688	4632	1692	3015 ab
	Market-driven	1620	6309	3642	2615	3547 ab
	High-risk and high-reward	1243	3565	3433	1128	2343 c
	Soil health-enhanced	2077	4359	4381	2453	3317 a
	Overall mean	1619 b	4290 a	3973 a	1828 b	
	P-value					
	Rotation	<0.0001				
	Year	<0.0001				
	Treatment × Year	0.202				
Scott	Conventional	3312	5186	3725	1568	3448 ab
	Pulse/oilseed intensified	3491	4152	2774	1456	2968 bc
	Diversified	2853	3426	2831	1317	2607 c
	Market-driven	5057	5882	3298	2015	4063 a
	High-risk and high-reward	2613	3544	2642	1483	2570 c
	Soil health-enhanced	3341	3585	3293	1934	3038 bc
	Overall mean	3445 b	4296 a	3094 b	1629 c	
	P-value					
	Rotation	<0.0001				
	Year	<0.0001				
	Treatment × Year	0.061				

Note: means followed by the same letter within the same row or column are not significantly different at $P < 0.05$.

Supplementary Materials

5. Quantitative Evaluation of Soil Health Based on a Minimum Dataset Under Various Short-term Crop Rotations on the Canada Prairies

Iheshiulo, E.M.-A., Larney, F.J., St. Luce, M., Chau, H.W., Lui, K., 2024. Quantitative evaluation of soil health based on a minimum dataset under diverse crop rotations on the Canadian prairies.

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Table S5.1. Result of principal component (PC) analysis of total dataset (TDS) across sites (combined dataset). Boldface factor loading values are considered highly weighted, while boldface and underlined loading values correspond to the indicator included in the minimum dataset (MDS) for the soil health index calculation.

Soil indicators [a]	Principal components				TDS	
	PC1	PC2	PC3	PC4	Comm.	weight
TC	−<u>**0.331**</u>	−0.107	0.200	−0.209	0.205	0.051
SOC	**−0.346**	−0.134	0.107	−0.194	0.187	0.047
TN	**−0.353**	−0.101	0.106	−0.106	0.157	0.039
POMC	**−0.362**	−0.053	0.017	0.018	0.134	0.034
POMN	**−0.360**	−0.060	0.048	0.003	0.136	0.034
AS	−<u>**0.331**</u>	−0.021	−0.249	0.064	0.176	0.044
BD	0.138	−<u>**0.637**</u>	0.090	−0.131	0.450	0.113
TP	−0.141	**0.635**	−0.112	0.119	0.450	0.112
FC	−0.241	−0.185	−0.369	0.450	0.431	0.108
PAWC	0.188	−0.301	−0.240	<u>**0.517**</u>	0.451	0.113
Macroporosity	−0.200	0.064	0.427	<u>**0.543**</u>	0.521	0.130
Mesoporosity	0.168	0.022	<u>**0.685**</u>	0.241	0.556	0.139
Microporosity	0.273	0.121	−0.073	−0.184	0.128	0.032
PCs' parameter						
Eigenvalue	7.197	1.995	1.295	1.164		
Explained variance, %	55.360	15.344	9.959	8.954		
Cumulative variance, %	55.360	70.704	80.663	89.617		
			MDS			
Weight	0.618	0.171	0.111	0.100		

[a] TC, total carbon; SOC, soil organic carbon; TN, total nitrogen; POMC, particulate organic matter carbon; POMN, particulate organic matter nitrogen; AS, aggregate stability; BD, bulk density; TP, total porosity; FC, field capacity; PAWC, plant-available water capacity; and comm., communality.

Table S5.2. Correlation matrix between soil health indexing (SHI) methods at Lethbridge, Scott, and Swift Current.

Indexing method [a]	Minimum dataset (MDS)				Total dataset (TDS)			
	SHI.LWA-MDS	SHI.LA-MDS	SHI.NLWA-MDS	SHI.NLA-MDS	SHI.LWA-TDS	SHI.LA-TDS	SHI.NLWA-TDS	SHI.NLA-TDS
Lethbridge, Alberta								
SHI.LWA.MDS	1.00							
SHI.LA.MDS	0.96***	1.00						
SHI.NLWA.MDS	0.93***	0.94***	1.00					
SHI.NLA.MDS	0.89***	0.94***	0.98***	1.00				
SHI.LWA.TDS	0.97***	0.96***	0.89***	0.87***	1.00			
SHI.LA.TDS	0.95***	0.90***	0.85***	0.80***	0.98***	1.00		
SHI.NLWA.TDS	0.94***	0.96***	0.98***	0.97***	0.96***	0.91***	1.00	
SHI.NLA.TDS	0.96***	0.94***	0.95***	0.92***	0.97***	0.96***	0.98**	1.00
Scott, Saskatchewan								
SHI.LWA.MDS	1.00							
SHI.LA.MDS	0.94***	1.00						
SHI.NLWA.MDS	0.99***	0.95***	1.00					
SHI.NLA.MDS	0.93***	0.99***	0.96***	1.00				
SHI.LWA.TDS	0.93***	0.81***	0.91***	0.81***	1.00			
SHI.LA.TDS	0.90***	0.76***	0.86***	0.75***	0.98***	1.00		
SHI.NLWA.TDS	0.95***	0.85***	0.94***	0.86***	0.99***	0.96***	1.00	
SHI.NLA.TDS	0.92***	0.80***	0.90***	0.80***	0.98***	0.99***	0.98***	1.00
Swift Current, Saskatchewan								
SHI.LWA.MDS	1.00							
SHI.LA.MDS	0.95***	1.00						
SHI.NLWA.MDS	0.98***	0.93***	1.00					
SHI.NLA.MDS	0.95***	0.98***	0.97***	1.00				
SHI.LWA.TDS	0.94***	0.99***	0.93***	0.97***	1.00			
SHI.LA.TDS	0.95***	0.96***	0.93***	0.95***	0.99***	1.00		
SHI.NLWA.TDS	0.94***	0.97***	0.96***	0.99***	0.99***	0.97***	1.00	
SHI.NLA.TDS	0.94***	0.95***	0.96***	0.97***	0.98***	0.99***	0.99***	1.00

[a] SHI.LWA.MDS, linear weighted additive SHI; SHI.LA.MDS, linear additive SHI, SHI.NLWA.MDS, non-linear weighted additive SHI; SHI.NLA.MDS, non-linear additive SHI; SHI.LWA.TDS, linear weighted additive SHI; SHI.LA.TDS, linear additive SHI, SHI.NLWA.TDS, non-linear weighted additive SHI; and SHI.NLA.TDS, non-linear additive SHI.

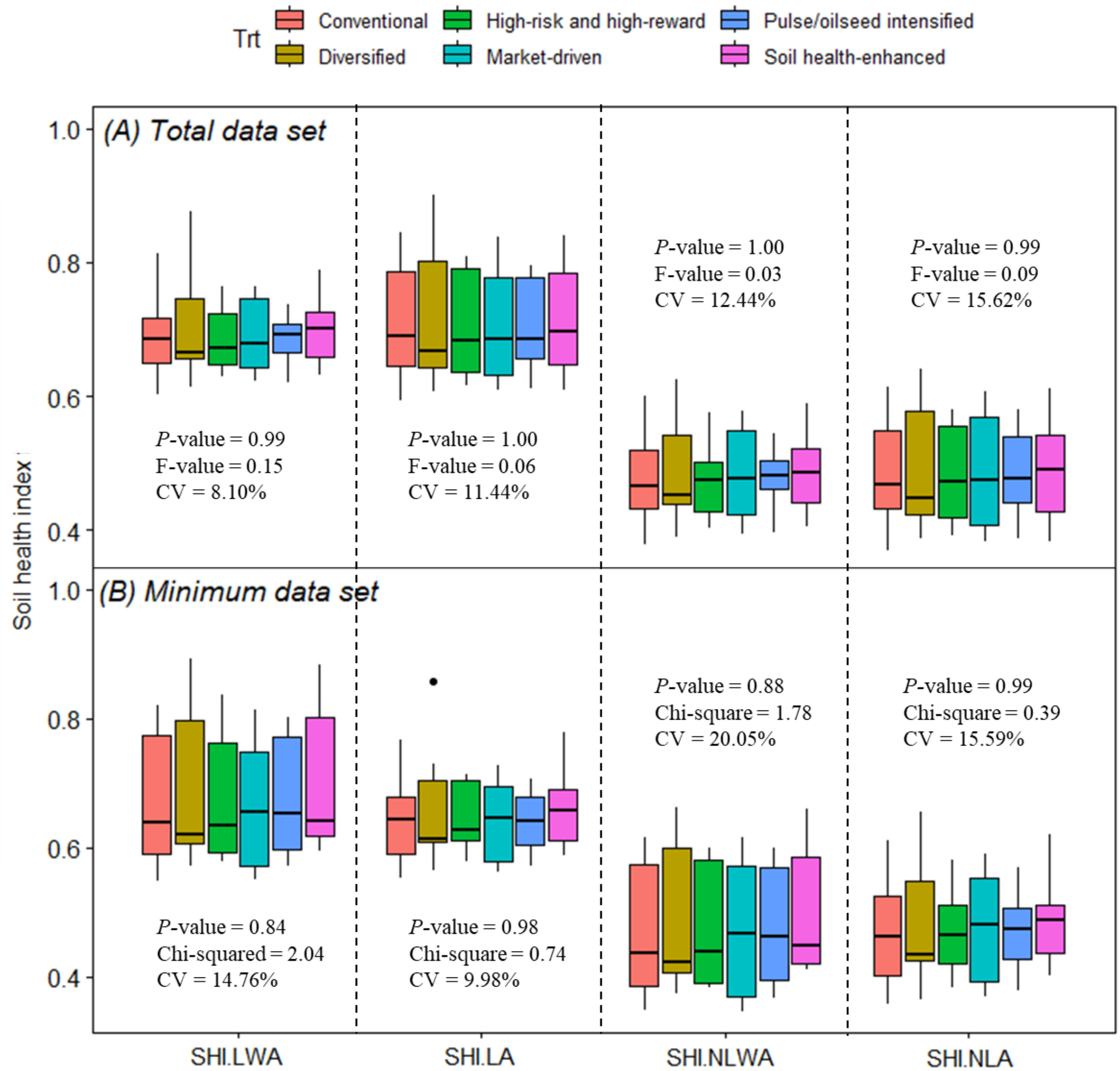

Figure S5.1. Soil health index (SHI) developed under different crop rotations across sites (combined dataset). SHI values were calculated using the (A) total and (B) minimum datasets. Mean SHI values did not significantly differ at $P > 0.10$. SHI.LWA, linear weighted additive SHI; SHI.LA, linear additive SHI, SHI.NLWA, non-linear weighted additive SHI; SHI.NLA, non-linear additive SHI; and CV, coefficient of variance. The *P*- and F-values were from ANOVA test results, while black dots outside the boxplot represent outliers.

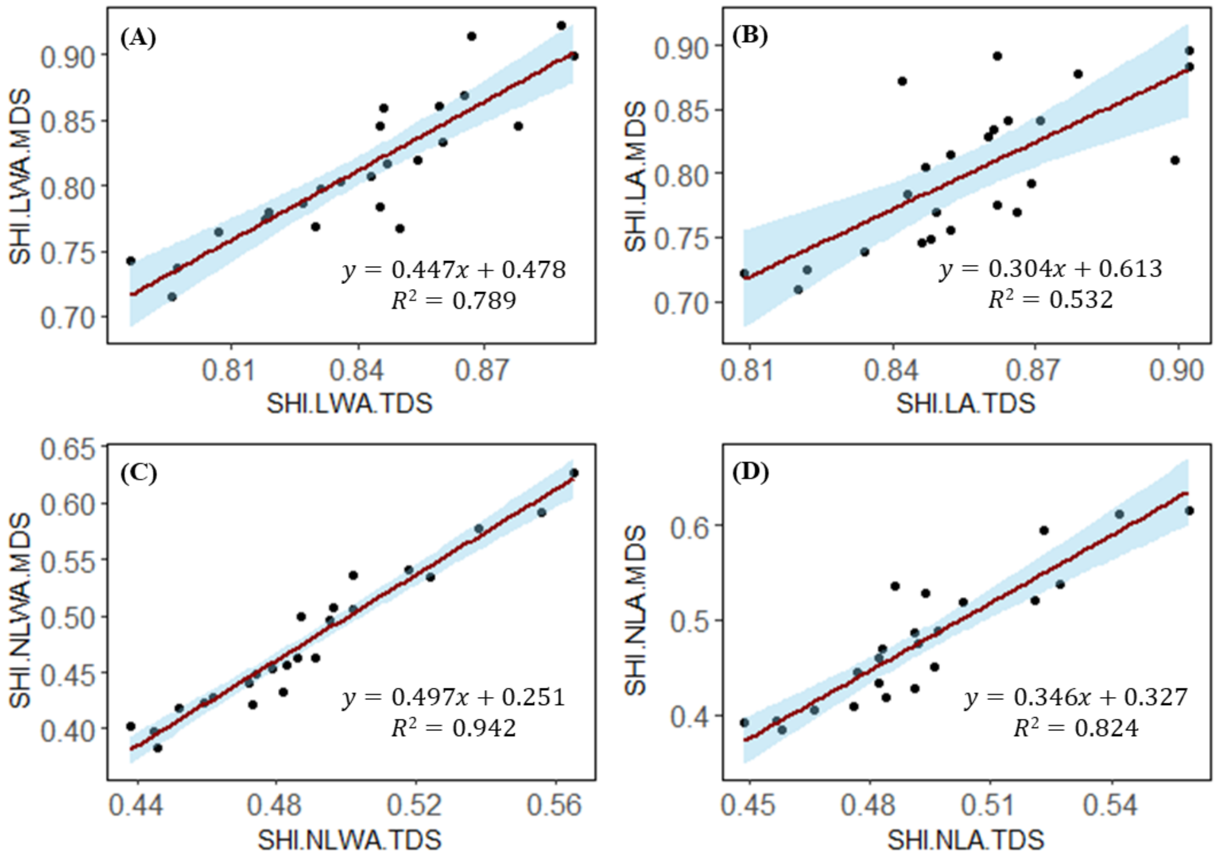

Figure S5.2. Regression analysis showing the relationship between calculated soil health index (SHI) using the total (TDS) and minimum (MDS) datasets at Lethbridge, Alberta. SHI.LWA, linear weighted additive SHI; SHI.LA, linear additive SHI, SHI.NLWA, non-linear weighted additive SHI; and SHI.NLA, non-linear additive SHI.

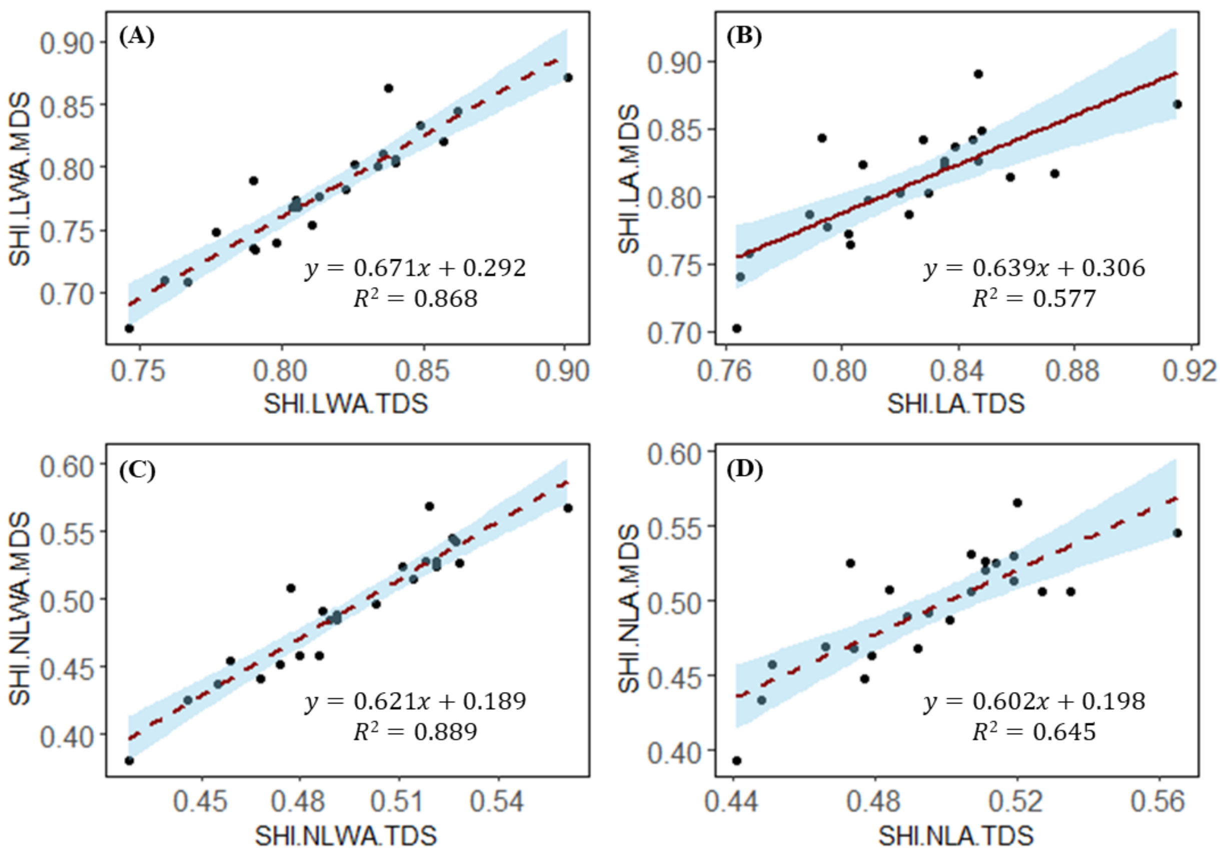

Figure S5.3. Regression analysis showing the relationship between calculated soil health index (SHI) using the total (TDS) and minimum (MDS) datasets at Scott, Saskatchewan. SHI.LWA, linear weighted additive SHI; SHI.LA, linear additive SHI, SHI.NLWA, non-linear weighted additive SHI; SHI.NLA, and non-linear additive SHI.

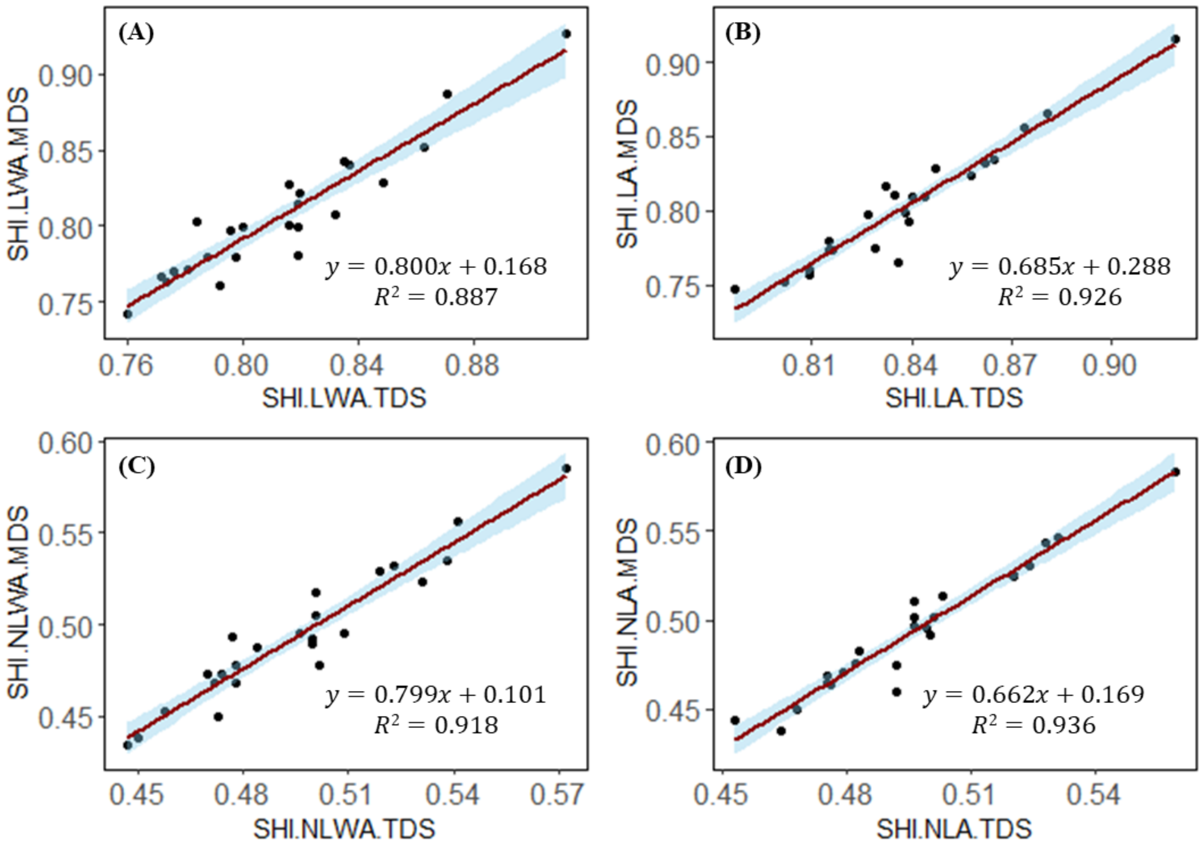

Figure S5.4. Regression analysis showing the relationship between calculated soil health index (SHI) using the total (TDS) and minimum (MDS) datasets at Swift Current, Saskatchewan. SHI.LWA, linear weighted additive SHI; SHI.LA, linear additive SHI, SHI.NLWA, non-linear weighted additive SHI; and SHI.NLA, non-linear additive SHI.