

**Evaluating the impact of subsurface drainage and subirrigation on
wheat production in heavy clay soils**

By

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A thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
In partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

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Abstract

Effective water management is crucial for optimizing crop productivity. This study investigated the effectiveness of subsurface drainage and subirrigation in managing soil water for wheat production in heavy clay soils at Arborg, Manitoba. Field experiments were conducted at the Prairie East Sustainable Agriculture Initiative (PESAI) farm at Arborg, Manitoba. Different subsurface drainage designs (30-ft (9.1 m) and 45-ft (13.7 m) spacing) were used for subirrigation during the 2022 and 2023 growing seasons. Soil moisture response under these systems was assessed at 0.2, 0.6, and 0.9 m depths using soil moisture sensors for continuous monitoring throughout the growing season. In 2022, with above-average rainfall, controlled drainage removed adequate amount of water and resulted in significantly higher yield ($p < 0.05$) midway-between-tiles in the 30-ft spacing plot compared to the non-tiled control. In contrast, during the dry year of 2023, despite subirrigation, yield from the 30-ft plot was lower than the average yield in the Interlake region due to insufficient water. However, the on-tile treatment in the 45-ft plot and control (non-tile) plot produced significantly ($p < 0.05$) above-average yields in 2023 due to less water being drained from the field compared to the 30-ft plot. The data from this research was used to calibrate and validate the DRAINMOD model to assess the influence of tile drain spacing and subirrigation on relative yield in 2021, 2022 and 2023. Simulation results indicated that in 2022, relative yields in the 30-ft and 45-ft plots were 97.2% and 97.0%, respectively. Subirrigation reduced drought stress in the 15-ft plot during 2021, a dry year. A six-day planting delay caused a 5.2% yield loss in 2023. These findings demonstrated the importance of optimally managing controlled drainage systems to enhance wheat yield in heavy clay soils.

Acknowledgements

I am eternally grateful to the universe for guiding me through my studies and enhancing my career. I would like to express my deepest gratitude to my advisor, Dr. Sri Ranjan, for accepting me as his student and for his unwavering support and guidance throughout this study. I also extend my heartfelt thanks to my committee members, Dr. Jian and Dr. Mante, for their invaluable guidance and insights.

I am especially grateful to my mother, Uma Karikalan, my father, Karikalan Paramasivan, my brother, Rishivarman Karikalan, my beautiful daughter, Biragathee Pakalavan, and my aunt, Ponmathy Pathmavarathan, for their unconditional support and encouragement throughout my entire academic journey.

A special appreciation goes to Thushyanthy Akileshan, a supportive lab mate and friend, for her assistance in my research work. I am also thankful for my encouraging lab mates Ishmeet, Ifeoluwa, Harmeen, Komlan, Mujibur, and Rahul. I would like to extend my gratitude to Emeka Leonard Ndulue for resolving the DRAINMOD problems and Akileshan Vamadevan for accompanying me to the field.

I acknowledge the funding support from the Sustainable Canadian Agricultural Partnership, Manitoba Agriculture, and the Government of Canada. I also want to thank Sass Alison of Manitoba Agriculture for providing the weather data used in Chapters Three and Four. I greatly appreciate the support from the PESAI team, especially Dr. Nirmal Hari and Shaun, in collecting soil moisture and yield data.

I am sincerely grateful to the University of Jaffna for providing me with a strong foundation in agriculture, which has significantly contributed to my success in my academic studies.

Lastly, I want to thank my friends Thulasi Raman, Kavimughil, David, Logesh, Chitra and Thirukumaran for their emotional support and care during the challenging times of my studies.

Dedication

To my dearest daughter, whose love and presence give my life endless meaning. Though I missed precious moments, every step I took was for our future.

To my beloved parents, who not only raised me but also cared for my daughter with unwavering love and sacrifice. Your strength and support made this possible.

With all my love and gratitude, I dedicate this work to you.

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CHAPTER ONE

GENERAL INTRODUCTION

1.1. Background of research

Water management plays a significant role in modern agriculture as we strive to meet food security for the rising population. The United Nations has predicted that the global population will increase to 9.8 billion by 2050 (United Nations 2017). According to the 2021 Census of Agriculture, in the Canadian Prairies, 59.5% of the land is used for crop production (Statistics Canada 2025). About 95% is dry-land agriculture, and 2-4% is supplemented with irrigation (CANCID 2014). Depending on the sub-climate and soil type, seasonal waterlogging and drought conditions may occur, which affect sustainable crop production.

In Manitoba, precipitation patterns show significant spatial and temporal variability. According to Manitoba Agriculture's weather condition reports, total accumulated precipitation varies significantly across the province, with some regions receiving as little as 31% of normal rainfall (73.3-127.2 mm) (Kola-Southwest Manitoba). Others experience up to 135% of normal precipitation (Pas-Northwest Manitoba) (Manitoba Agriculture 2024). This variability necessitates adapting water management strategies across the province.

According to the Government of Manitoba, approximately 12% of the province is considered arable agricultural land (Government of Manitoba 2024). Within that 12% agricultural portion, heavy clay (> 60% clay) areas (the Red River Valley and similar locales) are regionally important (Brierley 1997; Manitoba Agriculture 2024). It represents 1-2% of Manitoba's land (Manitoba Agriculture 2024; Agriculture and Agri-Food Canada 2002). Water

management for heavy clay soils is inherently challenging due to their low permeability and high water retention capability. Excess moisture delays planting, creating anaerobic soil conditions that stunt growth and predispose plants to root diseases (Reeves et al., 2022).

Waterlogging is a major cause of yield loss. Wheat yield reductions of 5-50% has been reported depending on the timing and duration of waterlogging (Wang et al. 2023). Historical crop insurance data show that planting delays due to saturated clay fields dramatically reduce yield (Manitoba Agriculture 2023). If seeding is pushed back by even one week due to spring flooding, wheat yields can drop 6-7% (Hussai et al. 2018; Narang et al. 2024). Prolonged drought through flowering and grain fill can cause catastrophic yield losses of 58-90% (Ji et al. 2017). Even mild water deficits at flowering can cut yields by up to 30% (Ji et al. 2017).

Also, there is a high risk of surface crusting in dry conditions due to high-intensity rainfall, reducing infiltration and exacerbating crop drought stress, leading to reduced yield (Leeds-Harrison et al. 1986). Mid-season drought typically causes 25-50% yield reductions in wheat grown on heavy clay soils (Campbell et al.1988; Kirkegaard et al. 2007). Drought during grain filling leads to 10-20% lower kernel weight (Lafond et al. 1994; Rajpar et al. 2018).

With the associated costs, the region's water dynamics variability necessitates adopting integrated management systems to manage water for sustainable crop production. In the past 15 years, the usage of tile drains and surface drains has been accelerated to remove excess water from fields in Manitoba (Kokulan 2019; Mante et al. 2018). Surface drainage removes excess water from the soil surface, and subsurface drainage focuses on removing excess water from the soil profile to lower the water table (Guitjens et al. 1997; Cordeiro and Sri Ranjan 2012; Mante et al. 2018). Subsurface drainage systems enhance root penetration, nutrient availability, and plant growth by improving soil aeration and reducing excess moisture.

Studies in Manitoba highlight that subsurface drainage systems in clay-dominated regions require 4.6-13.7 m (15-45-ft) tile spacing to mitigate saturation and improve crop yields (Manitoba Agriculture 2005; Ndulue and Sri Ranjan 2022). Considering the risk of drought during the mid-season in the region, such close subsurface drainage spacing and typical depth (0.9 m) of tile placement can be leveraged for subirrigation to meet the crop water demands in the mid-season (de Wit et al. 2024). However, the effectiveness of such a system is dependent on the type of soil, weather, design criteria, economy, agronomic practices, field data availability, and experience. Using subsurface drainage for subirrigation in heavy clay soils has not been explored in Manitoba.

In this study, subsurface drainage at 0.9 m depth and spacings 4.6 (15-ft), 9.05 (30-ft) and 13.7 (45-ft) m depths were installed in heavy clay soil at the Prairie East Sustainable Agriculture Initiative (PESAI) Arborg, Manitoba to evaluate the effectiveness of tile drainage system utilized for subirrigation to manage soil water for wheat production. Also, DRAINMOD was used to simulate water table elevation under different subsurface drainage spacings and subirrigation events during the growing season and determine the impact of the water table elevation on wheat yield.

1.2 Objective of the research

The overall objective of this research was to evaluate the effectiveness of subsurface drainage utilized for subirrigation to manage soil water for wheat production in heavy clay soils at Arborg, Manitoba. The specific objectives were to:

- evaluate the impact of different subsurface drainage spacing (9.05, 13.7 m and no-drain) and subirrigation on soil water content during the growth stages of wheat production

- evaluate the effectiveness of DRAINMOD in simulating water table response to different tile drain spacing and subirrigation events to meet wheat water demand for optimal yield.

1.3 Scope of the research

This research focuses on the primary challenges that limit agricultural production and efficient water management in the Canadian Prairies. It aims to enhance wheat production in Southern Manitoba by implementing subsurface drainage and subirrigation systems.

This research comprises five chapters. Chapter One provides the general introduction, which covers the background information that supports this research, the research objective, and the scope. Chapter Two presents the literature review on several aspects of wheat production and water management for sustainable production. Chapter three evaluates the impact of different subsurface drainage spacing and subirrigation on soil water content during the growth stages of wheat production. Chapter four evaluates the effectiveness of DRAINMOD in simulating water table response to different tile drain spacing and subirrigation events to meet wheat water demand for optimal yield. Chapter five provides conclusions from the research and recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1. Wheat (History, type, nutritional composition)

Wheat is one of the first cereals to be domesticated during human evolution. Wheat grains and their products are significant in the human diet (Sherway and Hey 2015). Wheat was first cultivated 10,000 years ago in the Neolithic Revolution, transitioning from hunting and gathering to cultivation. Wheat genetics has changed dramatically naturally and artificially during domestication, and the current worldwide cultivars are mainly two types: *Triticum aestivum* (Bread wheat) 95% cultivars and *Triticum durum* (Durum wheat) 5% cultivars (Sherway and Hey 2015). Bread wheat has more than 25,000 varieties (Feldman et al. 1995). Wheat can be classified into white and red wheat, soft and hard wheat, spring and winter wheat, and weak and strong wheat. These classifications are based on endosperm texture, seed coat, dough strength, colour, and planting season (Khalid et al. 2023). Among them, the standard wheat classification is spring and winter wheat. Spring wheat is cultivated in cold regions once the snow melts, and it has a total spring period to grow and mature. Whereas winter wheat is cultivated in moderately cold places before the snowfall, the saplings will be covered by snow and undergo vernalization. The crop starts to grow right after the snow thaws in the spring. Comparatively, winter wheat flourishes more by eliminating the delayed planting caused by the snowmelt. However, in warmer climate conditions, there is not much difference between spring and winter wheat (Khan 2016).

Next to corn, wheat is the second most widely produced grain variety globally. Global wheat consumption has gradually increased over the past years, and 791 billion kg was consumed in

2022/2023 (Statista 2024). Wheat contains more than 60-70% starch, which could be the sole source that satisfies the calorie needs of a human. It contains 10-20% protein (Šramková et al. 2009; Iqbal et al. 2022). Among 20 amino acids, 10 are essential (cannot be synthesized by animals) for human and animal growth and development (Sherway and Hey 2015). It is also a good source of vitamins B, K, E, A, C, iodine, sodium, magnesium, molybdenum, potassium, zinc, aluminum, copper, phosphorus, sulphur and iron (Khalid 2023).

2.2. Wheat lifecycle

Different scale systems describe the growth stages of wheat. Feekes, Zadoks, and Hayn scales are the most widely used scales. Zadoks is the most descriptive scale (Miller 1999). Spring wheat and winter wheat have significantly different life cycles. Winter wheat is subjected to vernalization before flowering, and it needs cold weather to initiate flowering. It has a prolonged vegetative period compared to spring wheat (Acevedo et al. 2002).

Spring wheat growth stages can be classified into ten principal stages according to Zadok scale system: germination (0); seedling development (1); tillering (2); stem elongation (3); booting (4); head emergence (5); flowering (6); milk development in kernel (7); dough development in kernel (8) and Ripening (9) (Zadoks et al. 1974). The studies by Khadka et al. (2020), Simmons (1987) and Acevedo et al. (2002) simplified the growth stages of spring wheat into seven stages, i.e. germination, seedling growth, tillering, stem elongation, heading, anthesis and grain filling. However, in our research, it is simplified into three classifications: early-stage, which includes germination, seedling growth and tillering; mid-stage, which includes stem elongation, heading and anthesis; and final-stage, which is grain filling/maturation.

2.3. Wheat physiology and abiotic stress

Abiotic stress refers to the impact of environmental conditions, individually or in combination, on the growth of crops. Various abiotic factors, including water stress, drought stress, heat stress, cold and freezing, salinity, and heavy metal toxicity, have negatively impacted the different wheat growth stages. Water stress is common for most crop production. The water deficit could stress plant growth when the evapotranspiration (ET) rate exceeds the water absorption rate. Crop evapotranspiration exhibits a direct and proportional correlation with grain yield. A study by Gupta et al. (2001) reported that the water stress at different stages affected crop growth and performance. In the anthesis stage, stress affects the shoot dry mass, grain numbers, and yield, while stress at the boot stage reduces the crop height and number of tillers.

Changes in precipitation patterns also cause drought stress in crops that would limit photosynthesis and lead to poor grain development. A study by Golfam et al. (2021) indicated that soil dryness affects starch synthesis and reduces nutrients, including fat and amylase content. Heat stress is another abiotic factor linked to water stress that affects wheat production and quality. In extreme heat situations, the transpiration mechanism keeps the crop cool. However, if there is water stress and the stomata of leaves close, the transpiration rate will decline and ultimately stop. That results in a rise in plant internal temperature more than the environmental temperature. Heat stress significantly reduces seed germination, growth and development, plant water uptake efficiency, and a crop's photosynthesis and total biomass. The rising temperature could cause a 6% reduction in global wheat production with each degree of rise in temperature (Zhao et al. 2017). Cold temperatures also affect wheat crops. Acevedo et al. (2002), Livingston et al. (2016), and Zheng et al. (2018) reported that in temperate regions, freezing temperatures in the spring season will significantly affect the growth of wheat.

The reproductive stage is more susceptible to freezing temperatures. In contrast, Li et al. (2014) reported that crops experiencing early spring cold could produce more tillers and improved tolerance to late spring freeze, reducing yield loss. However, severe frost could cause necrosis and death of crops (Acevedo et al. 2002). According to FAO, over 6% of the global area is affected by either salinity or sodicity — poor water quality, poor drainage, and high evapotranspiration cause salinity in soil (Turki 2012). Wheat is moderately tolerant to salinity; however, increased soil salinity could reduce the biomass of cell growth. Electrical conductivity above 4.5 dS/m will decrease the number of plants growing per unit area, and if the salinity is above 8.8 dS/m, it will reduce the plant emergence by 50% (Francois et al. 1986).

Two main factors could alleviate these abiotic stresses: i. Breeding techniques, ii. Agronomic practices. Many researchers have developed different hybrids and breeds that are tolerant or resistant to abiotic factors. However, several other factors also influence farmers' selection of wheat cultivars, mainly the demand and product purpose, which play a significant role in the selection of wheat.

According to Canadian Grain Commission Regulations, seven major cultivars are grown in Eastern Canada, and ten different cultivars are grown in Western Canada. The four main types of wheat grown in Canada are: Canada Western Red Spring (CWRS), Canada Western Amber Durum (CWAD), Canada Prairie Spring Red (CPSR), and Canada Eastern Soft Red Winter (CESRW). On the other hand, agronomic strategies are essential to manage available soil moisture, plant growth, biomass, and yield in different agroecological lands. Nezhandahmadi et al. (2013) and Schneeklth et al. (1991) reported managing the frequent drought stress through proper irrigation techniques and crop rotation. Schneeklth et al. (1991) also claimed that crop rotation of corn following the wheat in west central Nebraska for dryland had yielded 8% more

than corn-alone cultivation. Abbas and Sri Ranjan (2016) also reported that the yield of corn was 16% higher than that of the overhead irrigated plots than in the non-irrigated plots. This study also found that overhead irrigation improved the water quality by diluting the saline water table. Singh and Nelson (2020) reported that subsurface drainage and subirrigation had improved the maize yield in clay pan soil by more than 60% compared to the no-drain yield, even under low precipitation and dry conditions. It is also reported that the long-term yield in narrowly spaced subsurface drain tiles with subirrigation reduced the grain variability in dry and wet climates.

2.4. Soil moisture and its impact on soil and wheat

Soil moisture refers to water held in soil pores, which is critical for wheat growth as it regulates nutrient availability, root development and photosynthesis (Wang et al. 2023). Optimal soil moisture (Volumetric water content: 20-35%) ensures efficient water uptake, while deviation impairs physiological processes (Pais et al. 2023). In deficit moisture stress during jointing, tillering is reduced, while excess moisture stress during flowering lowers grain weight (Day and Intalap 1970). Monitoring soil moisture is essential to balance irrigation/drainage and mitigate yield losses (Pais et al. 2023).

2.4.1. Excess moisture

Waterlogging (soil saturation >90%) depletes soil oxygen, inhibiting root respiration and nutrient uptake in wheat (Barrett-Lennard 2003; Manitoba Crop Alliance 2021). In Manitoba clay soil, 7-day waterlogging at jointing reduces yields by 38% due to delayed tillering and head emergence (Crittenden et al. 2024; Manitoba Agriculture 2024). Prolonged saturation (>14 days) damages root membranes, increasing susceptibility to pathogens (Barrett-Lennard 2003). High-clay soils exacerbate waterlogging risks due to slow infiltration (0.3–3.3 mm/h) (Kandel et al. 2013, Manitoba Agriculture 2024).

High clay content in soil can cause soil particles to agglomerate, leading to increased pore size and improved aeration quality and water circulation (Li et al. 2019; Nimmo 2004). This can be helpful for crop growth. However, excess water content surpassing the soil water holding capacity can damage the soil agglomeration, resulting in smaller pore size and more compacted soil (Kemper and Rosenau 1984), which can restrict crop root development and harm crop development.

2.4.2. Soil moisture deficit

Drought stress (<15% volumetric water content) reduces wheat photosynthesis by 40–60%, shortening grain-filling periods (Farook et al. 2014; Liwani 2017). In semi-arid regions, irrigation at 45 mm potential soil moisture deficit (PSMD) maximizes yields ($R^2=0.89$) (Farooq et al. 2014). Deficit irrigation below 75 mm PSMD decreases tiller numbers and spike length, lowering yields by 25–30% (Namdeo et al. 2023).

2.5. Water table impact on soil and soil moisture

The groundwater table is the upper boundary of the saturated zone where soil pores are filled with water. It critically influences soil moisture availability, root development, and agricultural productivity by regulating water storage and movement in the root zone (Wang et al. 2015).

The primary water source in the Arborg is the shallow water table and precipitation. During the spring season, a high-water table limits the expansion of roots into deeper layers, and they remain confined to the near-surface layer. As crops mature, evapotranspiration lowers water tables to 1.5–2.0 m, enabling deeper root penetration and reducing hypoxia (Satchithanatham 2014; Manitoba Agriculture 2013). Research conducted by Satchithanatham and Sri Ranjan (2015) and Cordeiro (2014) has demonstrated that the water table in Southern Manitoba

fluctuates seasonally, reaching 2 m depth in summer. In this situation, irrigation could be a valuable source to supplement groundwater or precipitation to fulfill crop water requirements. Farmers use several types of irrigation practices, including surface, overhead, drip, and subsurface irrigation. Irrigated farming accounts for nearly 40% of global food production despite utilizing less than 18% of available arable land (Ayars et al. 2009). A thorough assessment of water quality, water usage, and farm management methods should be considered before applying irrigation to meet the agricultural water demand. Disregarding this impact and focusing on immediate development objectives such as profit and food security will negatively affect soil productivity and water resource availability (Mante et al. 2018; Wichelns and Oster 2006).

2.6. Water management in soil – Drainage

Drainage is an ancient technique employed by early civilizations to remove surplus water in periods of flooding. Smedema and Ochs (1997) state that almost one-third (33%) of agricultural land worldwide is subject to drainage. Early European immigrants introduced drainage systems to North America (Madramootoo et al. 2007), and it is now present in nearly all world regions. Drainage methods and practices have progressed from surface ditches and canals to subterranean drainpipes. Furthermore, it has progressed from using cumbersome clay and concrete tiles to using corrugated plastic tubing. The introduction of corrugated plastic tubing and the laser-controlled drain plow (initially created in Canada) significantly transformed the drainage sector (Madramootoo et al. 2007). Drainage is commonly employed in humid locations, but it also provides benefits in the semi-arid environment of the Canadian Prairies (Ayars et al. 2006; Mante et al. 2018; Dou et al. 2021; Ndulue and Sri Ranjan 2022).

Out of two drainage types, surface and subsurface drainage, surface drainage is a cost-effective method (Grigg et al. 2003). However, Madramootoo et al. (2001) countered that although surface drainage is adequate compared to subsurface systems in removing water, it limits the use of farm machines. Furthermore, scientific literature supports the idea that surface drainage has caused an increase in nutrient levels in water bodies. This is due to the greater runoff and peak outflow compared to subsurface drainage. Several studies have provided evidence for this, including those conducted by Schindler et al. (2012), Rabalais et al. (2007), Blann et al. (2009), Smith et al. (2015), King et al. (2015), Stamm et al. (1986), and Sharpley and Menzel (1987).

In contrast, subsurface drainage eliminates excess water located beneath the soil profile. It regulates salinity and maintains salt equilibrium within the profile (NRCS 2001). The method employs drainage ditches and subsurface perforated pipes to lower the water table to the intended level. This method is suitable for regions characterized by a high natural water table, inadequate internal drainage, and water-saturated soils (Madramootoo et al. 2001; Huffman et al. 2011). Subsurface drainage has increased due to intensified farming practices in North America and other parts of the world (Gramlich et al. 2018). It has been shown that artificially drained lands are the most productive when excessive rainfall or over-irrigation occurs (Skaggs et al. 1994). It removes gravitational water, and the water table is maintained at or below the level of the tile drains. This facilitates maintaining a lower water table, which is favorable for growing deeper roots and allowing field operations to proceed without obstruction.

There are several factors influencing the performance of drain tiles. The soil type significantly influences the amount and rate of tile drainage. Clark et al. (1988) discovered that

heavy clay soils have a delayed initial drainage response. Cracks that primarily develop during seasons of low moisture create pathways that rapidly rising drainage process (Clark et al. 1988).

The spacing of tile drains directly impacts the water discharged via the tiles. Hoover and Schwab (1976) discovered that using tile spacings of 9.1 m (30-ft) resulted in a 50% increase in tile flow discharge compared to using spacings of 15.2 m (50-ft). Schwab et al. (1961) compared 9.1 m and 18.2 m tile spacing. The study showed tile flow was significantly higher for the 9.1 m spacings than for 18.2 m. Plamenac (1988) graphed the rates at which water was discharged from tiles placed at different intervals in dense clay soil. While the maximum discharge volumes were comparable, tiles spaced wider exhibited longer drainage times. The drainage process for tiles placed 20 m apart required approximately 40 hours, whereas tiles placed 50 m apart needed approximately 125 hours. In the study by Ndulue and Sri Ranjan (2019), the controlled drain spacing plot (8 m apart) resulted in a higher yield of 3.51 Mg/ha than the no-drain plot and free-drain plot (15-m drain tile spacing) in sandy loam soil in Manitoba.

2.6.1. Free Drainage (FD)/ Conventional Drainage

Free drainage is considered the earliest form of subsurface drainage. It reduces the water table below the active root zone through gravity flow towards the drains using shallow drains, thereby increasing crop yield. In a three-year study conducted by Ndulue and Sri Ranjan from 2019 to 2021 in Southern Manitoba, the canola yield in 2021 from free drainage was greater at 1.52 Mg/ha compared to the control yield (1.14 Mg/ha) and the no drainage yield (1.07 Mg/ha). In their study, Schott et al. (2017) performed a five-year comparison of four drainage methods in Iowa: no drainage, shallow drainage, conventional drainage, and controlled drainage. The results indicated that shallow drainage was the most effective method, achieving a 60% reduction in flow and a 61% decrease in nitrate loss. In Nova Scotia, a study by Smith et al. (2019) found that

shallow drainage was more effective than controlled drainage and conventional drainage in reducing nitrate loading, resulting in a nitrogen load reduction of 54.9 to 73.1%.

2.6.2. Controlled drainage (CD)

Controlled drainage (CD) is an improved technique over free drainage (FD). It applies to a control structure on the outflow of a subsurface drainage system to manage or maintain the water table depth beneficial to crop roots. Many researchers have indicated the performance of CD in different climatic conditions, soil types, and crops. They reported that CD increases the yield, decreases the phosphorus and nitrate conditions, improves the economic profit and controls disease. Crabbe et al. (2012) reported that CD fields in the South Nation River basin in Eastern Ontario yielded 3 and 4% more corn and soybeans (2005-2009) than conventionally drained fields. The CD, controlled water tables can also decrease levels of the pesticide atrazine in shallow groundwater. Kalita and Kanwar (1992) observed an increase in corn yield in a conventionally drained field with a 2.5% slope when the water table depth increased from 0.3 m to 0.9 m in Nicollet silt loam soil.

However, subsurface drainage from fields to surface water bodies contributes to dissolved phosphorus (King et al. 2015). Hypoxia and harmful algal blooms can result from excess surface water nutrients (Brush et al. 2020). Many Southeastern Michigan and Northern Ohio residents' drinking water has been contaminated by algae in 2014. Water quality declined in 2015 due to algal blooms (International Joint Commission. 2015). Leaching nutrients into the water stream is a serious issue to consider in subsurface drainage practices.

2.7. Water management in soil –Subirrigation (SI)

Subirrigation (SI) is a potential method for minimizing nutrients leaching into water streams. It involves collecting and reusing drained water through drain tiles based on the specific water requirements of the crops. This has enhanced crop growth and nutrient uptake and ultimately increased the crop yield (Singh et al. 2022). A 5-year study by Drury et al. (2009) investigated the efficacy of CD with SI and FD in reducing phosphorus loss. According to their research, implementing CD with SI reduced total phosphorus and particulate phosphorus by 12% and 15%, respectively. According to Nelson et al. (2017), drainage and subirrigation decreased water use compared to overhead irrigation. These technologies enhance the resilience of maize output in years characterized by harsh weather events.

2.8. Role of Soil moisture sensors in soil water management.

Several methods are available to precisely measure the soil water content in the field. Soil moisture measurements are divided into two categories: classical methods and modern sensor methods. The classical method involves the removal of soil moisture through evaporation or chemical reaction to assess the moisture content. The two primary techniques used are thermo-gravimetric measurement and the calcium carbide procedure. The thermo-gravimetric approach is commonly known as the standard method. It involves obtaining soil moisture by drying soil samples in an oven. This method is used to calibrate other available methods. However, this method is destructive and cannot be repeated in the exact location over time (Zazueta and Xin 1994). The other method (calcium carbide technique) measures the soil moisture content of a specific soil sample, either in the field or in a laboratory. It involves a chemical reaction between calcium carbide and the moisture content in the soil. Nevertheless, this technique has challenges

when applied to high plastic clay soils or soils that retain excessive moisture within clumps (Su et al. 2014).

Modern sensor technologies utilize techniques such as measuring the electrical conductivity of the moist soil and utilizing radioactive and infrared radiation. The infrared moisture approach employs the principle of electro-balancing coupled with infrared heating to determine the moisture content in the soil. Innovative microprocessors help achieve precise, accurate, and fast measurement of soil moisture content. The primary constraints of this equipment include its limited sample weight of under 2-5 g, high cost, and exclusive use for laboratory measurements (Robinson et al. 2008; Terhoeven et al. 2008). Other modern techniques can be used in the laboratory and field. The neutron scattering technique (NMM) is one of the radioactive techniques where the radioactive source releases neutrons. These neutrons are then attenuated by the hydrogen nuclei of water molecules, causing the neutrons to slow down. A meter is used to detect these neutrons with low energy levels. The number of neutrons that are reduced in intensity is directly related to the hydrogen nuclei and, consequently, the amount of water in the soil system (Laryea et al. 1996; Mante et al. 2018). The neutron moisture meter is an exact method for measuring soil moisture. To minimize the risk of radiation release, it is necessary to have specialized staff training in radiation safety protocols and proper handling techniques (Evet 2003). The other radioactive method is the gamma attenuation technique. In this method, gamma-ray scattering and absorption help to evaluate the changes in saturated density. Which, in turn, allows for the determination of moisture content. However, Gamma rays are very hazardous, and their performance is restricted to 25 mm or less soil depth (Evet 2003).

Gypsum block sensors are a different technique for determining soil water potential. They assess soil conductivity and are mainly employed to monitor variations in soil matric potential.

The soil water retention characteristic curve for the particular soil is needed to transform the soil matric potential into volumetric soil water content (Mante et al. 2018).

A tensiometer is an apparatus that directly measures the soil's matric potential (capillary tension). This device utilizes a porous ceramic cup connected to a water-filled tube. The tube is inserted into the soil, and upon contact with the dry soil, fluid is drawn via the porous ceramic cup, establishing equilibrium with the soil moisture. The pressure decrease is quantified using a vacuum gauge connected to a tube.

The time domain reflectometry (TDR), frequency domain reflectometry (FDR), and capacitance sensors are three dielectric techniques used for soil moisture measurements. The dielectric difference in dry soil (2-5) and pure water (81) concept is used to measure soil moisture. A capacitance sensor employs the soil as a capacitor component and exploits the soil's ability to store charge to measure and adjust for water content. A time domain reflectometry (TDR) sensor quantifies the duration for an electrical energy pulse to travel over a transmission line and be reflected. The duration of the journey is dependent on the soil's capacity to store charge and its volumetric water content. Notably, TDR encompasses a spectrum of frequencies in the signal rather than just a singular frequency. It aids in mitigating errors caused by soil salinity. FDR utilizes the soil as a capacitor to determine the highest resonant frequency in the electrical circuit and establish a correlation between the resonant frequency and the moisture content. The temperature also affects electrical permeability (Selig and Mansukhani 1975; Campbell 1990; Topp et al. 1980).

Among all different types of soil moisture sensors, electrical conductivity (EC) sensors are cost-effective and provide continuous data. Moisture increases ion mobility, raising EC, which correlates with water content (Corwin and Lesch 2005). However, salinity and

temperature require calibration to avoid inaccuracies (Bogene et al. 2015). Dielectric sensors (e.g., TDR) mitigate salinity effects but are more expensive (Evelt 2003).

2.9. Simulation of hydrological processes in wheat growth and yield

Integrating the modelling of agricultural systems into field research is crucial for enhancing agriculture. Field studies are primarily restricted to specific measurements due to the high cost and time requirements when conducted across a larger area. Agricultural system models minimize this limitation of field studies. Multiple models are accessible for examining the influence of various hydrological processes on the dynamics of soil water flow. Among the widely used tools, HYDRUS, AquaCrop, RZWQM2, and DRAINMOD offer distinct capabilities for analyzing hydrological and agronomic processes.

The HYDRUS models simulate multi-dimensional water/solute transport using finite element method (FEM) in variably saturated soils (Simunek et al. 2022). Simunek et al. (2022) also reported that HYDRUS-3D supports complex geometries and dual-permeability flow in fractured clay. The HYDRUS-1D employs Richards' equation to simulate 1-D water and solute transport in variably saturated soils for soil moisture predictions in vertically layered systems (Taftah and Sepaskhah 2012). Its strength lies in modelling infiltration and salt leaching under drip irrigation. Though its 1-D framework limits lateral flow representation critical for tile-drained landscapes (Wang et al. 2021). In contrast, AquaCrop, developed by FAO, predicts yields in water-limited systems (Raes et al. 2009). It uses the canopy as a transpiration proxy to effectively schedule irrigation (e.g., maize $R^2=0.89-0.93$) (Raes et al. 2009). Its soil module lacks subsurface drainage functions (Kisekka et al. 2017).

The RZWQM2 combines crop growth and contaminant transport models. It analyzes tile drainage, nutrient flow, and crop productivity. Its drainage component requires more than 12 soil parameter calibrations (Ma et al. 2012). This limits applicability in data-scarce regions.

DRAINMOD empirically predicts water tables, drainage efficiency, and nutrient flow in different types of soils (Skaggs et al. 1890). It is one of the best models to predict hydrological effects in poorly drained soil (Singh et al. 2016; Skaggs et al. 1890). This software benefits the farmers due to its capability to predict the yield. Kandel et al. (2013) found that simulated yield correlation was improved by 18–22% on wheat and soybeans in heavy clay soil. DRAINMOD uses six inputs to simulate tile drain effects versus RZWQM's more than 25 (Cordeiro and Sri Ranjan, 2015). It assesses 4-year flood risks with 89% accuracy (Moriassi et al. 2015). In the study of Ale et al. (2010), the Nash-Sutcliffe efficiency coefficient (NSE) for DRAINMOD was $NSE=0.82$, which surpasses HYDRUS (0.61) and RZWQM (0.68). These findings suggested the efficiency of DRAINMOD over other software to simulate water table elevation, tile drain effect, and yield prediction.

Model performances are evaluated using both qualitative and statistical analysis.

Qualitative evaluation involves developing a graph that compares observed data to simulated data on a 1:1 scale with no intercepts. Standard statistical tests employed in hydrologic model evaluation comprise the coefficient of determination (R^2), Nash Sutcliffe efficiency (NSE), root mean square error (RMSE), mean percent error (MPE), and mean absolute error (MAE). Further chapters give specific information regarding statistical indices. Typically, when the NSE and R^2 values are close to 1, and the error indices (RMSE, MAE, MBE) are close to 0, it indicates a flawless model (Moriassi et al. 2015; Jackson et al. 2019).

Coefficient of Determination (R²)

The R² measures the proportion of the observed data variation explained by the predicted values. It reflects the model's performance, where a value of 1 indicates a perfect fit, and 0 suggests the model fails to explain any variation in the data.

$$R^2 = 1 - \frac{\sum_{i=1}^n (\text{Observed}_i - \text{Predicted}_i)^2}{\sum_{i=1}^n (\text{Observed}_i - \text{Mean}_{\text{Observed}})^2} \quad (1)$$

Root Mean Square Error (RMSE)

The RMSE calculates the square root of the mean of the squared differences between the observed and predicted values. This metric emphasizes larger errors, making it particularly sensitive to outliers.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\text{Observed}_i - \text{Predicted}_i)^2} \quad (1)$$

Average Absolute Deviation (AAD)

The AAD calculates the mean of the absolute differences between the observed and predicted values. This metric evaluates the overall deviation of the model's predictions from the observed data, treating all errors equally regardless of their direction.

$$AAD = \frac{1}{n} \sum_{i=1}^n | \text{Observed}_i - \text{Predicted}_i | \quad (2)$$

Nash-Sutcliffe efficiency (NSE)

The Nash-Sutcliffe Efficiency compares the model's predictive performance using the mean of the observed data as a predictor. It measures how well the model's predictions align with the observed values. An efficiency score of 1 indicates perfect agreement, while a score below 0 suggests that the model performs worse than simply using the observed mean.

$$E = 1 - \frac{\sum_{i=1}^n (Observed_i - Predicted_i)^2}{\sum_{i=1}^n (Observed_i - Mean_{Observed})^2} \quad (3)$$

Mean Bias Error (MBE)

Mean Bias Error (MBE) is a statistical metric used to measure the average bias (systematic error) between simulated (predicted) values and observed (actual) values. It helps determine whether a model systematically overestimates or underestimates the observed data. A positive MBE indicates model overestimation, while a negative MBE signifies underestimation. An MBE of zero means no systematic bias, as overestimations and underestimations balance out.

$$MBE = \frac{\sum (Simulated - Observed)}{n} \quad (4)$$

2.10. Summary of literature review

This chapter reviewed wheat and water management practices to improve crop growth and yield. Soil and water management practices are influenced by climate, soil type, crop selection, and data availability. Previous studies indicate that regions like Southern Manitoba require tailored approaches to address excess soil moisture. Subsurface drainage systems have been widely studied for improving crop yields by mitigating waterlogging. However, leveraging subsurface drainage design for subirrigation to support soil water management in wheat production has not been explored well in Manitoba. In past studies, the impact of subsurface drainage on heavy clay soil in Arborg, Manitoba, was evaluated by Ndulue and Sri Ranjan (2022). However, they did not account for subirrigation. Also, it is important to use advanced soil moisture water table monitoring in real-time due to variable moisture conditions. It was also demonstrated that a better understanding of local conditions is necessary for advancing soil water management systems for sustainable crop production.

CHAPTER THREE

EVALUATE THE IMPACT OF SUBSURFACE DRAINAGE AND SUBIRRIGATION DURING THE GROWTH STAGES OF WHEAT PRODUCTION IN HEAVY CLAY SOILS

Abstract

This study evaluated the impact of different subsurface drainage spacing (30-ft and 45-ft) and non-tile (control) and subirrigation through the tiles on soil water dynamics in heavy clay soil for wheat production in Arborg, Manitoba, over the 2022 and 2023 growing seasons. In 2022, characterized by above-average rainfall, 30-ft midway-between-tiles gave significantly higher ($p < 0.05$) yields compared to the non-tiled control plots. Under the drought conditions in 2023, 45-ft drain spacing on-tile treatment and control plots gave significantly higher wheat yield ($p < 0.05$) compared to the 30-ft tile spacing locations. Soil moisture sensors provided valuable insights into the water content at different depths (0.2, 0.6, and 0.9 m), showing soil water content near the lower end of the readily available water content across growth stages in 2023. The water table depth (WTD) remained below the tile drain depth (0.9 m) throughout the growing season in 2023. However, WTD fluctuations were observed during periods of subirrigation. Findings highlighted the necessity for better management of drainage systems using real-time soil moisture data. This research contributes to understanding water management in heavy clay soils, recommending precision agricultural practices to ensure sustainable and resilient wheat production.

3.1. Introduction

Canada is a major contributor to global agricultural production and exports of agricultural goods (FAO 2024). The primary agricultural region is the Canadian Prairies (Manitoba, Saskatchewan, and Alberta). These regions produce canola, wheat, barley, and pulses. Canada's wheat exports have consistently ranked high and typically in the top five globally (FAO, 2024). The 30-year average for global wheat exports ranks Canada second (FAO, 2024). In 2022, Canada's total wheat production reached 34.3 million tonnes, the highest production level since 2020 (Statistics Canada, 2023). However, wheat production decreased by 6.7% in 2023, with a total production of 32 million tonnes in Canada. This decline was mainly due to lower production in the Prairies, likely caused by dry conditions (Smith et al. 2024).

Wheat is the most widely cultivated crop in Manitoba. It generated \$1.68 billion in 2022 (Agriculture and Agri-Food Canada, 2023). Wheat production value increased by 15.7% to \$1.94 billion in 2023, despite a decline in total Canadian wheat output (Statistics Canada, 2024). It reached an average price of \$401 per tonne (\$0.401 per kg) in 2022. The anticipated price for 2023 was \$325 per tonne (\$0.325 per kg) (Agriculture and Agri-Food Canada, 2024). Several factors influence the annual wheat production and its market price. These include the area cultivated, specific crop type, management practices, prevailing weather conditions and soil water availability are key determinants (Brown & Miller, 2022).

Fluctuations in wheat production are often linked to hydrological extremes. These include waterlogging, drought, and heat waves (Anderson, 2021). The maturation of crops is influenced by heat accumulation. However, the potential yield is primarily determined by moisture availability. Research suggests climate change will bring seasonal shifts, with wetter springs and drier summers (Sauchyn and Kulshreshtha, 2008). This could severely impact farm operations

and lead to significant yield losses. Therefore, proper water management is essential to regulate soil moisture effectively. It also ensures optimal soil workability, trafficability, and timeliness of farm operations. Ultimately, this helps in attaining the maximum possible yield. Farmers cultivating in regions like Arborg face unique challenges due to the predominantly heavy clay soils and shallow water table (Ndulue and Sri Ranjan, 2022; Manitoba Agriculture, Food and Rural Initiatives, 2010). Regulating soil moisture is particularly difficult in this area due to waterlogging during wet seasons and water stress during dry periods (Singh and Nelson, 2021). Implementing subsurface tile drainage is a recommended practice. It enhances the trafficability of machinery and minimizes potential damage to the soil structure (Steinhardt and Trafford, 1974). Farmers have used subsurface (tile) drainage systems for years to drain excess soil water and lower the water table in humid regions (Kandel et al. 2013).

Drainage structures can also offer an additional benefit by holding back excess water for storage. This stored water can then be used for subirrigation during extended dry periods. However, the performance of these drainage systems is location-specific. Drainage is subject to change based on various influencing factors. It includes waterlogging, surface runoff, and the swelling property of clay (Towner and Youngs, 1986; Turtola and Paajanen, 1995). The specific effect of subsurface drainage and subirrigation on wheat yield in Arborg is yet to be studied. Understanding how water moves through the soil profile is vital for effective soil water management. Soil moisture sensors help understand the water movement in the soil. Various soil moisture sensors are commercially available to determine soil moisture. Approximately 3-4% of farmers in Southern Alberta utilize these sensors. They use them as part of their water management strategies (Wang et al. 2015). Utilizing soil moisture sensors to study the effect of tile drain spacing would provide valuable insights for farmers. These insights would be

particularly relevant for cultivating soils in Arborg to maximize crop yield potential. The objective of this research is to determine the effectiveness of different drain spacing (controlled drainage and subirrigation) on soil moisture dynamics and its impact on wheat yield in heavy clay soils.

3.2. Methodology

3.2.1. Study area

This study was conducted at Arborg, Manitoba, Canada's PESAI (Prairies East Sustainable Agriculture Initiative) research plot (latitude 50.9°N, longitude -97.3°W, elevation 229 m) during the growing seasons of 2022 and 2023. According to Bueckert et al. (2013), the area has warm summers and cold, dry winters due to its semi-arid climate. The region's topography is a 0.01% slope, which is almost levelled. The soil type is the poorly drained Fyala soil series, which is built up of Rego Humic Gleysol soil, which develops lacustrine clay layers that are weakly to moderately calcareous (Manitoba Agricultural 2010; Podolsky 1982). The soil in 0.3-0.2 m is heavy clay, which is hard when dry and firm when moist. The next 0.2-0.33 m is a dark grayish-brown soil that is extremely hard when dry and firm when moist. The next layer (0.33-0.51 m) is similar to the top 0.2 m (Manitoba Agriculture 2010). Due to its structural variability, impermeable layer formation might occur during dry or wet years. Due to its high clay content (> 60%), the soil is prone to shrinking and swelling. As a result, soil cracks are frequent in the fields (Ndulue and Sri Ranjan 2022). According to Ojo and Manaigre (2021) it has shallow water table depth and peat content. The bulk density of predominantly heavy clay is 1.07 g/cm³ (0-0.15 m red river heavy clay) (Ndulue and Sri Ranjan 2022). Seasonally, crops such as soybeans, canola, and wheat are planted in the allocated plots. The soil saturation point is 53.5% (Manitoba Agriculture 2020). The study area was divided into three plots with a length of 660 m and a

width of 30 m. Each plot was divided into three equal replicates, and a 5-m buffer zone separated the three main plots.

3.2.2. Experimental Design

The experimental area was divided into four sections, and plots were named T1, T2, T3, and T4 (Fig. 3.1). Drain tiles were installed at different spacings: T1- 4.57m (15-ft), T2- 9.1m (30-ft) and T3-13.7 m (45-ft), and T4-non-tile installed. In 2022, the experiment was conducted in the 30-ft drain spacing, the non-tile (Control) plot, and the 2023 experiment in the 30-ft, 45-ft drain spacing plots and the no-drain (Control) plot. These plots comprised three replicates (R1, R2, and R3). The dimensions of each block were 220 m in length and 30 m in width.

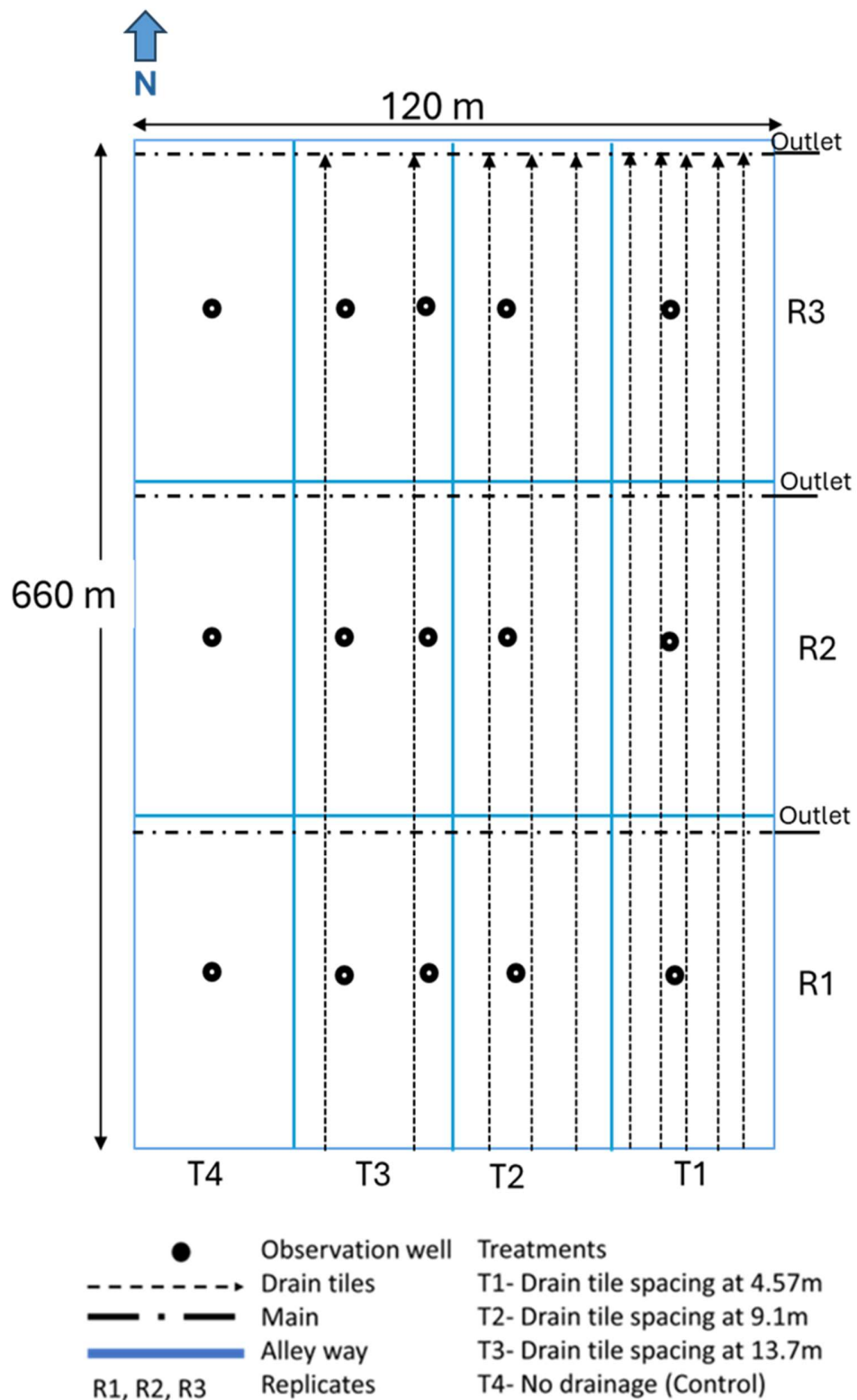


Fig. 3.1: Arborg field layout (Not to scale).

3.2.3. Instrumentation and data collection

3.2.3.1. Soil moisture monitoring

Soil moisture sensors (Meter ZL6 data logger, Hoskin Scientific, CA) were installed in each plot midway-between-tiles at three different depths, 0.2 m, 0.6 m and 0.9 m from the ground surface (Fig. 3.2). Sensors were connected to the data acquisition system in each plot. Sensors were used to measure the volumetric water content and soil temperature. In addition, the electrical conductivity was also measured at 0.2 m. Real-time data updates were received and stored in the Zentra cloud at one-hour intervals throughout the growing season.

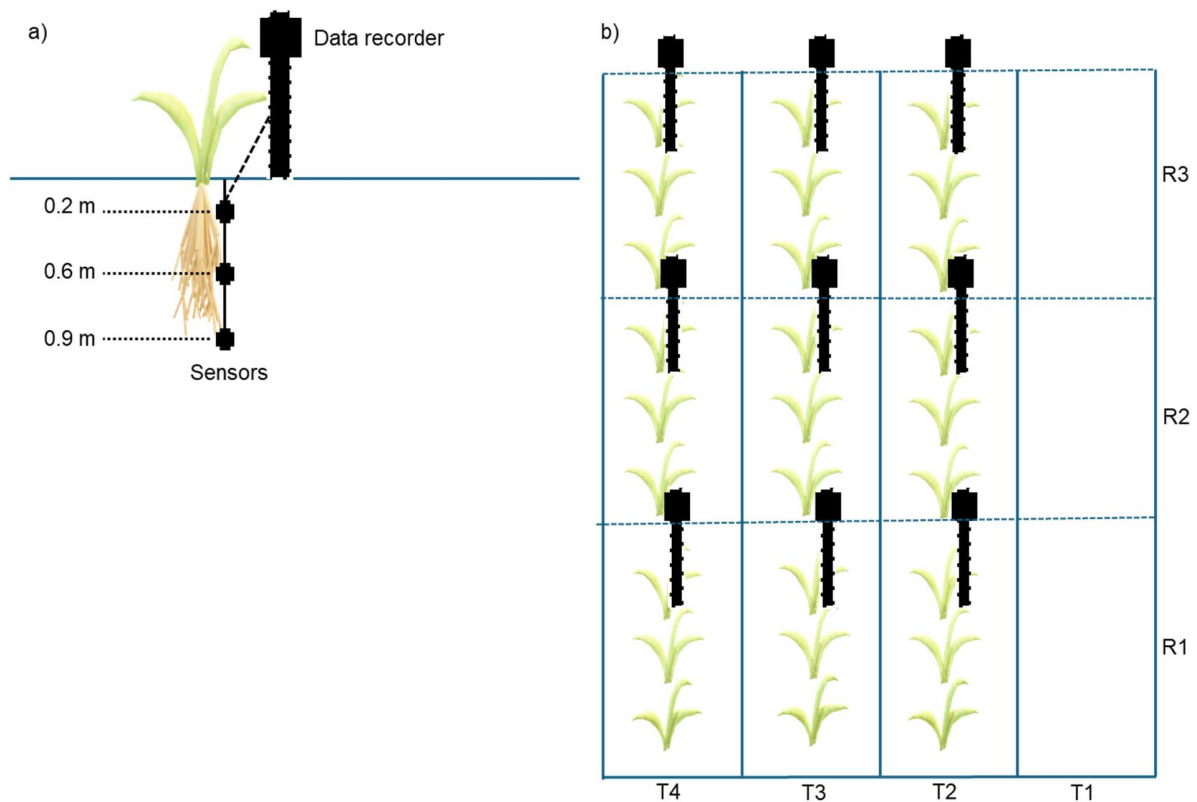


Fig. 3. 2: Location of soil moisture sensors in the study field. a) arrangement of sensors in the soil profile and b) overall view of installed locations.

3.2.3.2. Weather data collection

Weather data collected includes average air temperature, solar radiation, rainfall data, relative humidity, wind speed, and direction from Manitoba Agriculture, which has a weather station in this area. Effective rainfall for the study period was calculated using the fixed percentage method (20% loss) (Ali 2017; Zhang 2024). Daily crop evapotranspiration was calculated using the Penman-Monteith method (Allan et al. 1998; FAO 2020). In addition, soil temperatures at 0.2 m, 0.6 m, and 0.9 m and electrical conductivity at 0.2 m midway-between-tiles of each plot were measured in real-time using a Meter ZL6 data logger. The data were stored in the Zentra cloud storage. Long-term average data was collected from Environment Canada Canadian Climate Normal data, which met the World Meteorological Organization (WMO) standards. Growing degree days (GDD) were calculated to determine the heat accumulated above the base temperature- 4.7°C (Manitoba Agriculture 2025).

3.2.3.3. Drainage monitoring

The laterals are installed at an average slope of 0.15%, varying in depth from 0.9 m to 1.1 m, in the North-South direction, and connected to 200 mm headers, which discharged into the outlets at the South edge of the field. The drain tiles are corrugated pipes 200 m long and 100 mm in diameter (Ndulue and Sri Ranjan 2022).

3.2.4. Subirrigation application

Irrigation was done at the early- to mid- stages of wheat growth from Jun 2 to July 7, 2023.

Overhead irrigation was done from June 2 to June 8 using surface irrigators. From June 12 to July 7, subirrigation was done through the drain tiles.

3.2.5. Water table depth (WTD) observation

Water table depth was measured throughout the year using a water level logger (Solinst Levelogger Junior 3001, Solinst, Canada, Ltd., Georgetown, Ontario, Canada) suspended inside a piezometer midway between two tile drains in each replicate of the plots. A total of 12 piezometers were installed in the wheat field. Level logger readings were recorded at 3-hour intervals.

3.2.6. Agronomic Practices

AAC Brandon variety wheat was sown in 0.19 m row spacing at a 151.3 kg/ha seeding rate in the 2022 and 2023 study periods. Seeds were planted on May 24, 2022; they attained their maturity on the 28th - 29th of August and were harvested on the 1st of September 2022. In 2023, seeds were sown on May 19. They attained their maturity on the 16th -22nd of August and were harvested on the 28th of August.

Fertilizers were applied in the year 2022 at the rate of 0:21 N:P (kg/ha) in all the experimental plots, and in 2023, at T2 (30-ft drain spacing) 18 kg MAP and 79.4 kg Urea, at T3 (45-ft m drain spacing) different fertilizer application plans implemented in triplicates such as 9.1 kg MAP and 59 kg Urea for R1 and R2 and 38.5 kg Urea for the R3. However, only 18 kg of MAP was applied to the T4 (No drain control) plots.

Total plant growth in 2023 was divided based on the Zadok's scale (Zadoks et al. 1974) and simplified into three growth stages: early growth stage (germination and tillering) 1-29 Days After Planting (DAP) (May 19-June 16), mid growth stage (stem elongation, flowering and heading) 30-61 DAP (June 17- July 18) and final growth stage (ripening and maturity) 62-102 DAP (July 19-August 28).

Before harvesting, five plants from different locations (on-tile and midway-between-tile) in each plot were taken randomly to measure the height above the ground surface in both years. Three plants were selected randomly at each replicate to determine the root mass. Those were carefully excavated at a depth of 0.3 m, soaked in water for seven days to loosen the soil, and then washed carefully. Finally, the root below the surface was cut and thoroughly cleared of debris. After air drying for a day, the wet mass was measured and oven-dried at 105°C for 48 hours until a stable weight was obtained. Average oven dry weight was calculated for on-tile, midway-between-tiles, and control plots in all three replicates.

Yield was calculated based on the weight of the seeds harvested from two approximately 20 m long strips and 1.25 m wide in each plot on-tile and midway-between-tile and control plots separately from each replicate.

3.2.7. Statistical analysis

Statistical analysis for plant height, root mass, and yield during the study period was done by two-way analysis of variance (ANOVA) using JMP, (Version 18.2, JMP, Cary, NC). Treatment means were compared using the TukeyHSD at $\alpha = 0.05$. The data on the tile and midway-between-tiles were nested within the 30-ft and 45-ft spacing treatments and compared to the non-tile (control) treatment. Yield data, root mass and plant height for compared for each year separately.

3.3. Results and discussion

3.3.1. Weather and crop evapotranspiration impacts on soil moisture, wheat growth, and yield

3.3.1.1. Rainfall and crop evapotranspiration

Rainfall (RF) data from 2022 and 2023 showed significant seasonal variations during the wheat-growing period. Seasonal RF (May-September) in 2022 and 2023 was compared to Arborg's 30-year Climate Normal (1981-2010). In addition, daily average crop evapotranspiration (ET_c) and effective RF are analyzed across growth stages in both years. Daily effective RF and ET_c during the growing season are shown in Fig. 3. and the monthly average RF is presented in Table 3.1.

In 2022, RF for May, June, and July exceeded the Climate Normal by at least 40%. The total RF between May and September was 483.4 mm, approximately 40% higher than the Climate Normal of 327.3 mm. In contrast, 2023 received only 204.1 mm of total RF, representing a 50% decrease compared to 2022 and well below the climate average. In July 2022, it received fourteen RF events totaling 187.5 mm. The highest single RF event occurred in mid-July, reaching 99.6 mm, whereas in 2023 it was 10 mm. This period is critical for wheat, as flowering and grain filling typically occurs at this stage. These phases demand up to 40% of the seasonal water requirement, approximately 4.8 mm/day (Howell et al. 1997). According to Singh et al. (2021) and Setter and Waters (2003), weekly moisture levels above 34-45 mm in heavy clay soils can result in waterlogging if drainage is inadequate. This typically occurs when intense rainfall events happen over short durations, leading to more than 45% of field capacity and potentially reducing yield. However, volumetric water content (VWC) was not monitored in 2022 to confirm soil waterlogging. A continuous visual observation indicated that waterlogged conditions were present during this period.

In 2023, the early- and mid-growth stages of wheat experienced low RF, with fewer events and reduced intensity. The effective RF was only 7 mm and 42.2 mm in early- and mid-growth stages, respectively. The snowmelt and RF before seeding contributed 18.7 mm in total RF during May 2023. In the final growth stage, the highest RF was received at 21.4 mm in August.

The ET_c was highest during the early and mid-growth stages in the year 2022 and 2023. In 2022, ET_c values were 128.4 mm and 123.8 mm, respectively. In 2023, the early-growth stage recorded 95.2 mm, while the mid-growth stage reached 178.3 mm. The water deficit observed in 2023 during these stages could not be met through RF alone. In Manitoba, wheat crops typically require between 275-325 mm (11-13 inches) of water from planting to maturity (He et al. 2020; Government of Manitoba 2025). Subirrigation was applied during the early and mid-growth stages in 2023 to meet the water deficit. Supplemental irrigation was provided from June to July, as shown in Fig. 3. Two tile drain spacing treatments, 30-ft (T2) and 45-ft (T3), were subirrigated. The 30-ft plot received a total of 154 mm, while the 45-ft plot received 104 mm of subirrigated water throughout the growth period in 2023. Due to closer spacing and a higher number of tile drains, the 30-ft plot received approximately 1.5 times more water than the 45-ft. Soil moisture analysis (Fig 3.) showed limited impact of subirrigation on upper layers (0.2 m and 0.6 m). A noticeable effect was observed only at 0.9 m depth in the T2 plot.

In the late-growth stage (2023), including the ripening phase, the total ET_c was 210.6 mm. However, effective RF was only 63.7 mm. This substantial water deficit likely hindered grain ripening and maturity, reducing yield.

Table 3.1: Average monthly rainfall during the study period and the Arborg Climate Normal (30-year) average monthly rainfall.

Months	Climate Normal (mm)	2022			2023		
		Total RF	Highest	Total RF	Total RF	Highest	Total RF
		(mm)	RF (mm)	event	(mm)	RF (mm)	event
May	54.2	113.1	21.9	19	18.7	7.3	07
June	80.9	116.9	34.2	13	29.3	13.7	09
July	70.3	187.5	99.6	14	51.1	10.0	16
August	68.9	39.4	12.4	09	53.8	21.4	10
September	53.0	26.5	13.08	10	51.2	24	09
Total	327.3	483.4	-	-	204.1	-	-

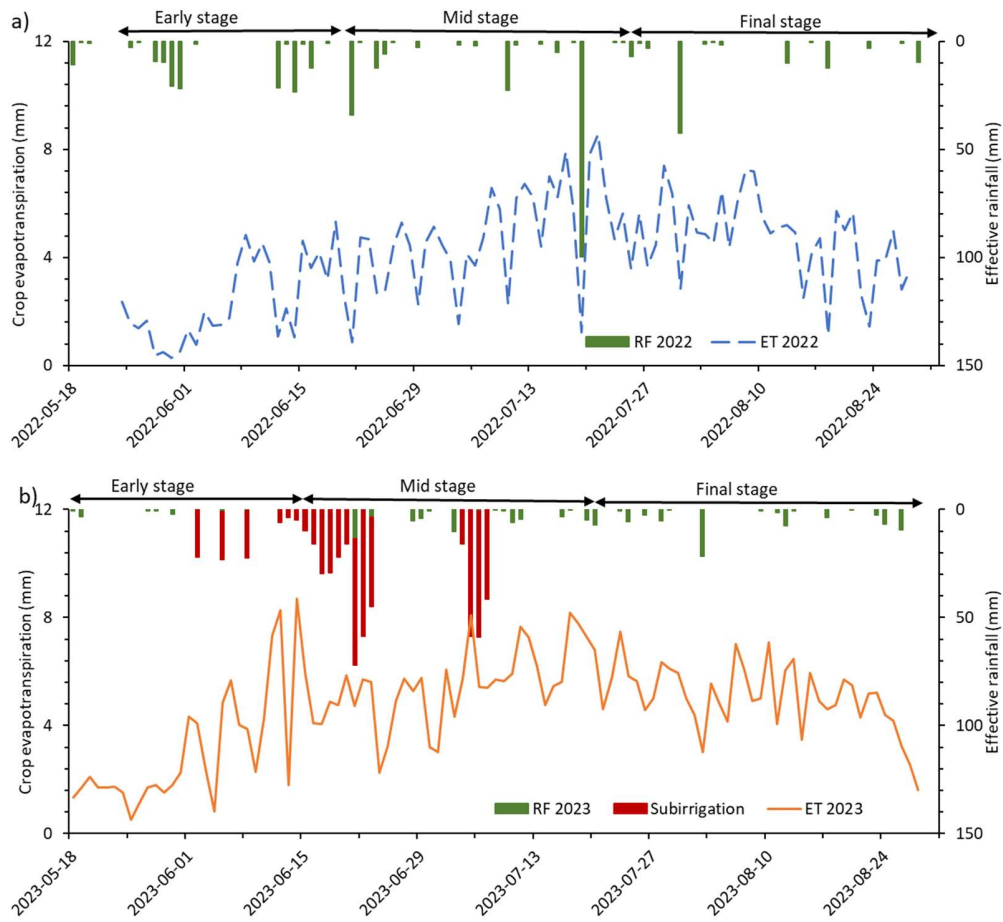


Fig. 3.3: Daily average crop evapotranspiration, effective rainfall, and total subirrigation during a) 2022 b) 2023 study period.

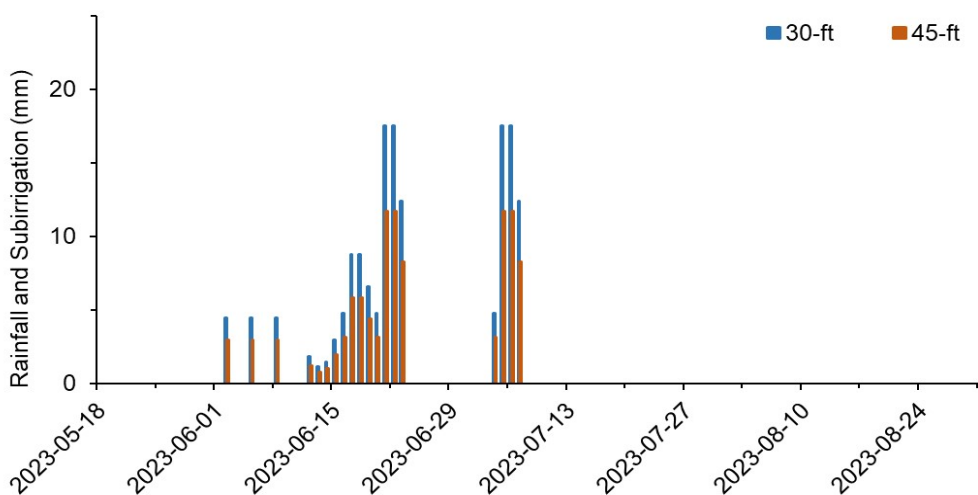


Fig. 3.4: Subirrigation applied in different tile drain spacing during 2023 study period.

3.3.1.2. Temperature

The average monthly air temperatures in 2022 and 2023 were compared with the Arborg Climate Normal (1982-2010), as shown in Table 3.2. The Fig. 3.5 Presents the growing degree days (GDD) of wheat during both years.

In the Early growth stages (May and June), average temperatures in 2023 were slightly warmer than in 2022, at 14.6 and 20°C, respectively. The average maximum and minimum temperature range in 2023 is higher than in 2022. However, GDD was higher in the mid (July) and final (August) growth stages of 2022, ranging between 133 and 140°C. In contrast, temperatures during these stages in 2023 were close to the Climate Normal, resulting in slightly lower GDD than in 2022. According to FAO, wheat requires a minimum of 400 GDD above a base temperature of 4.7°C to reach maturity (FAO 2001; Brown and McCall 2001; Zhou et al. 2024). In this study, the total GDD in the 2022 and 2023 growing periods were 444 and 447°C. Both slightly exceed the minimal requirement for maturity.

The daily average soil temperature (DST) at 0.2, 0.6, and 0.9 m depths in 2023 is shown in Fig. 3.. Real-time sensors were used to monitor the DTS at these depths. The optimum growing temperature ranges for early, mid and final growth stages are indicated in green in Fig 3.6. During June, DST shows a sharp increase across all depths, consistent with air temperature trends and GDD accumulation (Fig. 3.5). In the early stage, DST in deeper layers (0.6 and 0.9 m) remained within the optimum range of 4-10°C. However, the top layer (0.2 m) exceeded this range.

In the mid-growth stage, DST at 0.2 and 0.6 m exceeded optimum levels. Elevated temperature during the early and mid-growth stage may lead to heat stress, potentially causing 10-30% yield (Reynolds et al. 2007; Farooq et al. 2011). During the final-growth stages, DST

remained within the optimum range across all depths. Cooler soils (<4°C) can delay emergence, while excessively warm soils (>20°C) can reduce seedling vigor, especially under dry conditions (Lafond et al. 2009; Manitoba Agriculture 2025). However, soil temperature at different depth did not exceed above 20°C.

Table 3.2: Monthly average temperature on different drain spacings at different depths throughout the study period

Months	Monthly	2022			2023		
	Climate	Average	Max	Min	Average	Max	Min
	Normal	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
	Temperature	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
	(°C)						
May	10.0	10.7	15.7	5.8	14.6	21.4	7.5
June	15.8	16.1	22.1	10.1	20.0	26.2	13.2
July	18.6	20.2	28.9	13.5	17.6	23.4	10.9
August	17.5	19.3	28.3	12.0	17.8	23.6	11.8

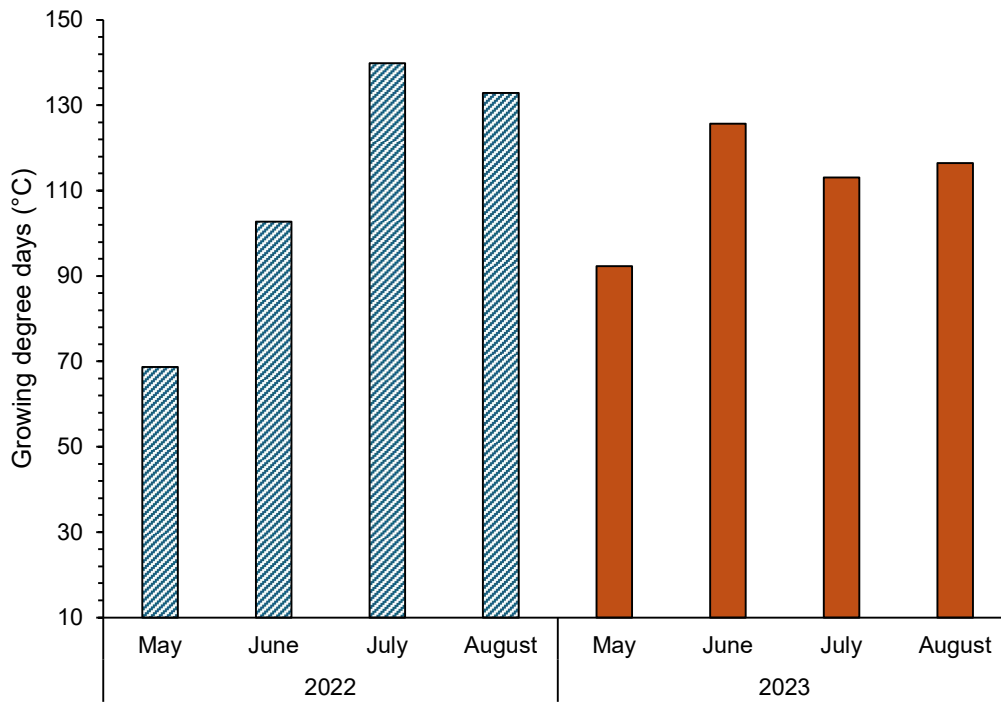


Fig. 3.5: Growing degree days of wheat in the growing period of 2022 and 2023

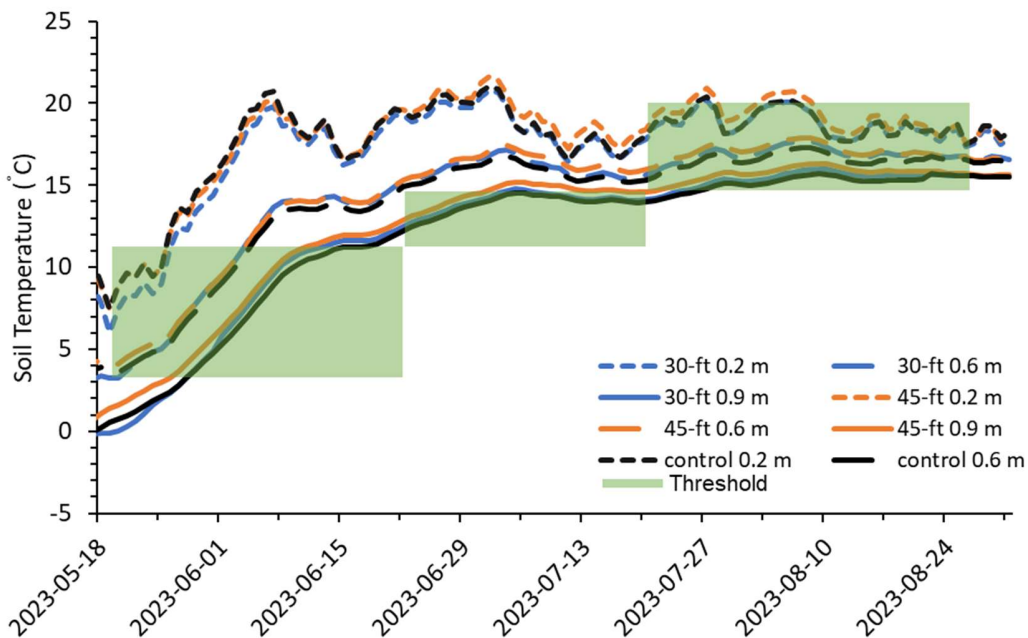


Fig. 3.6: Daily average soil temperature at different depths during the 2023 study period.

3.3.2. Water table depth

The water table depth throughout the 2023 study period is shown in the Fig. 3. One observation well was installed in the 30-ft drain and non-tile (control) plots. Due to the wider spacing in the 45-ft plot, two observation wells were installed: one midway-between-tile and one directly on-tile.

In both the non-tile plot and the midway-between-tile of the 45-ft plot, water table depth decreased gradually over the growing season and showed minimal response to RF. In contrast, subirrigation was applied in the 30-ft and 45-ft plots, leading to elevated water table levels in the 30-ft on-tile and 45-ft on-tile plots. Surface irrigation was applied using an irrigator pump from June 2nd - 8th. However, this method did not influence the elevation of the water table. This suggests that surface irrigation is ineffective in raising the water table in heavy clay soils due to limited infiltration to deeper layers. Subirrigation through tile drains, at the beginning of the mid-growth stage, caused a steady increase in water table depth. However, a rapid decline of water level was followed in the subsequent days. This is likely due to increased water uptake by plant roots during a period of high ET_c. This may also be attributed to the very low rate of water supply, which was insufficient to maintain a stable rise in the water table level.

In the 45-ft on-tile, the water level fluctuated in response to subirrigation during the mid-growth stage. However, due to wider spacing, the rise in the water table was slower compared to the 30-ft plot. The water received by subirrigation was utilized by the crops between irrigation intervals. The 45-ft midway-between-tiles showed no significant response to either subirrigation or effective RF, indicating that the wider spacing limits lateral water movement in the soil profile. Therefore, a 45-ft midway-between-tile response is similar to a non-tile plot.

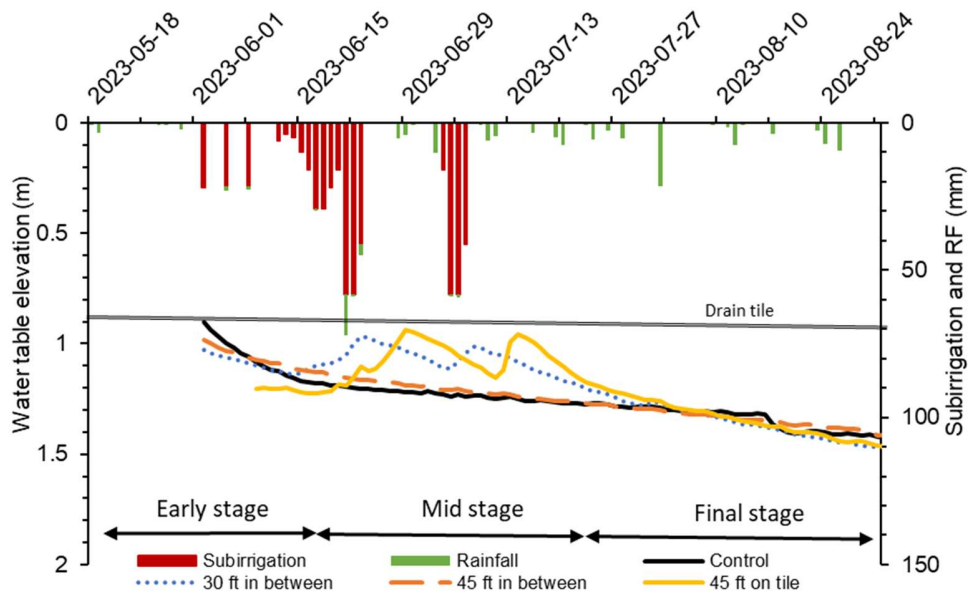


Fig. 3.7: Average water table elevation, rainfall, and subirrigation during the 2023 study period.

3.3.3. Soil Moisture Dynamics– year 2023

A comparison of volumetric water content (VWC) in 30-ft, 45-ft drain spacing, and non-tile (control) plots at three different depths (0.2, 0.6, and 0.9 m) is shown in Fig. 3.8. According to Manitoba Agriculture, field capacity (FC), lower end of readily available water (RAW) and Permanent wilting point (PWP) for the heavy clay soil (Red River) are 46, 36.4 and 26.75%. These were used as thresholds to determine the VWC effect on wheat growth and yield. According to Spoor et al. (2003), soil water content at or exceeding field capacity indicates "wet" soil conditions. This causes a negative impact on different growth stages and ultimately results in poor yield. The VWC in all three plots never reached the FC however, during the VWC during final-growth stage was below the lower end of RAW in all three plots. Therefore, in 2023, the soil condition described as “dry”. This was mainly due to low RF and the lower water table in 2023.

The highest VWC nearing or above RAW during the study period in 0.2 m layer was observed in the early growth stage. This was primarily because of the soil moisture storage from

snowmelt and precipitation that occurred at the beginning of the year and the lower active root zones of the crops. Blankinship et al. (2014) also found snowmelt is typically the largest wetting event, restoring hydrologic connectivity to dry winter soils.

In the control (non-tile) plot, VWC showed minimal variation across soil depths. The top layer (0.2 m) exhibited a mild response to rainfall events during the mid- and late-growth stages. VWC remained near the lower end of the RAW zone but dropped below this threshold from the mid to late stages of crop development. In the 30-ft plots, VWC at the 0.2 and 0.6 m depths remained above RAW lower end until the early mid-growth stage. However, it declined below the RAW threshold during the late-growth stage, likely due to high ET_c and increased crop water demand. The 0.9 m depth VWC was 3% lower than the upper layers throughout the season, remaining below the RAW limit regardless of RF and subirrigation. This indicates that narrower tile spacing (30-ft) may have led to over-drainage, reducing deep soil moisture availability during the dry year. Conversely, in the 45-ft tile plots, VWC at 0.9 m depth was at least 1% higher than the other upper layers at all growth stages. This is likely due to the wider drain spacing allowing better retention of water from snowmelt, rainfall, and subirrigation. Despite this, VWC at all three depths remained below the RAW upper limit, indicating that the stored moisture was still insufficient for optimal plant uptake.

VWC in the three different tile drain spacing plots ranged from 0.30 to 0.38 m³/m³ but never reached the FC of this soil. This was primarily due to the very low RF in 2023, which was 38% below the 30-year average, combined with a high seasonal evapotranspiration (ET_c) of 484 mm. These conditions posed a significant challenge for the crop to access sufficient moisture, particularly in the midway-between-tile areas.

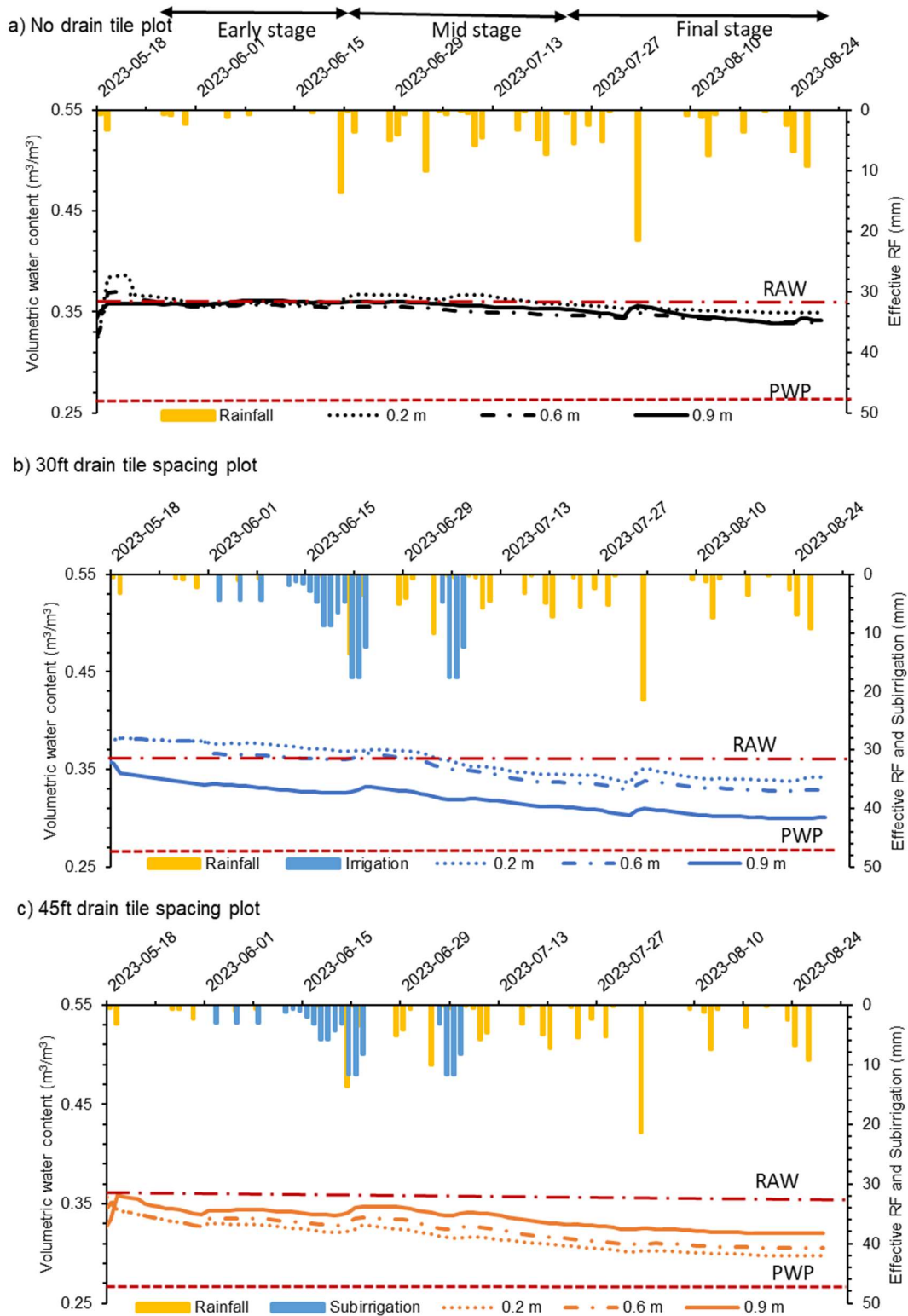


Fig 3.8: Daily average Volumetric water content, RF and subirrigation across different tile drain plots during the 2023 study period

3.3.4. Plant height and root mass

Plant height was measured before harvest during the 2022 and 2023 growing seasons and is shown in Fig. 3.. In 2022, the average plant height across all treatments was 790 mm, showing no significant difference in plant height among the treatments.

In 2023, plant heights in the 30-ft plot locations showed no significant difference ($p < 0.05$) between the locations (on-tile and midway-between-tile). This could be attributed to the effectiveness of drainage and subirrigation across the plot, facilitated by the narrower drain spacing compared to the other plots. Due to narrower spacing, moisture distribution or drainage effect reached across the plot compared to the wider (45-ft) spacing. The 45-ft midway-between-tile recorded a significantly lower ($p < 0.05$) plant height of 675 mm compared to both 45-ft on-tile (785 mm) and non-tile (764 mm) plots. No significant differences ($p < 0.05$) were found between the non-tile and the 30-ft and 45-ft on-tile treatments. This is mainly due to subirrigation, which resulted in uniform plant height comparable to the non-tile plot, in the dry year.

According to the Canadian Food Inspection Agency, the standard height for AAC Brandon is 860 mm, with a standard deviation of 21 mm. In 2022, the variety withstood flooding conditions and recached a uniform height.

Root mass data from the 2023 season are shown in Fig. 3.. The 30-ft on-tile treatment was significantly higher ($p < 0.05$) root mass than both the 30-ft midway-between-tile and 45-ft plots. This can be attributed to the higher amount of subirrigated water received during early and mid-growth stages in the 30-ft on-tile plot. This promoted more active root development compared to other locations. However, a significantly lower ($p < 0.05$) root mass of 0.33 mg was obtained in 30-ft midway-between-tiles. This result aligns with the observed plant height, suggesting that the

narrower tile drain spacing facilitated rapid water drainage, potentially reducing water availability essential for plant growth during 2023, a dry year.

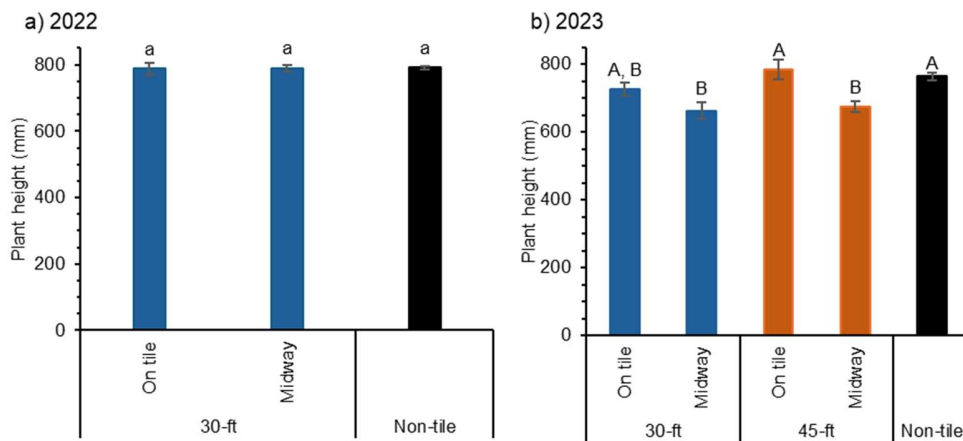


Fig. 3.9: Average plant height across different subsurface drainage spacing plots during a) 2022 and b) 2023.

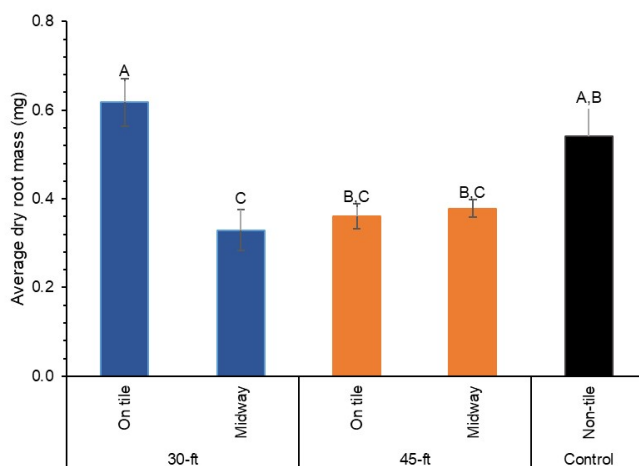


Fig. 3.10: Average dry root mass across different tile drain plots during the 2023 study period.

3.3.5. Yield

The year 2022 experienced higher-than-normal precipitation. Wheat was cultivated in the 30-ft drain spacing plots, as well as in the control plots. The yield was measured in the 30-ft drain spacing plots on-tile and midway-between-tiles and the non-tiled control plots. The mean precipitation for the cultivation period (May 1–September 30, 2022) amounted to 480 mm. The

Fig. 3.3 shows the average Interlake yield and average yield in 2022 and 2023. In 2022, the Interlake region average yield was 4380 kg/ha. However, in the 30-ft drain spacing, the midway-between-tiles yield exceeded the Interlake region's average yield, reaching 5425 kg/ha. It was also significantly higher ($p < 0.05$) than other locations. This indicated the beneficial effects of closer spacing of tile drains in a wet year.

On the other hand, the on-tile yield in the 30-ft drain spacing was 4632 kg/ha. This was higher than the regional average, but there were no significant differences between the other treatments. This could be attributed to limited drainage from the intermittent operation of the drainage lift pump at the outlet, which kept the water table shallower on-tile compared to midway-between-tiles. The absence of tile drains in the control plot led to excessive water accumulation within the crop root zone, which resulted in a lower yield than the tiled plots. The control plot with non-tile yielded 4362 kg/ha, significantly lower ($p < 0.05$) than the 30-ft midway-between-tiles treatment but similar to the average Interlake region yield.

The cumulative average precipitation throughout the growing season, from May 1-September 30, 2023, amounted to 201 mm. This was considerably lower than the 30-year average, making it a dry year. The yield was assessed in three separate locations: (i) a control plot with no drainage, (ii) on-tile, and (iii) midway-between-tiles in both the 30-ft and 45-ft tile spacing plots. The Interlake region achieved an average total production of 5391 kg/ha, surpassing the output in 2022. Within the 30-ft tile spacing plot, there was no significant difference ($p < 0.05$) between the yield of on-tile (3035 kg/ha) and midway-between-tile (3272 kg/ha) treatments. However, both were significantly lower ($p < 0.05$) than the yields observed in the 45-ft on-tile plot and the control (non-tile) plot. The 30-ft plot yield is also lower than the Interlake region's yield. The lower yield in the 30-ft plot may be attributed to over-drainage

during a dry year, which likely reduced soil moisture availability necessary for optimal crop growth. Notably, the control (non-tiled) plot yielded 5,985 kg/ha, significantly higher ($p < 0.05$) than both the 30-ft plot and the 45-ft midway-between-tile treatment. It suggested that uncontrolled tile drainage may negatively impact yield by over drainage in a dry year. Scheduled subirrigation could be beneficial in mitigating such effects in dry years. The 45-ft on-tile plot appeared to efficiently utilize subirrigated water, producing a yield of 5,043 kg/ha. That exceeded the regional average yield.

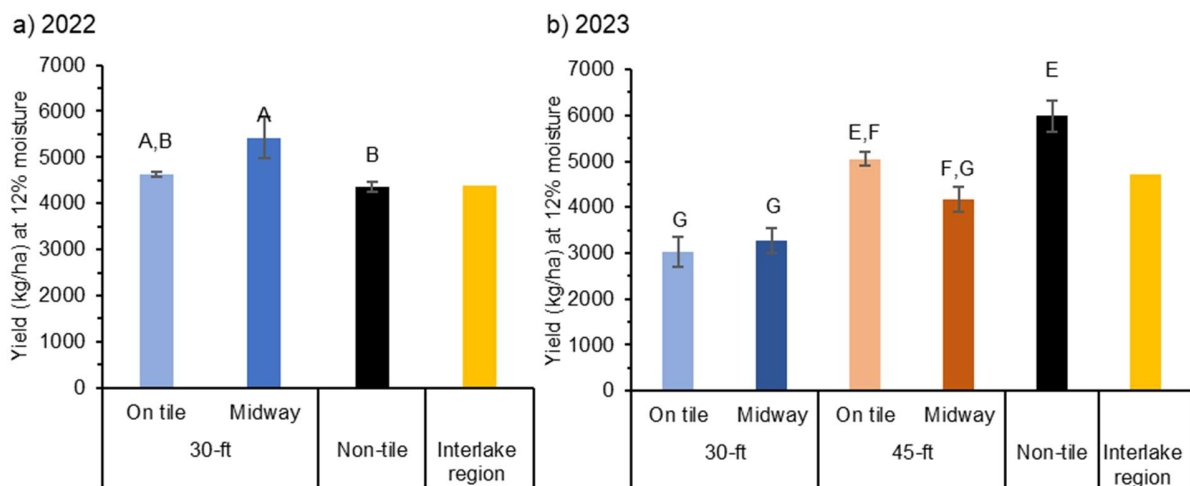


Fig. 3.3: Average yield across different subsurface drainage spacing and Interlake region during a) 2022 and b) 2023.

3.4. Conclusion

This study examines the impact of tile drainage spacing and soil moisture dynamics on wheat growth and yield in heavy clay soils. The 2022 season was wet, receiving 483.4 mm of seasonal RF (1.5 times higher than Climate Normal). On the other hand, the year 2023 was characterized as a dry year with 204.1 mm seasonal RF. It is 1.6 times lower than the climate-normal RF. The water table depth during 2023 was below the tile drains, which indicates the year's dryness. However, subirrigation aided soil moisture retention in 30-ft plots and 45-ft on-tile plots.

Volumetric water content in midway-between-tiles during the growing period ranged between 0.30 to 0.38%. It was below FC (46%) and below mid-way point at the lower end of the RAW (36.45%) during mid- and final-growth stages. However, VWC in all plots remained above the PWP enabling root water uptake, though with considerable difficulty due to limited availability. Real-time soil moisture monitoring will be beneficial in knowing the VWC during growing period, managing the drainage control structures to regulate the outflow and subirrigation. Plant height during 2022 showed no significant difference between the treatments. However, the observed uniformity in plant height may also reflect the flood tolerance of the AAC Brandon wheat variety. In 2023, the non-tile plot plant height was significantly ($p < 0.05$) taller than the midway-between-tile treatments in the 30-ft and 45-ft plots.

In 2022, a wetter year, the closer tile spacing of 30-ft mitigated waterlogging and promoted higher yields in the midway-between-tiles compared to the control (non-tile) treatment. The lower yield in the on-tile treatment may have resulted from the intermittent pump operation holding more water back in the field than necessary. Conversely, during the dry year (2023), a wider tile spacing of 45-ft proved beneficial resulting in significantly higher yield ($p < 0.05$) compared to the 30-ft spacing plot. Scheduled subirrigation during critical growth stages can enhance crop growth and yield, even in years with very low RF. These findings suggested that flexible, site-specific drainage strategies, assisted by real-time moisture monitoring, are crucial for optimizing wheat yield in heavy clay soils.

CHAPTER FOUR

DRAINMOD SIMULATION OF DRAIN SPACING IMPACT ON WHEAT YIELD IN HEAVY CLAY SOILS IN THE CANADIAN PRAIRIES

Abstract

Effective water management is essential for optimizing wheat production in the Canadian Prairies, where variable precipitation, excess moisture, and drought stress impact yield. This study used the field data to calibrate and validate the DRAINMOD model to assess the influence of drain tile spacing (15-ft, 30-ft, and 45-ft) and subirrigation on relative wheat yield in heavy clay soils. Simulations were done for 2021 (dry year), 2022 (wet year), and 2023 (dry year) to evaluate yield responses under different hydrologic conditions. The results showed that subirrigation effectively mitigated drought stress in dry years, leading to higher relative wheat yields. In 2022 (wet year), relative yields reached 97.2% and 97.0% in the 30-ft and 45-ft plots due to improved water balance. In 2021 (dry year), subirrigation mitigated drought stress in the 15-ft plot, though a six-day planting delay resulted in a 5.2% yield reduction. The low rainfall year (2023) produced stable yields exceeding 96% across all plots due to strategically designed subirrigation. Beyond precipitation, factors such as antecedent water table depth, early-season precipitation, and planting delays influenced yield outcomes. These results highlight the importance of optimized drainage system design for improving wheat yield.

4.1. Introduction

The water relations in the soil-plant continuum are often unfavourable due to water imbalances such as water deficit or waterlogging (Ondrasek et al. 2014). Crop yield is compromised due to water stress, which frequently exacerbates other limitations, including soil salinity and organic matter depletion. Shallow groundwater table, heterogeneous soil stratigraphy, and poor soil permeability often result in waterlogging or water stress. However, the water table depth (WTD) plays a major role in regions like Southern Manitoba, which has shallow water tables. A shallow water table can fulfill half of the crop water requirement without irrigation in the growing season (Ayars et al. 2009). The Canadian Prairies encounter water-related challenges caused by unpredictable weather patterns, including heavy snowfall, extended dry seasons, and long-term variations in annual precipitation and seasonal rainfall distribution patterns. These patterns significantly impact the soil water content and water table, making it challenging for farmers to manage crops and achieve optimal yields effectively. An integrated drainage system consisting of surface drainage channels, tile drainage and subirrigation has been identified as one of the most effective restorative solutions (Ondrasek et al. 2014).

Before settlements in Manitoba, most of the area had flooded plains or swamps. As a result, extensive drainage design is essential for cultivating Manitoba's Southern to Central regions. Since the beginning of civilization, drainage systems have played a crucial role in eliminating excess soil water from fields with inadequate natural drainage, enabling timely field activities (Madramootoo et al. 2007; Müller et al. 2011). Surface drainage and subsurface drainage systems are two main types of field drainage systems. Surface drainage systems remove excess water from the top layer since the poorly permeable strata prevent infiltration and percolation at shallow depths (Smedema et al. 2004). Subsurface drainage mainly lowers the

water table below the effective root zone by removing gravitational water from the soil through the deployed underground perforated corrugated pipes (Guitjens et al. 1997; Cordiero 2014). Of the two different drainage systems, subsurface drainage systems improve soil water conditions more effectively, enabling timely field activities (Paul and DeVries 1979; Müller et al. 1990; Evans et al. 1996; Mante et al. 2009; Müller et al. 2011).

However, predicting the water table dynamics to improve water management, reduce crop losses and improve yield is often complex due to several influencing factors, including crop type, soil type, climate, topography and management practices (Ndulue and Sri Ranjan, 2022). Different hydrologic models have been developed to address these challenges and ensure environmental sustainability (Masasi et al. 2020). The models integrate various agricultural and environmental attributes, such as hydraulic parameters, climatic conditions, crop parameters, soil characteristics, and tile drainage properties. This approach enables examination and understanding of several factors such as soil composition, crop characteristics, long-term weather patterns, and management practices. It helps assess drainage design, solute leaching, crop development, and water table management strategies. The models DRAINMOD, HYDRUS, and ADAPT are tools for optimizing crop productivity by implementing a cost-effective drainage system (Singh et al., 2006; Ndulue and Sri Ranjan, 2022). Among them, the common hydrologic model for managing water in soils with poor drainage is DRAINMOD (Skaggs 1978; Skaggs et al. 2012). It often uses directly measured values from the field; some values are uncertain, such as soil hydraulic parameters (Singh et al. 2006). Inaccurate and uncertain input parameters may increase prediction error. This inaccuracy can be decreased using field measurements to calibrate and validate the model. In the calibration phase, the simulated model values are compared with

the observed field values, and the observed and predicted state variables for an independent dataset are used to validate the indirectly derived input parameters.

There was limited use of DRAINMOD in Canadian Prairies. The model was assessed by Cordeiro and Sri Ranjan (2015) and Satchithanatham and Sri Ranjan (2015) for corn and potato production in sandy loam soil in Southern Manitoba. Ndulue and Sri Ranjan (2024) used the model for growing canola in clay soils. However, the model performance varied according to the location and crops, even under similar climatic conditions (Orth et al. 2015).

Further assessment of models is required, particularly in cold climates, diverse soil types, various crops, and different management approaches (Yang et al., 2007; Saadat et al. 2020). Therefore, the overall objective of this study is to evaluate the DRAINMOD model in heavy clay soil under wheat production. The specific objectives are (1) to simulate water table depth under wheat production in the Interlake region of Manitoba, Arborg, and (2) to evaluate the impact of different drain spacing (30-ft, 45-ft) on wheat yield under subdrainage and subirrigation.

4.2. Materials and methodology

4.2.1. Study area

Field drainage experiments were conducted on the Prairies East Sustainable Agriculture Initiative (PESAI) farm in Arborg, Manitoba, Canada: latitude 50.904° N, longitude -97.273° W, elevation 229 m. The climate of this region is characterized by cold and dry winters and warm summers (Bueckert et al. 2013). Arborg soil is heavy clay, predominantly soil with low permeability, deep water table depth and peat content. This soil belongs to Rego Humic Gleysol soils, and its parent material is poorly drained Lacustrine and Fyala soils (Podolsky, G. 1982). The soil in 0.3-0.2 m is heavy clay, which is hard when dry and firm when moist. The next 0.2-0.33 m is a dark

grayish-brown soil that is extremely hard when dry and firm when moist. The next layer (0.33-0.51 m) is similar to the top 0.2 m (Manitoba Agriculture 2010). Due to its structural variability, impermeable layer formation might occur during dry or wet years. Due to its high clay content (> 60%), the soil is prone to shrinking and swelling. Due to its high clay content, the soil is prone to shrinking and swelling. As a result, soil cracks are frequent in fields. The bulk density of predominantly heavy clay is 1.07 g/cm³ (0-0.15m red river heavy clay) (Ndulue and Sri Ranjan 2022).

4.2.2. Experimental design

The total experimental area of this research was divided into four sections (T1, T2, T3 and T4) according to the drainage treatments **Error! Reference source not found.** Each plot was 220 m in length and 30 m in width with three replicates (R1, R2 and R3), and a 5 m buffer zone separated these plots. Drain tiles were installed at depths between 0.9-1.1 m in three sections at three different drain spacings, and one section without drain tile served as a control in the experiment. Drain tiles consisted of 200 m long and 100 mm diameter corrugated pipes, which were installed at 4.57 m (15-ft) at T1, 9.14 m (30-ft) spacing at T2 and 13.72 m (45-ft) at T3. This study area was under crop rotation each season. The most common crops cultivated in this area were wheat, canola and soybean. In 2022, wheat was grown in T2 and Control and 2023 in T2, T3 and Control. In a North-South orientation, laterals were installed at an average slope of 0.15%, ranging from 0.9 m to 1.1 m in depth. The 200 mm headers connected all the laterals and discharged into the outlet located at the Northeastern boundary of the field.

4.2.3. Water table data collection

Water table depths (WTD) in the 2023 growing season were collected using water level sensors (Solinst Levelogger Junior 3001, Solinst Canada Ltd., Georgetown, Ontario, Canada). These

sensors were hung in piezometers installed in midway-between-spacing 9.1 m plots and 13.7 m plots. Additionally, a Solinst Barologger, which measures barometric pressure, was installed above the water level 1. This was done to adjust the levellogger readings for changes in atmospheric pressure. WTD were measured from the 2nd of June to September 2023 at 3-hour intervals.

4.2.4. DRAINMOD model calibration and validation

4.2.4.1. Model input

DRAINMOD (version 6.1) is a field scale model that simulates hydrological processes in tile-drained agricultural fields (Skaggs 1978; Ndulue and Sri Ranjan; 2022 and Satchithanatham and Sri Ranjan, 2015). The model can predict surface runoff, sub-surface drainage, evaporation, infiltration, crop output, and water table depth at daily, monthly, and yearly intervals (Skaggs 1978).

The DRAINMOD model requires input data, including weather data such as daily rainfall, maximum and minimum daily temperature, and potential evapotranspiration (PET). PET can be automatically calculated by including the location, longitude and latitude. Another input factor is soil data, where the model allows input for five layers of characteristics, including lateral saturated hydraulic conductivity, residual (θ_r) and saturated (θ_s) water content, a pore size distribution parameter (n), saturated hydraulic conductivity (K_s), a matching factor (K_o), and an empirical tortuosity parameter (L).

Calibration was done by changing the parameters to one-third of the 30-ft plot data and then validating the remaining two-thirds of the 30-ft plot data. The same calibrated and validated

model simulated the 45-ft spacing plot data by changing only the drain tile spacing and irrigation parameters.

The DRAINMOD model estimates relative crop yield using the stress-day method, which accounts for factors like excessive water, drought, delayed planting, and salinity (Evans and Skaggs 1991). Measured soil electrical conductivity (EC) was shown in the Fig. 4.1. In this study, salinity was not considered because the measured EC ranged between 0-4.5 dS/m is less than the threshold (6-8.6 dS/m) that causes yield reduction in wheat (Shrestha 2006; Iqbal et al. 2022; Hall et al. 2019). Therefore, the relative yield is computed as the product of YR_w , YR_d , and YR_p .

$$Y_R = YR_w \times YR_d \times YR_p \quad (6)$$

where Y_R is the overall relative yield, YR_w is the relative yield due to water stress only, YR_d relative yield due to drought only, YR_p and relative yield due to planting delay only. The linear functions showing yield reduction arising from wet stress, drought, and planting delay are given by Evans and Skaggs (1991).

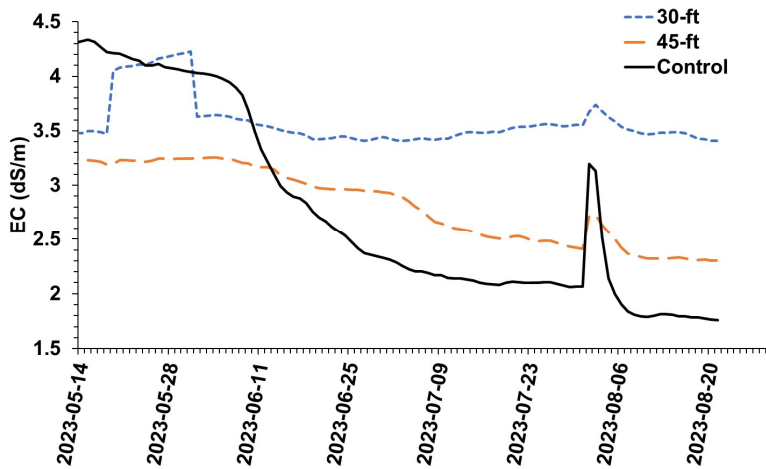


Fig. 4.1:Electrical conductivity (EC) at different drain spacing during the 2023 study period.

4.2.4.2 Weather data

On-site weather station data was input to the DRAINMOD model to calculate potential evapotranspiration. DRAINMOD uses Thornthwaite's (1948) PET equation to calculate the PET using the daily maximum and minimum temperature, hourly seasonal precipitation, geographic locations, and monthly correction factors.

4.2.4.3. Soil data

Soil layers were divided into the top (0-0.40 m), and deep (0.40-2.50 m) layers and soil hydraulic parameters including saturated water content, residual water content, curve parameter, curve-shaped parameter, matching point at saturation, tortuosity parameter and the saturated hydraulic conductivity were obtained from the research literature done by Ndule and Sri Ranjan (2022) for the same research field. The same reference was used to find the soil properties, including bulk density, field capacity and soil textural classification. The ROSETTA software was used to find soil water retention and hydraulic properties (Schaap et al. 2001). According to Ndulu and Sri Ranjan (2022), the soil profile was divided into two layers: the top layer (0-0.4 m) and the bottom layer (0.4-2.5 m). Table 4. 1 shows the calibrated soil hydraulic parameters.

Table 4. 1: DRAINMOD hydraulic parameters.

Hydraulic parameters	Top layer (0-0.4 m)	Bottom layer (0.4-2.5 m)
Residual water content (θ_r)	0.01094	0.01942
Saturated water content (θ_s)	0.516	0.540
Curve parameter (α)	0.021	0.019
Tortuosity/connectivity parameter (L)	-0.6831	-0.8319
Curve shape parameter n (-)	1.13	1.12
Saturated hydraulic conductivity K_{sat} (cm/day)	24	23.5
Matching point at saturation K_o (cm/d)	20	20

Ndulue and Sri Ranjan (2022)

4.2.4.4 Drainage system

Table 4. 2: DRAINMOD model inputs.

Parameters	30-ft	45-ft
Drain spacing (m)	9.1	13.72
Drain depth (m)	1.06	1.06
Effective drain radius (mm)	51	51
Drainage coefficient (cm/day)	1	1
Distance from surface to impermeable layer (m)	6	6
Maximum surface storage (m)	0.5	0.5
Kirkham's depth for flow to drain	0.25	0.25
Desired planting date (Day)	139	139

Last day of the year to plant without yield loss (Day)	141	141
Length of growing season (Day)	100	100
Days required to prepare seedbed and plant (Day)	1	1
Root zone lower water content (cm ³ /cm ³)	0.17	0.17
Limiting water table depth (m)	0.3	0.3
Period to count wet and dry days	May 20 – Aug 30	
Yield reduction parameters		
The linear relationship relating excess water stress to relative yields	Intercept- 0.3%	100% Slope-
The linear relationship relating drought stress to relative yields	Intercept- 0.3%	100% Slope-
Crop susceptibility factors (DAP)	1-6 (0), 7-8 (0.05), 9-12 (1), 13 (1.75), 14-15 (2.1), 16-20 (1.3), 21 (1.2), 22 (1), 23 (0.5), 24-32 (0)	
Trafficability		
	Period 1	Period 2
Start counting workdays (Day)	Apr 1	Sep 30
End counting workdays	Sep 15	Nov 15
Minimum air volume required to work the land (m)	0.15	0.15
Minimum rain to stop delayed work (m)	0.01	0.01
Minimum time after rainfall before work can restart (Day)	2	2
Soil temperature		
Soil thermal conductivity (W/m/ °C)	a = 0.5, b = 1.5	

Average air temperature which precipitation is snow (°C)	0	0
Average air temperature above which snow starts to melt (°C)	2	2
Snowmelt coefficient (mm/day/°C)	3	3
Critical ice content above which infiltration stops (cm ³ /cm ³)	0.2	0.2
Diurnal phase lag of air temperature (°C)	8	8

4.2.4.5 Crop data

Crop data for 2023, including planting and harvest dates, effective root depth, and stress parameters, were input into the model. The AAC Brandon wheat variety typically matures in about 104 days (Kumar et al. 2024). Wheat root growth generally ranges from 0.7 m to 2 m (Hurd, 1968; Lupton et al. 1974; Black et al. 1981). However, root length can vary significantly depending on soil type. According to Hashemi et al. (2020), the effective root depth is the zone where 70% of water uptake occurs. In the Arborg region, past studies indicated that in heavy clay soils, the effective root depth for wheat varies between 30 mm and 450 mm, as shown in Table 4.3. This depth plays a vital role in the model, as it defines the area from which water is drawn to meet evapotranspiration (ET) demands under soil water-limiting conditions. Additionally, the crop susceptibility factors, as detailed in Table 4.2 and based on Ndulue and Sri Ranjan (2022), were adjusted through interpolation across specific dates to enhance the model's accuracy.

Table 4. 3: Effective root depth of wheat during the growing season.

Month	Day	Depth (mm)
1	1	30
4	25	30
5	14	150
5	27	300
6	1	300
6	20	300
7	24	400
8	20	450
9	24	30
10	25	30
12	31	30

4.2.5. Model performance

The performance of the DRAINMOD model was evaluated using a combination of visual and statistical methods. A graphical comparison between the simulated and observed water table depths showed a strong agreement, indicating satisfactory performance. Additionally, several widely used statistical metrics were employed to assess the model's accuracy. These included the coefficient of determination (R^2), root mean square error (RMSE), Average absolute deviation (AAD), and Nash-Sutcliffe Efficiency (NSE).

Coefficient of Determination (R²)

The R² measures the proportion of the observed data variation explained by the predicted values. It reflects the model's performance, where a value of 1 indicates a perfect fit, and 0 suggests the model fails to explain any variation in the data.

$$R^2 = 1 - \frac{\sum_{i=1}^n (\text{Observed}_i - \text{Predicted}_i)^2}{\sum_{i=1}^n (\text{Observed}_i - \text{Mean}_{\text{Observed}})^2} \quad (5)$$

Root Mean Square Error (RMSE)

The RMSE calculates the square root of the mean of the squared differences between the observed and predicted values. This metric emphasizes larger errors, making it particularly sensitive to outliers.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\text{Observed}_i - \text{Predicted}_i)^2} \quad (6)$$

Average Absolute Deviation (AAD)

The AAD calculates the mean of the absolute differences between the observed and predicted values. This metric evaluates the overall deviation of the model's predictions from the observed data, treating all errors equally regardless of their direction.

$$AAD = \frac{1}{n} \sum_{i=1}^n |\text{Observed}_i - \text{Predicted}_i| \quad (7)$$

Nash-Sutcliffe Efficiency (NSE)

The Nash-Sutcliffe Efficiency compares the model's predictive performance using the mean of the observed data as a predictor. It measures how well the model's predictions align with the observed values. An efficiency score of 1 indicates perfect agreement, while a score below 0 suggests that the model performs worse than simply using the observed mean.

$$E = 1 - \frac{\sum_{i=1}^n (Observed_i - Predicted_i)^2}{\sum_{i=1}^n (Observed_i - Mean_{Observed})^2} \quad (8)$$

Mean Bias Error (MBE)

The Mean Bias Error (MBE) is a statistical metric used to measure the average bias (systematic error) between simulated (predicted) values and observed (actual) values. It helps determine whether a model systematically overestimates or underestimates the observed data. A positive MBE indicates model overestimation, while a negative MBE signifies underestimation. An MBE of zero means no systematic bias, as overestimations and underestimations balance out.

$$MBE = \frac{\sum (Simulated - Observed)}{n} \quad (9)$$

4.3 Results and Discussion

4.3.1 Weather variables

The total seasonal (May-September) rainfall in 2023 was 204 mm, and the Climate Normal average based on 30 years (1981-2010) of data was 327.3 mm. Fig. 4.2 shows the average monthly rainfall and subirrigation during 2023 and Climate Normal monthly average rainfall. The year 2023 was considered a dry year since it only received 37.64% less rainfall than the Climate Normal. Subirrigation was done during the growing season to compensate the low rainfall. Table 4. 4 summarizes the amount of subirrigation applied during the growing season. In total, 154 mm and 103 mm of water were applied through the drainage control structures into the tiles as subirrigation to 30-ft and 45-ft plots, respectively.

Monthly average temperatures and long-term temperatures are shown in Table 3.2. The temperature in 2023 was almost similar to the Climate Normal temperature. However, May (14.6°C) and June (20°C) were warmer than the long-term average.

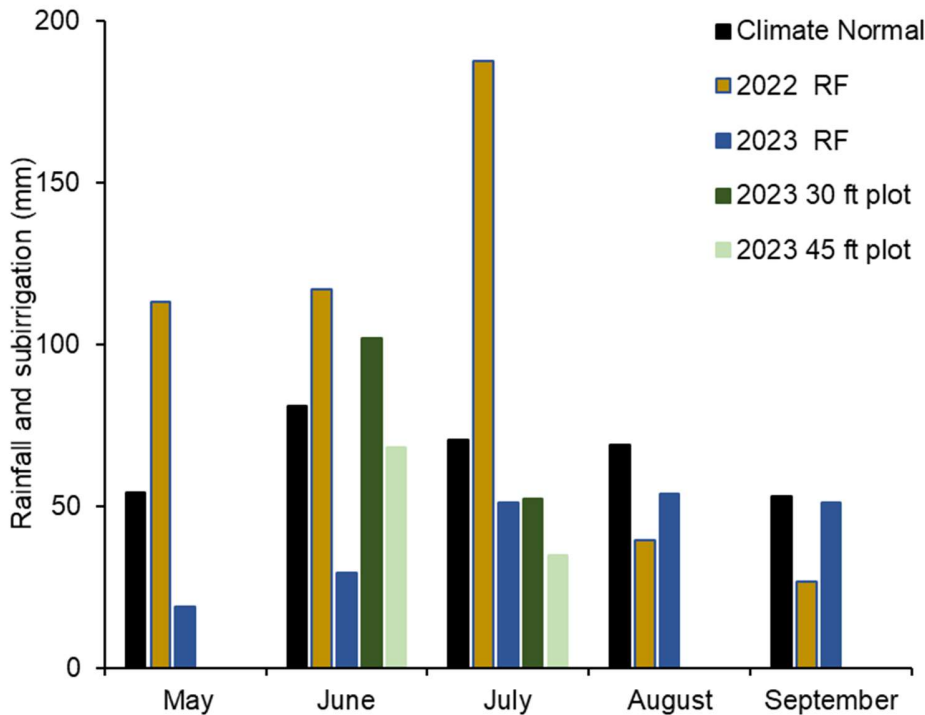


Fig. 4.2: Monthly average rainfall, subirrigation and Climate Normal during 2023 study period.

4.3.2 Model parameterization

The model was calibrated by changing parameters affecting the hydrology of agricultural fields and the initial values were obtained from the literature (Ndulue and Sri Ranjan 2022; Cordeiro and Sri Ranjan 2015; Satchithanatham and Sri Ranjan 2015). Subirrigation was applied during the growing season as shown in Table 4. 4 and the weir settings were adjusted to account for the subirrigation. The calibrated monthly ET correction factors from January to December are 2.01, 2.32, 2.1, 1.72, 1.23, 1.0, 0.86, 0.82, 0.92, 1.05, 1.22, 1.44. Initial soil temperature data were obtained from the weather station and soil temperature sensors installed in the different plots.

Table 4. 4: Subirrigation during the 2023 growing period.

Days	Subirrigation (mm)	
	30-ft	45-ft
2-Jun	4.53	3.02
5-Jun	4.53	3.02
8-Jun	4.53	3.02
12-Jun	1.83	1.22
13-Jun	1.13	0.75
14-Jun	1.46	0.97
15-Jun	2.92	1.95
16-Jun	4.74	3.16
17-Jun	8.75	5.84
18-Jun	8.75	5.84
19-Jun	6.57	4.38
19-Jun	4.74	3.16
20-Jun	17.52	11.68
21-Jun	17.52	11.68
22-Jun	12.42	8.28
4-Jul	4.74	3.16
5-Jul	17.52	11.68
6-Jul	17.52	11.68
7-Jul	12.42	8.28
Total	154	103

4.3.3 Water table dynamics

The observed and predicted water table depth (WTD) alongside daily rainfall in the 30-ft and 45-ft drain tile spacing plots during the 2023 growing season is shown **Error! Reference source not found.** The key factors influencing WTD fluctuations were rainfall, evapotranspiration (ET), and drainage.

In the 30-ft drain tile spacing plot, the average observed WTD was 1.2 m, while the simulated WTD was 1.1 m. Model performance during the early growth period was accurate. Until the end of June, most rainfall events were below 3 mm, except for the highest recorded event of 13.7 mm on June 21. During this period, the model satisfactorily predicted WTD fluctuations in response to rainfall, demonstrating its reliability under conditions of limited precipitation.

During the mid-growing period from June to early July, subirrigation through drain tiles significantly influenced WTD fluctuations. The simulated WTD increased to 1.4 m, whereas the observed WTD remained below 1 m. This could be attributed to the presence of impermeable soil layers and soil heterogeneity, which restricted water movement to the deeper layers. The inability of the model to capture these local variations suggests that additional soil property considerations may be necessary for improving simulation accuracy.

As the growing season progressed, total rainfall was insufficient to meet crop water requirements. Consequently, the wheat crop relied on capillary action and groundwater uptake to sustain growth. Due to increased ET and high-water uptake by crops, WTD continued to decline. The heaviest rainfall event of 21.43 mm, recorded on August 2, resulted in a slight increase in WTD in both observed (1.3 m in 30-ft) and simulated (1.1 m in 30-ft) models. However, the

observed WTD declined more rapidly than the simulated values, likely due to the inability of the limited rainfall to break the hydraulic barrier caused by prolonged dryness. The model failed to account for this hydraulic restriction, leading to a relatively stable simulated WTD with minor fluctuations.

The statistical evaluation of the model's performance for the 30-ft plot indicated satisfactory accuracy. The R^2 was 0.81, suggesting a strong relationship between observed and predicted values. The RMSE was 0.14, while the AAD was 0.10. The NSE value was 0.81, and the MBE was 0.08. These results suggest that while the model effectively predicted WTD fluctuations, it underestimated the effects of impermeable soil layers and hydraulic barriers.

In contrast, the observed WTD in the 45-ft drain tile spacing plot showed a continuous decline over the growing period. This was likely due to the wider drain tile spacing and the presence of a heterogeneous layer, which prevented deeper infiltration of rainfall. Instead, most of the rainfall was either absorbed by crop roots or lost through transpiration. Unlike the observed data, the simulated model did not fully account for the influence of the heterogeneous layer. Following frequent rainfall events on June 24 and August 3, the model predicted a slight increase in WTD (1.2 m), while observed values remained lower due to limited infiltration.

The statistical evaluation of the model's performance in the 45-ft plot demonstrated excellent accuracy. The R^2 value was 0.97, indicating a near-perfect correlation between observed and predicted values. The RMSE was 0.07, while the AAD was 0.06. The NSE was also 0.97, and the MBE was 0.03. The near-zero MBE value suggests that the model was unbiased, and the high R^2 and NSE values confirm low error rates.

Overall, the model was effective in predicting WTD fluctuations, with higher accuracy observed in the 45-ft plot compared to the 30-ft plot. However, the model struggled to simulate the impact of prolonged dryness on hydraulic barriers, resulting in overestimated WTD stability in the later growth stages. While the results indicate that the model performed satisfactorily in both cases, improvements in handling soil variability and hydraulic barriers could enhance future simulations.

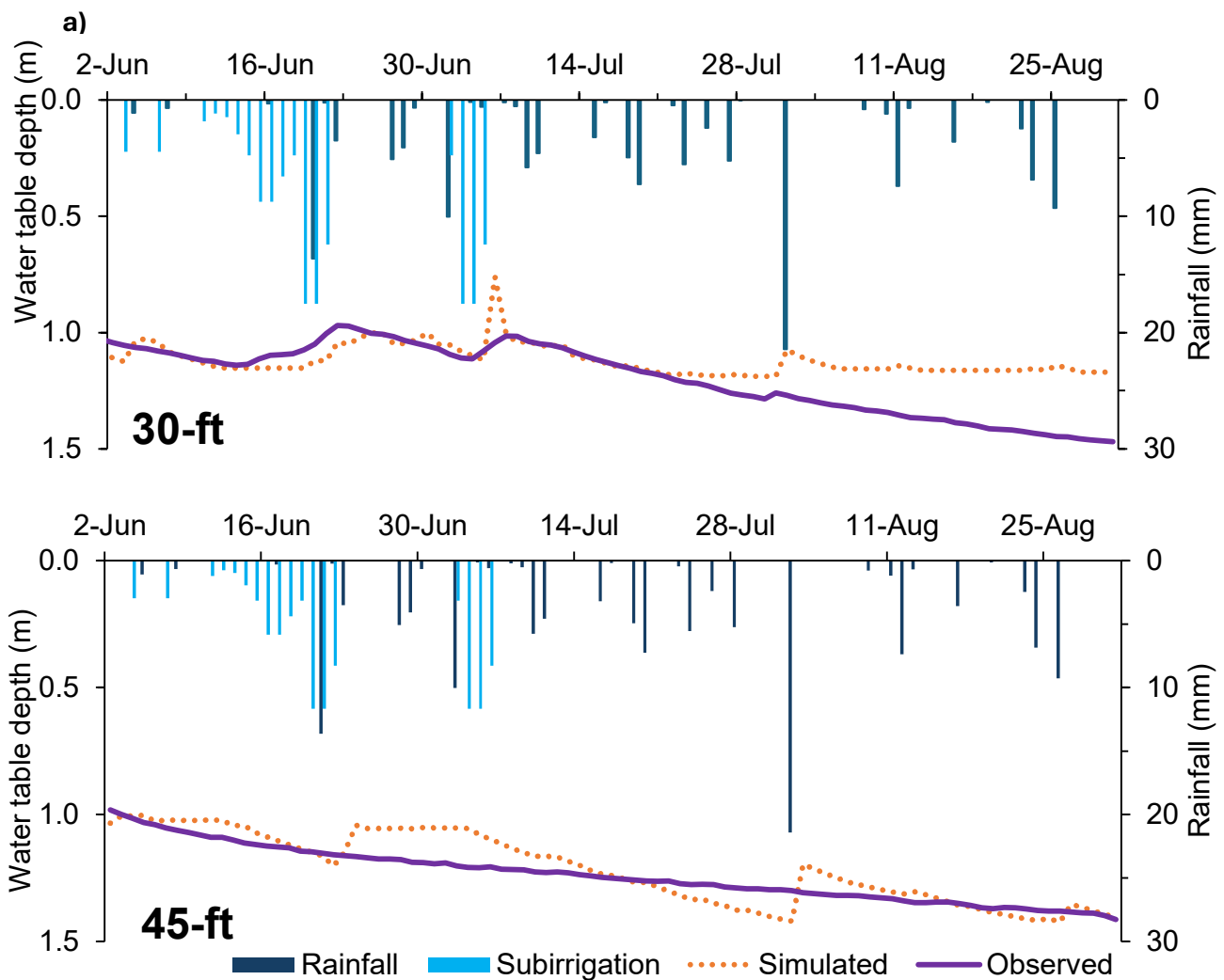


Fig. 4.3: Comparison of simulated and observed WTD in response to rainfall in a) 30-ft and b) 45-ft plots.

Table 4. 5: Summary of statistics indices on DRAINMOD performance for simulating WTD.

	45-ft	30-ft	Accepted Values
Root mean squared error (RMSE)	0.06	0.14	Closer to 0
Coefficient determination (R ²)	0.97	0.81	Closer to 1
Average Absolute Deviation (AAD)	0.06	0.10	Closer to 0
Mean Bias Error (MBE)	0.03	0.08	(+)ve over prediction (-)ve under prediction
Nash- Sutcliffe efficiency (NSE)	0.97	0.81	Closer to 1

4.3.4 Impact of drain spacing in wheat yield

DRAINMOD-validated model for 2023 was used to predict relative wheat yield under combined (subirrigation and controlled drainage) and controlled drainage-alone conditions for the years 2021, 2022, and 2023. The simulation results indicated that wheat yield was above the threshold level (80%) in all three years across all drain tile spacing plots (15-ft, 30-ft, and 45-ft) under combined conditions. It is shown in Fig. 4.4

The year 2022 was characterized by above-average rainfall, with 117 mm in June and 188 mm in August. The model predicted significant excess water stress with stress indices of 23.5, 9.2, and 9.9 in the 15-ft, 30-ft, and 45-ft plots, respectively. Consequently, the relative wheat yield in combined conditions were 92.9, 97.2, and 97.0% for the respective plots. Under controlled drainage, the excess water stress was reduced by approximately 5.4 units, leading to a slight increase in relative yield across all plots. In contrast, the year 2021 experienced low precipitation, resulting in high drought stress indices of 22.1 in the 15-ft plot and 18.7 in both the

30-ft and 45-ft plots. Consequently, the relative yield fell below the 80% threshold in the absence of subirrigation in 15-ft and 45-ft plots, were 73% and 77.6% respectively. However, subirrigation effectively alleviated drought stress. Resulted relative yield, 85.7% in the 15-ft. In the 30-ft and 45-ft plots, drought stress was reduced to 4.9 and 5.5, leading to relative yields of 94% and 93.3%, respectively.

The year 2023 experienced moderate rainfall, leading to lower drought stress indices across all drain tile spacing plots, with values of 3.2 for the 15-ft plot and 3.0 for both the 30-ft and 45-ft plots. As a result, the relative yields were high, with 96.1% in the 15-ft plot and 96.3% in the 30-ft and 45-ft plots. These findings suggest that subirrigation plays a crucial role in maintaining high relative yields, particularly in years with moderate rainfall. Despite this improvement, a six-day planting delay resulted in a 5.2% relative yield loss in 15-ft plot.

In addition to annual rainfall, other environmental factors influenced wheat yield. Late-season precipitation from the previous year affected antecedent water table depth, which in turn influenced soil moisture retention and planting conditions for the following year. Furthermore, high early-season precipitation in 2022 exceeding 50 mm during the early and mid-season was associated with yield reductions due to wet stress, planting delays, and non-workable field conditions. The impact of drain tile spacing on moisture stress was also evident, with narrow spacing (15-ft) being more susceptible to both drought and excess moisture stress, resulting in greater variability in yield. Conversely, moderate spacing between 30-ft and 45-ft provided a better balance of drainage and moisture retention, reducing both drought and wet stress, particularly when combined with subirrigation and controlled drainage.

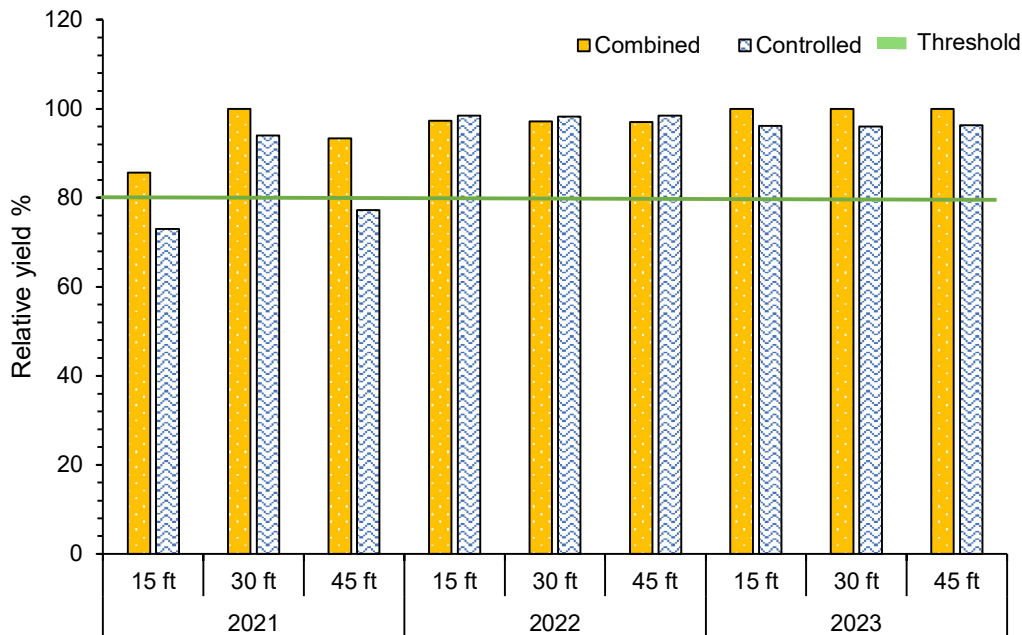


Fig. 4.4: Predicted relative yield in combined and controlled conditions during 2021 to 2023.

4.4. Conclusion

The results demonstrated that subirrigation significantly mitigates drought stress, leading to higher relative wheat yields across different drain tile spacing plots (15-ft, 30-ft, and 45-ft). The simulation results reinforced the importance of integrating subirrigation with controlled drainage to optimize crop production in heavy clay soils in the Canadian Prairies.

The findings showed that wheat yield was highly influenced by annual precipitation patterns and seasonal variability. During the wet year (2022), excess moisture stress was evident, however simulated model with controlled drainage has slightly higher relative yield than with combined drainage (subirrigation and controlled drainage). Conversely, in the dry year (2021), drought stress was a major limiting factor, particularly in plots with narrower tile spacing (15-ft), where relative yields fell below the 80% threshold. However, the combined model concludes that subirrigation effectively alleviated drought stress, particularly in the 15-ft plot,

despite minor yield losses (14.3%) caused by planting delays. The low rainfall year (2023) simulated model resulted in higher and more stable yields, highlighting the critical role of subirrigation in sustaining wheat production in fluctuating climatic conditions.

Beyond annual precipitation, additional factors such as antecedent water table depth, snowmelt, and early-season precipitation significantly influenced wheat yield. Excess moisture in early spring was linked to wet stress, planting delays, and non-workable field conditions, which negatively impacted yield potential. The results align with findings from previous studies on subsurface drainage and controlled drainage in the Canadian Prairies, particularly those evaluating the DRAINMOD model for corn and canola yield simulations (Cordeiro and Sri Ranjan 2015; Ndulue and Sri Ranjan 2022).

Overall, this study confirms that subirrigation and controlled drainage are effective strategies for improving wheat yield stability in the Canadian Prairies. Future research should focus on long-term performance assessments, optimizing drainage system design, and refining DRAINMOD simulations to account for site-specific soil properties. Additionally, investigating climate change projections and their potential impact on subsurface drainage performance will further enhance water management efficiency and sustainable crop production in cold climates.

CHAPTER FIVE

CONCLUSION

5.1. Main findings

This research investigated the impact of different tile drain spacing, subirrigation and soil moisture dynamics on wheat yield in heavy clay soils in Arborg, Manitoba. The main conclusion of this research includes:

- In 2022, being a wetter year, the closer tile spacing of 30-ft mitigated waterlogging and promoted higher yields in the midway-between-tiles compared to the control. The lower yield in the on-tile treatment may have been the result of excess water being held back in the tiles.
- Soil moisture sensors installed at different depth (0.2 m, 0.6 m and 0.9 m) provided real-time monitoring. Volumetric water content (VWC) in early growth stage was high and it continued to deplete over the growing season because of higher water uptake. During the dry year of 2023, wider tile spacing of 45-ft proved beneficial, retaining sufficient soil moisture which resulted in higher crop yield.
- Combination of scheduled subirrigation and controlled drainage in heavy clay soil is essential for ensuring optimal growth and yield in the long term.
- The DRAINMOD model was calibrated and validated, effectively predicting water table depth (WTD) fluctuations and yield responses for the Arborg, MB location. The model predicted a higher relative yield for subirrigation combined with controlled drainage in dry years.

5.2. Practical application and contribution

This research has direct implications for farmers, agronomists and policymakers seeking to improve crop water management in heavy clay soils similar to Arborg, Manitoba. The key contributions include:

- The 30-ft drain spacing was found to be better than the 45-ft spacing in wet years in the clay soils of Arborg, MB.
- The over-drainage from narrower drain tile spacing can be mitigated by better management of controlled drainage and subirrigation.
- Real-time soil moisture monitoring can help better manage the controlled drainage.

5.3. Future recommendations

- Future studies can consider measuring evapotranspiration using instruments like “Sapflow meter” coupled with soil moisture measurements to understand plant water uptake.
- Long-term subirrigation schedule according to the predicted weather pattern can help improve yield.

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