Agronomic and Environmental Impacts of Corn Production under Different Water Management Strategies in the Canadian Prairies

by

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ABSTRACT

A major challenge facing agriculture is to improve water use and minimize environmental impact while increasing productivity levels. This study, carried out in Winkler, Manitoba, tested four water management treatments: no drainage and no irrigation (NDNI as control), no drainage with overhead irrigation (NDIR), free drainage with overhead irrigation (FDIR), and controlled drainage with subirrigation (CDSI). Each treatment was replicated in three plots during two growing seasons (April-October) in 2010 and 2011. The monitored variables included soil moisture content, water table depth variation, drainage outflow volume and quality, weather parameters, and agronomic indices. In 2010, yields were 8.48 (NDNI), 10.36 (NDIR), 10.10 (FDIR), and 9.22(CDSI) Mg ha^{-1} with only the mean yield difference for the NDIR and the CDSI treatments being statistically significant ($p = 0.014$). In 2011, yields were 9.25 (NDNI), 10.47 (NDIR), 11.28 (FDIR), and 9.49 (CDSI) Mg ha^{-1} with no statistically significant differences in yield. In 2010, the exports of NO_3-N (138 kg ha^{-1}), PO_4-P (0.6 kg ha^{-1}) and salts (2.34 Mg ha^{-1}) from the FDIR treatment were significantly larger ($p <0.05$) than exports from CDSI, which were 0.07 kg ha^{-1}, 0.08 kg ha^{-1}, and 0.41 Mg ha^{-1}, respectively. In 2011, the exports of NO_3-N (36 kg ha^{-1}), PO_4-P (0.27 kg ha^{-1}), and salts (1.1 Mg ha^{-1}) from FDIR were significantly larger ($p < 0.05$) than the exports from CDSI which were 10 kg ha^{-1}, 0.08 kg ha^{-1}, and 0.39 Mg ha^{-1}, respectively. These results indicate that irrigation was the main factor driving corn yields under the conditions prevailing in the Canadian Prairies, while subsurface drainage had a beneficial impact when the beginning of the season was wet. Also, this study showed the advantage of controlled drainage over free drainage in reducing the nutrient and salt exports.

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DEDICATION

To my wife and parents.

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1. INTRODUCTION

1.1 Overview

The global food production increased exponentially after 1945 and gained momentum through the 1970s and 1980s (Dull, 2010). Particularly in the last quarter of the past century, agriculture achieved impressive results (Tilman, 1999). Grain production, mainly from wheat, rice, and maize, increased at a rate greater than that of human population. Among the factors contribution to this increase were i) the development of higher-yielding strains of crops and better agricultural practices, ii) the increased use of herbicides for weed control and insecticides and fungicides for pest control, iii) the marked increases in the amounts of nitrogen and phosphorus fertilizers applied, iv) increases in the proportion of arable land that was irrigated, and v) the increase in the total amount of land that was cultivated. Despite this unprecedented increase in production in recent years, the shift of dietary preferences from grain to meat has caused the global demand for agricultural crops to increase, and it is expected to keep growing in the coming decades (Tilman et al., 2002). In order to meet this growing demand, agriculture will likely rely on both land clearing and more intensive use of existing croplands to increase crop production.

While increase in crop production due to agricultural intensification was a remarkable achievement from a human perspective, it led to negative impacts on the environment, such as intensive water use and eutrophication of water bodies (Burney et al., 2010; Matson et al., 1997). The increase in world food production was only able to outpace population growth by adopting farming systems that require higher water inputs (Molden et al., 2007). According to Postel (1998), the volume of water consumed in producing current food supplies is much larger than typical estimates of agricultural water use. While these estimates have focused almost exclusively on the volume of water withdrawn for irrigation from the rivers, lakes, and underground aquifers, they typically neglect the rainfall input that is consumed by agricultural cropping systems, pastures, and grazing lands. As a result, the water demand of cropland ecosystems is much larger than that of crops themselves. According to Postel (1998) estimated that the crop water requirement in 1995 was 3,207 km^3 yr^{-1}, while the water consumption by crops and associated cropland biomass was, in fact, 7,500 km^3 yr^{-1}. More recent estimates indicated a global crop water consumption of 7,130 km^3 yr^{-1} (De Fraiture and Wichelns, 2010). Forecast of global water diversions to agriculture in the future is difficult because it depends on assumptions regarding trade, water use efficiency, area expansion, and productivity growth in rainfed and irrigated agriculture (De Fraiture et al., 2007). In attempting to estimate the global agricultural water diversion by 2050, De Fraiture and Wichelns (2010) proposed different scenarios with different assumptions. In an optimistic scenario, that assumes that 80% of the yield gap (i.e. the difference between the maximum attainable yield and yields that are actually achieved) is bridged by 2050, the area under rainfed agriculture would have to increase by 7%, while that under irrigation would have to increase by 16% with a corresponding increase in irrigation withdrawal by 13%. However, meeting this increasing water need will be more difficult in the future because agriculture will face intense competition from other users (De Fraiture et al., 2007). While agriculture will remain the largest water user worldwide, demand for water in domestic and industrial sectors is expected to grow by a factor of 2.2 by 2050.

Considering the water quality aspects relating to agriculture, nitrogen and phosphorus have been singled out as the leading causes of accelerated eutrophication of fresh and salt-water environments (Beaulac and Reckhow, 1982; Goolsby et al., 2001). Nitrogen and phosphorus input to the land surface from fertilizer and manure is potentially available for export to streams and rivers, where it may contribute to local water-quality problems and eutrophication of downstream water bodies (Sprague and Gronberg, 2012). Nitrogen from crop production is by far the single largest cause of human alteration of the global cycle of this nutrient (Smil, 1999). Liu et al. (2010) state that the doubling of world food production in the past four decades could be achieved only with an almost sevenfold increase of nitrogen fertilization. These authors calculated the total global nitrogen flow for the year 2000 and found that mineral fertilizer was the single largest nitrogen input to cropland, accounting for almost 50% of the global input, while manure accounted for another 13%. Combined, these two sources corresponded to almost two thirds of the 136.6 Tg (Trillion grams) of N that comprised the global nitrogen input to cropland in the year 2000. The nitrogen output in the same year was 148.14 Tg, which is 8% larger than the input. Out of this, 55% of the nitrogen output was removed by harvested crops (35%) and crop residues (20%). The remainder was lost through leaching (16%), soil erosion (15%), and gaseous emission (14%). As for nitrogen, there was also a surplus of phosphorus in agricultural systems budgets calculated for the year 2000 (Bouwman et al., 2011). Phosphorus input to agricultural systems as mineral fertilizer and manure totalled 31 Tg, while the total withdrawal was only 19 Tg. The phosphorus surplus of 12 Tg was lost by runoff or accumulated as residual soil P. Projections for 2050, indicate that the average surplus of both nitrogen and phosphorus will rise to around 166 and 17.5 Tg, respectively (Bouwman et al., 2011), thus increasing the risk of negative impacts on the environment.

Given this scenario, agriculture will have to find strategies to improve water use to meet the fresh water challenge (De Fraiture et al., 2010) and minimize environmental degradation caused by nutrient export (Tilman, 1999). Some of these strategies are to improve rainwater management, adapt irrigation to new needs, enhance water productivity (De Fraiture et al., 2010), and use and recycle nitrogen and phosphorus more efficiently in agro-ecosystems (Tilman, 1999). In irrigated agriculture, a major challenge is to adapt yesterday's irrigation systems to tomorrows needs using a mix of technological and managerial upgrades. In this context, drainage is also an important a factor. For example, the management of surface water flow and drainage is an important tool for conservation of soil, nutrient, and water in crop production in the United States (Christensen, 2002). Maize (Zea mays L.) is one of the crops most affected by the challenges mentioned above. It is the third most important grain crop, behind wheat and rice; it is widely grown throughout tropical, subtropical, and temperate areas of the world (Sicher and Kim, 2011); and it is one of the major irrigated crops (Tardieu and Welcker, 2011). Corn production is mainly dedicated to feeding animals, human consumption, and industrial applications such as biofuel production (Sicher and Kim, 2011). Thus, water and nutrient management strategies that improve water use efficiency and minimize nitrogen and phosphorus export from farmland is important for economic and environmental sustainability of this crop.

1.2 Objectives

The aim of this research was to investigate which combination of irrigation and subsurface drainage leads to the highest yield of corn, while minimizing the impacts on water quality in the Canadian Prairies. The specific objectives were to:

1. measure water content spatially and temporally to understand the water redistribution pattern within the root zone of corn after a complete irrigation;

2. determine the contribution of the groundwater table to the soil moisture within the corn root zone;

3. simulate the soil water content and upward flux of water in the corn root zone using the Hydrus-1D model to verify the ability of the model to predict the changes in soil water status in response to crop water use;

4. assess how different water management treatments affect corn performance in terms of yield and grain quality;

5. test the accuracy of simulations of water table and drainage outflow using the hydrological model DRAINMOD; and

6. assess which combination of irrigation and drainage described in Objective 4 results in minimized export of nitrogen and phosphorus from corn fields.

1.3 Scope

The uncertainty in supply of water for irrigation at currently practiced levels, the changing farming practices, and the need for minimizing the environmental footprint, represent a set of challenges facing agriculture in the near future, which will have to be met under an increased demand for food production. This research focuses on these challenges in the Canadian Prairies' context, and investigates how water management strategies using current irrigation and drainage practices, coupled with the investigation of soil-plant-water interactions, affect corn yields and export of nutrient and salts from the farmland. This study is attempt to fill the existing knowledge gap in agronomic performance of corn under subsurface drainage, which is quickly expanding in the Canadian Prairies. The work was carried out under the specific physiographic conditions of Southern Manitoba and incorporated agronomic practices adopted in this region. It also considered the impact of specific hydrologic mechanisms to water management, such as contributions from shallow groundwater to the soil water content of the root zone through upward flux. While the hydrologic, agronomic, and environmental impacts of corn production under different water management strategies are studied and discussed, an economic or financial analysis is out of the scope of this research because it would require access to economic indices or private financial information, which were not readily available. Specifically, the uses of corn, characterization of the Maize plant and its nutritional requirements, the role of irrigation and drainage on agricultural production, and the environmental impacts of nutrients exported through drainage systems are described in Chapter 2. The water redistribution within the corn root zone, the contribution from groundwater during periods of high corn evapotranspiration, and the simulations of the changes in soil moisture and upward water flux using Hydrus-1D are presented in Chapter 3. The effect of different combinations of overhead irrigation, sub-irrigation, uncontrolled drainage, and controlled drainage on corn yield and grain quality is presented in Chapter 4. The DRAINMOD model simulations of water table elevation and drainage outflow during the growing season, as well as the evaluation of the subsurface drainage design criteria recommended for Manitoba, are presented in Chapter 5. The effect of controlled drainage as a best management practice to decrease the nutrient and salt exports from farmland under corn production is presented in Chapter 6. While this chapter compares the reduction of nutrient and salt export in the drainage outflow promoted by controlled drainage, a nutrient and salt balance was not attempted because some components of the nutrient and salt balance in the soil were not monitored during the experiment (e.g., nitrogen mineralization and immobilization, contribution of groundwater to nutrient and salt balance). Chapter 7 describes the practical applications of this research, while Chapter 8 summarizes the main conclusions of this study. Chapter 9 presents some recommendations for future research. References for all the chapters are presented after Chapter 9.

2. LITERATURE REVIEW

2.1 Corn Uses and Production

Corn is an ingredient in a wide variety of products, including food items (e.g. carbonated beverages and instant coffee), medical drugs (e.g. antibiotics and analgesics), cleaning products (e.g. soaps and cleaners), personal-care products (e.g. shaving cream and lotions), and fuel (i.e. ethanol) (Grain Farmers of Ontario, 2011). One of the largest uses of corn is in the livestock industry. The US and Brazil, the world's two largest producers of beef, use corn as the predominant feed grain, while China, the third largest producer, has followed the trend in Asia and has shifted from wheat to corn in the 1990s (FAO, 2009a; Steinfeld et al., 2010). Particularly in the US, the livestock industry alone consumes about 40% of the corn produced (US National Corn Growers Association, 2013). In fact, the use of coarse grains in livestock production is projected to reach 553 million tonnes by 2050 (FAO, 2009b), driving an increased demand for corn.

In North America, biofuel production has been driving the corn demand up and consequently the price. The Energy Independence and Security Act of 2007, in the US, will drive a 5-fold increase in the biofuel production causing an expansion of the corn-planted area (Landis et al., 2008). Canada, which is committed to diversify its energy sources, had a policy of reaching an average of 5% renewable content in gasoline by 2010 and 2% renewable content in diesel fuel and heating oil by 2012 (APEC, 2008). Ethanol and biodiesel are the main renewable fuels in the Canadian portfolio, with corn accounting for 77% of all ethanol feedstock in 2006. About 7% of the total corn produced and imported into Canada was used for ethanol production in 2006, while a larger portion was used by the livestock industry.

Corn production has increased in the last few years in response to increased demand. The US, the world's largest corn producer with more than 3 x 10^8 metric tonnes produced in 2008 (FAO, 2008), has expanded its area under corn by 19% from 2006 to 2007, reaching 37.9 million ha planted (Landis et al., 2008). In China, the world's second largest producer with 1.66 x 10^8 metric tonnes produced in 2008 (FAO, 2008), the percent of arable land planted with corn increased from 25.2% to 34% in the past 15 years (Peng, 2011). The trend is also increasing in Canada, with the largest historical production in the last few years (Index Mundi, 2011). Corn was ranked the fourth largest crop produced in 2009 (1.06 x 10^7 metric tonnes), following wheat (2.86 x 10^7 metric tonnes), canola (1.26 x 10^7 metric tonnes), and barley (1.18 x 10^7 metric tonnes) (Statistics Canada, 2009). Canadian land under corn reached 1.25 x 10^6 ha in 2000, driven by the demand created by the hog and ethanol industries (Statistics Canada, 2002).

2.2 Characterization of the Corn Plant

2.2.1 Origin and Morphology

Maize (i.e. corn plant, *Zea mays* L. ssp.) is a grass which originated in southern Mexico and Guatemala from a wild breed called teosinte (Maiti and Wesche-Ebeling, 1998). Among the morphological characteristics that distinguish maize from its ancestor are the exposed kernels, single stem and single tassel, larger grain weight, and fewer numbers of larger ears. Corn became the world's third most important cereal (Fageria et al., 2011) through domestication of wild cultivars, adaptation to agricultural environments, and breeding for yield (Evans, 1993). This last phase encompasses important factors from the modern agriculture's standpoint, such as genetic yield potential, plant process efficiency, crop stature, earliness and longevity, and photosynthetic rate.

Fageria et al. (2011) divide maize's morphology into roots, stem and leaves, and inflorescence (i.e. reproductive structures). The initial small seminal root system, which supplies most of the nutritional needs during the first two weeks after germination, loses functionality and is replaced by a large fibrous system originating from the lower nodes of the stem (i.e. nodal root system). Fast root growth occurs in the first eight weeks after planting (Anderson, 1987). At the tasseling stage, nodal roots reach their maximum depth, and from tasseling to grain filling stage, stout brace roots develop from nodes near the base of the stem (Larson and Hanway, 1977). The root system grows to 1.2 m or even deeper; however, 60% of the moisture used by the plant comes from the top 0.6 m of the soil profile, while less than 10% comes from below 0.9 m (NDSU, 1997a). In fact, 90% of the roots are in the top 0.90 m of the soil, which is considered the rooting depth for irrigation purposes because corn plants can withdraw water from this soil depth. The radial root distribution is limited, with high root density found in the row, directly under the plant (Anderson, 1987).

The aboveground biomass is comprised of stem, leaves, and reproductive structures, and can reach 2.5 to 3.5 m in most corn hybrids (Fageria et al., 2011). The stem consists of leaf sheaths, nodes, and internodes, while the latter consist of a thin, flat blade. The number of leaves per plant varies from 7 to 30 in tropical cultivars, while the temperate-climate hybrids have between 16 and 23 leaves (Tollenaar and Dwyer, 1999). The corn plant is called cross-pollinated because it has separate male and female inflorescences on the same plant: the tassel and the ear, respectively (Fageria et al., 2011). Maize plants usually have one ear per plant, although up to eight ears may have been initiated (Tollenaar and Dwyer, 1999).

2.2.2 Classification of Plant Development Stage

Larson and Hanway (1977) describe the plant growth and development into five distinct periods: planting to emergence, emergence to tasseling, tasseling to silking, silking to maturity, and dry-out period. During the planting to emergence phase, warmth and moisture are essential. Under the right soil conditions, emergence from the soil takes place in four to five days after planting. However, deep planting depth or soil crusting can hinder the seedling emergence. Between emergence and tasseling, the photosynthetic capacity of the plant is fully established; as a result, the dry matter and nutrient accumulation is rapid. Due to the fast growth, the demand for nutrients is high and any deficiency will limit plant growth and the potential final yield. Since the growing point of the plant is still below the soil surface during the first two or three weeks of this period, damage by frost or hail has little effect on yield. However, any water and nutrient stress before tasseling could compromise the photosynthetic activity later in the season or the number of potential kernels initiated in the ear. In the tasseling to silking period, the silks (i.e. stigmas from female maize flowers) must be pollinated so that kernels can develop. The plant is particularly susceptible to water, light, or soil fertility stress during this time, which may delay silking and reduce seed set due to inadequate pollination. The corn grains are produced during the period between silking and maturity. The cob, husks, and shank have complete development during the two weeks after silking. Then, starch accumulates in the endosperm and the plant dry matter accumulation occurs entirely in the kernel. There is also the transport of nutrients from other parts of the plant to the kernels. While unfavorable environmental conditions will result in unfilled kernels, yield is not as subject to water stress as it is during the silking phase. When the kernel is mature, the plant will start to dry out. The moisture content in the kernel is around 30% at maturity, and the rate of drying will depend on climatic conditions, husk properties, and corn hybrid.

From an agronomic standpoint, classification methods have been created for corn vegetative and reproductive development (NDSU, 1997b). The leaf collar method determines leaf stage (i.e. vegetative stage) of corn by counting the number of leaves with visible leaf collars (i.e. discolored line between the leaf blade and leaf sheath) on a plant (Nielsen, 2010). The counting starts with the lowermost, short, rounded-tip true leaf and ends with the uppermost leaf with a visible leaf collar, which is a band located at the base of the exposed leaf blade. The vegetative stages are described as "V" stages, going from VE (i.e. emergence), through V1 (first leaf), V2 (second leaf), V3 (third leaf), up to VT (i.e. tasseling) (NDSU, 1997b). Leaves within the whorl, not fully expanded and whose collar is not visible, are not counted in this method (Nielsen, 2010). The reproductive classification has six stages going from R1 to R6, which represent silking, blister, milk, dough, dent, and physiological maturity, respectively (NDSU, 1997b).

The developmental phases described above are a function of temperature rather than time after planting. Thus, temperature-based methods have been devised to determine the maturity of corn. One such method used in the United States is the growing degree-day (GDD), which is calculated by (Tollenaar and Dwyer, 1999):

$$GDD = \frac{(T_{\max} + T_{\min})}{2} - T_{base} \quad (1)$$

where T_{max} = daily maximum temperature, T_{min} = daily minimum temperate, and T_{base} = base temperature, which is usually taken as 8 or 10°C. The GDD is calculated within the upper and lower temperature limits of 30 and 10°C, respectively. Thus, T_{max} = 30 if the daily maximum is equal to or larger than 30°C. Likewise, T_{min} = 10 if the daily minimum is equal to or less than 10°C. Another heat unit system used is the crop heat unit (CHU), which is adopted in Canada. This system uses separate calculations for day and night (Brown and Bootsma, 1993), which are given by equations (2) and (3):

$$Y_{min} = 1.8 \times (T_{min} - 4.4) \quad (2)$$

and

$$Y_{max} = 3.33 \times (T_{max} - 10) - 0.084 \times (T_{max} - 10)^2 \quad (3)$$

where Y_{min} = nighttime (minimum) temperature relationship, Y_{max} = daytime (maximum) temperature relationship, T_{min} = daily minimum temperature (°C), and T_{max} = daily maximum temperature (°C). Y_{min} equals zero if $T_{min} < 4.4$°C, while Y_{max} equals zero if $T_{max} < 10$°C (Tollenaar and Dwyer, 1999). Daily crop heat units (CHU) are then calculated by averaging the two daily values from Eqs. (2) and (3); that is:

$$CHU = \frac{(Y_{min} + Y_{max})}{2}, \quad (4)$$

where Y_{min} and Y_{max} are the same as above. Most corn hybrids have been rated for southern Manitoba in terms of CHU requirements (MAFRI, 2011). For silage, most hybrids require from 2,000 to 2,100 CHU/crop growing season to reach physiological maturity, while for grain, this range increases to 2,200-2,400 CHU/crop growing season. Figure 2.1 shows the average cumulative CHU across southern Manitoba.

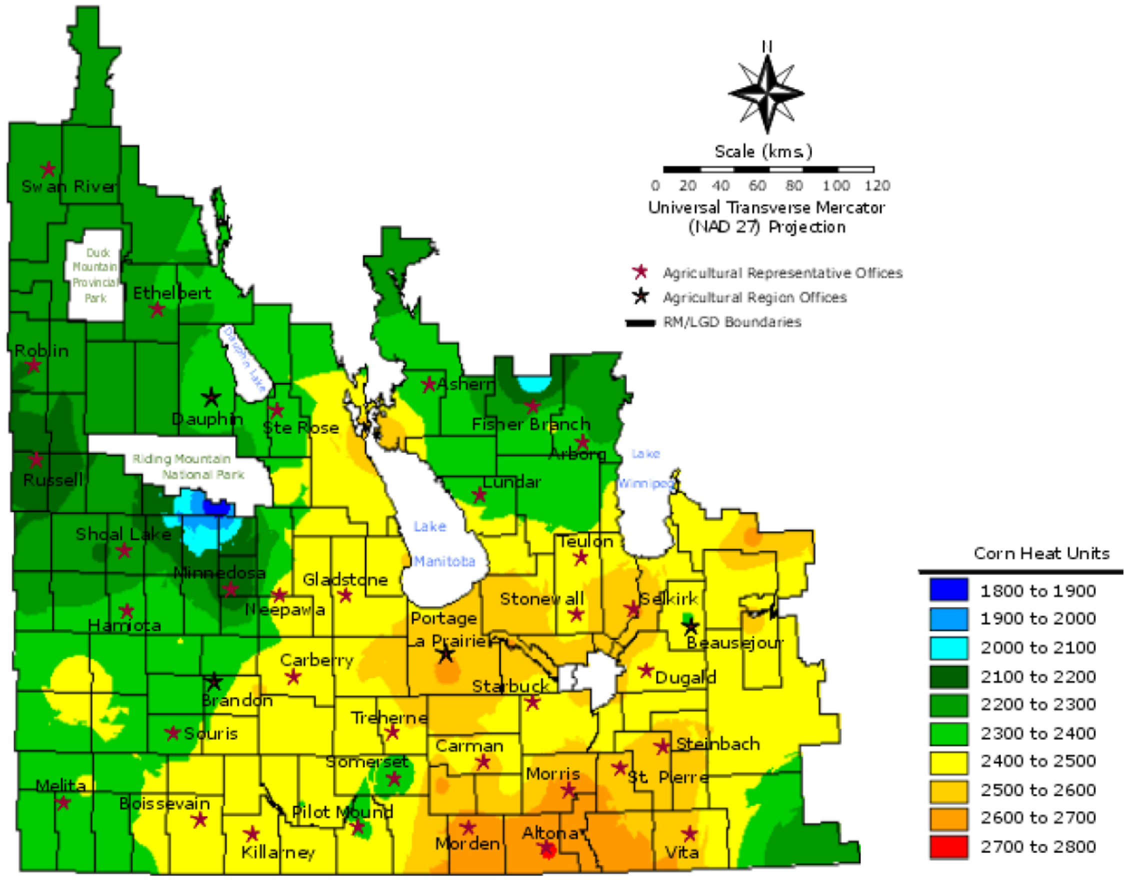

Figure 2.1. Average annual crop heat units across southern Manitoba. (Source: MAFRI, 2011).

2.3 Nutrient Requirements

Agronomically, mineral nutrition plays an important role in increasing crop yield, along with plant cultivar, water availability, disease, weed, and pest control (Fageria, 2009). Mineral nutrition refers to the supply, availability, absorption, translocation, and utilization of inorganically formed elements for growth and development of crop plants. Yield increase in many parts of the world was substantially driven by the use of chemical fertilizer, especially nitrogen, which promoted better crop nutrition. Modern intensive agriculture relies on commercial fertilizers to avoid nutrient depletion and ensure crop productivity (Stewart et al., 2005). This is particularly true for the top corn producers in the world. In the US, the world's largest corn producer, corn is the most fertilizer-dependent crop, with an estimated 41% reduction in yield if no N fertilizer is used. According to Stewart et al. (2005), the estimated yield reduction would have been even greater if the effects of other nutrients (e.g. P and K) had been taken into consideration. The dependence on chemical fertilizer is still greater in the tropics. In the Amazon basin, where crops are established in deforested areas, the soil fertility is usually low. An 8-year study in Brazil and a 15-year study in Peru indicated that yields attributed to fertilizer and lime was never below 90% (Stewart et al., 2005).

According to Fageria (2009), plants require 17 essential nutrients for optimal growth and development, namely, carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), boron (B), molybdenum (Mo), chlorine (Cl), and nickel (Ni). These elements can be divided into macro- and micro-nutrients, according to quantities required by the plant. The classification of the above elements according to the plants' needs is given in Table 2.1. Since nitrogen, phosphorus, and potassium are the major nutrients considered in fertilizing programs, only these elements are discussed below in more detail.

Table 2.1. Classification of essential nutrients for optimal plant growth and development[†].

Classification	Element	Comments
Macronutrient		
	C	Not considered in fertilizer programs
	H	Not considered in fertilizer programs
	O	Not considered in fertilizer programs
	N	Primary nutrients in fertilizer programs
	P	Primary nutrients in fertilizer programs
	K	Primary nutrients in fertilizer programs
	Ca	Secondary nutrients in fertilizer programs
	Mg	Secondary nutrients in fertilizer programs
	S	Secondary nutrients in fertilizer programs
Micronutrient		
	B	Added for special crops or specific soil situation
	Cl	Added for special crops or specific soil situation
	Cu	Added for special crops or specific soil situation
	Fe	Added for special crops or specific soil situation
	Mn	Added for special crops or specific soil situation
	Mo	Added for special crops or specific soil situation
	Zn	Added for special crops or specific soil situation

[†] Adapted from Aldrich and Leng (1969).

2.3.1 Nitrogen

While nitrogen is regarded as the key factor influencing corn yield and economic returns, difference in yield response to N fertilizer depends on a number of factors, such as timing and frequency of precipitation, yield potential of the corn hybrid, physical properties and fertility of the soil, and N–content in the soil organic matter (Oberle and Keeney, 1990; Schlegel and Havlin, 1995). Given this variability, the N application rates vary largely across different field conditions and have to be adjusted according to site-specific parameters (Fageria et al., 2011). Oberle and Keeney (1990), using regression analysis and long-term data, showed that N fertilizer rates to maximize yields are lower on rainfed silty loam and silty clay loam soil (174-235 kg ha^{-1}) than on irrigated loamy sand or sandy loam soils (196-258 kg ha^{-1}). Decisions concerning optimum fertilization rates involve, directly or indirectly, fitting some type of model to yield data obtained at several fertilizer application rates. Cerrato and Blackmer (1990) argue that while several models can be used to fit the data, interpretation of such models may be misleading. In their 12 site-year, 10 N application rates, study of corn yield response to N fertilization using five different models (i.e. linear plus plateau, quadratic plus plateau, quadratic, exponential, and square root; fig. 2.2), the R^2 statistic indicated that all the models fit the yield data equally well and predicted similar maximum yields. However, the models showed discrepancies on the predictions of the economic optimum rates of N fertilization. Since there is only a single optimum fertilization rate for a given site-year, taking the R^2 statistic as the sole parameter when adopting a model is not reliable to define the optimum N application rate. Statistical analysis revealed that the quadratic model, largely adopted for determining N application rates, tends to overestimate these rates, and that the quadratic plus plateau model best represented the yield responses observed in the study (Cerrato and Blackmer, 1990).

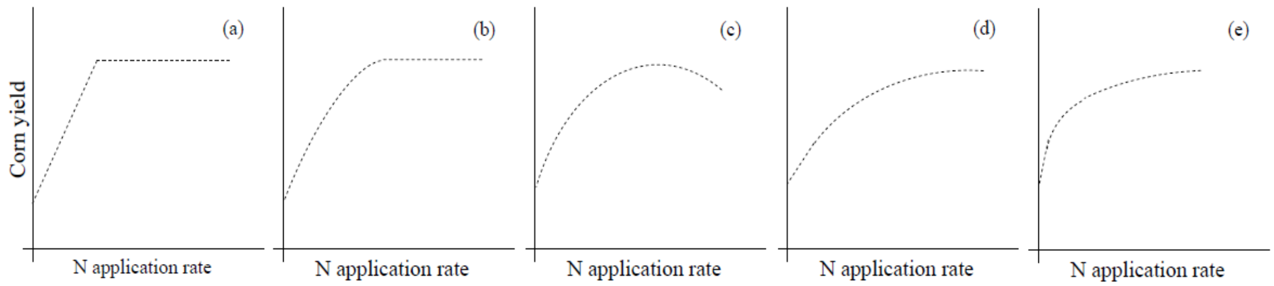

Figure 2.2. Fitting models for corn yields in response to N application rates. Models are (a) linear plus plateau, (b) quadratic plus plateau, (c) quadratic, (d) exponential, and (e) square root. Adapted from Cerrato and Blackmer, 1990.

At the farm level, definition of N application rates usually rely on tables developed by government agencies based on research done under specific conditions (MAFRI, 2007). In Ontario, for example, the Ministry of Agriculture, Food, and Rural Affairs offers fertilizer recommendation tables for corn (OMAFRA, 2011). These tables take into consideration a base N requirement according to soil texture and region of the province, yield adjustment based on projected yield, heat unit adjustment, and previous crop adjustment. In Manitoba, the spring, band-applied N fertilization rates suggested by the Ministry of Agriculture, Food and Rural Initiatives are based on target yield, and NO_3-N soil tests done in the previous fall (MAFRI, 2007). However, the agency stresses that those rates are suggested as guidelines, which are not intended to supersede provincial laws or to serve as application limits.

Nitrogen fertilizer application can also be accomplished by using manure. The Tri-Provincial Manure Application and Use Guideline (PPCLDMM, 2011) presents the basis for use of manure as nitrogen fertilizer for Manitoba, Saskatchewan, and Alberta. The recommended manure application rates varies according to manure nutrient content, predicted manure nutrient availability, available soil nutrient content, and the anticipated crop nutrient requirement. However, it is difficult to meet exact crop requirements for two or more nutrients coming from manure because, unlike commercial fertilizers, the nutrients in manure are not balanced for optimal crop growth. Thus, when manure is applied based on one nutrient, other nutrients are usually either over- or under-applied. In the Prairie region, nitrogen-based application rates are the accepted practice.

2.3.2 Phosphorus

Deficiency in phosphorus is the principal yield-limiting factor for annual crops in acid soils in temperate and tropical regions (Fageria et al., 2011) because soil acidity decreases P use efficiency in crops (Fageria, 2009). Phosphorus is also extremely chemically reactive; consequently, P in soils is the most immobile, inaccessible, and unavailable of all nutrient elements (Holford, 1997). The quantity of P in the soil solution is relatively low because of the very low solubility of P compounds in the soil and the tendency of P equilibrium to favor the solid phase. These characteristics make this element the second nutrient to limit the agricultural production in most regions of the world.

Phosphorus application rates depend mainly on i) the existing level of available soil P, ii) the optimum level of soil P for the crop, and iii) the level of fertilizer to be applied to raise available soil P to the optimum level (Fageria et al., 2011). As for nitrogen, methodologies for determining P application rates are based on the soil P status of the field and projected yield. Fertilizer recommendations for Ontario use calibration data.

The calibration is done on selected soil extractants against response to added fertilizer over a wide range of soils in field trials. The most economic fertilizer application rate (MER) is identified based on the soil test level (Miller et al., 1997). This rate will be less than that required to produce the maximum crop yield but will produce the most economic yield (MEY). Beyond MEY, the cost of the additional fertilizer to produce extra yield is greater than the value of the extra yield. In Manitoba, the majority of the soils cannot supply adequate phosphorus for optimum yields (MAFRI, 2007). In recent years, 25% of the fields have been rated as very low and low in P. The recommended application rates are based on soil tests and plant requirement, but the MAFRI recommended rates range between 34 and 45 kg ha^{-1} when no soil test is done. For manure fertilization, much of the P is present in organic form and only 50% of the total P content is considered available for the crop following application. Application rates are based on manure nutrient make-up, availability, and release from organic forms, as well as losses during storage and application, and method of application.

2.3.3 Potassium

While potassium deficiency is not as common as N and P deficiencies in crop plants across different agro-ecosystems, K uptake by field crops may be as high as N uptake (Figeria, 2009). Symptoms of potassium deficiency are not as apparent as N and P deficiencies (Figeria, 2009); however, deficiency symptoms on cereal grains appear as a burning or scorching of the lower leaves (Alberta Agriculture and Rural Development, 2000). In Ontario, the recommended rates are based on soil tests, as for phosphorus. However, K applications higher than the recommended rates may be required to achieve MEY in some instances (Miller et al., 1997). In Manitoba, most soils contain adequate amounts of available K for crop production (MAFRI, 2007). Soils likely to be low in K are coarse-textured sands, sandy loams and organic soils. Potassium may be required on about 6% of arable Manitoba soils for maximum production of commonly grown annual crops such as cereals, canola and flax. About one-third of Manitoba soils require additional K for the production of special crops such as corn, potatoes and small fruit or vegetable crops because potassium is required in greater amounts by these crops when compared to other crops such as soybeans and wheat. Potassium fertilizer should be placed with the seed for the most efficient use by cereal crops. Placement of K fertilizers should be side-banded to the side and/or below the seed (Alberta Agriculture and Rural Development, 2000; MAFRI, 2007). If potash is broadcast, the recommended rate for seed placement or side banding should be doubled to obtain equal crop response.

2.4 The Role of Irrigation and Drainage on Agricultural Production

2.4.1 Irrigation

Irrigation has been the foundation of several civilizations across different regions and times (van Schilfgaarde, 1994). Egypt has relied on irrigation for over 8,000 years, while Mesopotamia and Asia have practiced it for 4,000 years. In the Americas, historical evidence of irrigation date back 2,000 years. Today, while irrigation is practiced in all the continents where conventional agriculture is practiced, the spatial distribution and intensity of irrigation vary greatly. According to the world irrigation map by Siebert et al. (2005), irrigation is widespread in arable lands of North America, Europe, and Asia; however, it is more intensive in parts of the United States, India, and China.

Irrigation – the artificial application of water for supplementing the naturally available soil moisture in the root-zone for agricultural production – is practiced where moisture available from rain or from underground water is not sufficient for plant requirements (Asawa, 2006). The supplemental water is used for processes such as germination of seeds, temperature regulations, dilution and leaching of salts, improvement of soil structure, application of fertilizers, and prevention of adverse effects of frost. A well-managed irrigation system optimizes the spatial and temporal water supply, not necessarily to obtain the highest yields per unit amount of land or water, but to maximize the benefit-cost ratio (Hillel, 1998). In fact, deficit irrigation strategies have been devised for regions where water is scarce or full irrigation is cost-prohibitive. These strategies are based on the sensitivity of specific crop to water stress during the whole growing season or different stages of growth (Dagdelen et al., 2006). Irrigation can be done by surface, sprinkler, subsurface, or trickle (i.e. drip) methods (Asawa, 2006). While a detailed description of irrigation systems is out of the scope of this review, a brief presentation of the different methods used in Manitoba is provided.

Sprinkler systems apply water to the soil surface in the form of a spray, which is somewhat similar to rain (Brouwer et al., 1989a). Water is distributed through a system of pipes usually by pumping. It is then sprayed into the air through sprinklers so that it breaks up into small water droplets, which fall to the ground. The pump supply system, sprinklers and operating conditions must be designed to enable a uniform application of water. Sprinkler methods include i) *travelling guns*, which consist of a wheeled cart with a large sprinkler, the main traveler machine with a hose reel, and an irrigation hose (Clemson University, 2011a); ii) *side-roll systems*, which consist of rigidly coupled aluminum pipes mounted on large wheels with the pipe acting as an axle and sprinklers installed on it (Irriline Technologies, 2011); iii) *hand move systems*, which is a simpler version of the side-roll system, where a power unit is not present and that can be moved from position to position by one person (Irriline Technologies, 2011); iv) *linear move systems*, where a single motorized lateral with sprinklers moves in a linear straight path, covers the entire width of the field, and waters the entire field in one pass (Clemson University, 2011b); and v) *centre pivot systems*, which consist of a single sprinkler lateral with one end anchored to a fixed pivot structure and the other end continuously moving around the pivot while applying water (Clemson University, 2011b).

Subsurface irrigation is done by means of a series of ditches having vertical sides or pipe distribution systems installed in the soil (Asawa, 2006). While subsurface drainage systems, which are discussed in detail in the following sub-section, can be adapted for subsurface irrigation by pumping water back into the drain tiles, there are specific design criteria for this type of operation. Sub-irrigation may be the governing design performance parameter since a closer subsurface conduit spacing is typically required to supply adequate sub-irrigation water to the soil profile than the conduit spacing required to remove excess soil-water from the root zone and soil profile (Fouss et al., 2007). The operation of the system, which can be run under conventional subsurface drainage, controlled drainage, or sub-irrigation mode, varies from day to day and from year to year, which increases the complexity of the design. For most locations, it is not clear whether the greatest demands on the system design are to provide good drainage under shallow water table conditions, or to provide sufficient sub-irrigation to meet evapotranspiration (ET) demands during the driest periods (Fouss et al., 2007). This aspect highlights the importance of research on drainage/sub-irrigation being done where no field data is available.

Surface irrigation is the most used worldwide and adopted in 73% of irrigated lands (Pallas, 1993). However, the method is considered inefficient due to lack of understanding, non-standardized evaluation procedures, and lower precision during design and operation (Lord Jr. and Ayars, 2007). Sprinkler irrigation, in turn, is the most studied, best understood, and most fully documented irrigation system of the three major methods (i.e. surface, sprinkler, and drip irrigation). According to Brouwer et al. (1989b), the field application efficiency depends on the irrigation method and the level of farmer discipline; however, the average field application efficiency increases from surface, to sprinkler, to drip irrigation, with values of 60, 75, and 90%, respectively.

Irrigation of corn depends on weather patterns, availability of water, and cost of irrigation. The production system in the three major corn producers in the world (i.e. US, China, and Brazil; FAO, 2009a) is quite contrasting in terms of irrigation. In the US Great Plains, which has limited rainfall and encompasses the High Plains of Texas, New Mexico, Oklahoma, southwestern Kansas, and southeastern Colorado, irrigation is an increasingly important practice for corn (Eck, 1986; Yazar et al., 1999). However, the trend is that irrigation in this region will decrease. In the Texas High Plains, irrigation peaked during 1970s, but has diminished due to ground water depletion, pumping energy costs, low farm profits, and government-driven programs (Musick et al., 1990). Despite this move towards less water-use intensive crops, corn still has an excellent water use-yield response curve and is often the most economically sound crop for irrigated production (Kansas State University, 2007). In case of limited irrigation, plant density may have to be adjusted. In Kansas, for instance, the plant density for irrigation-limited conditions ranges from 59 to 69 x 10^3 plants ha^{-1} (Kansas State University, 2007). Under water-limited conditions, the critical water requirement for corn is at the beginning of its reproductive stage. Eck (1984), citing several authors, reports that depletion of soil water to wilting point for 1 or 2 days during tasseling or pollination resulted in 22-50% yield reduction. Also, water applied to maintain low soil water tension before tasseling through silking stages was used more efficiently than that applied later in the season. In China, much of the corn is produced in the North China Plain, which accounts for 56% of total China's land but holds only 24% of the country's water resources (Islam et al., 2011). Irrigation is crucial to maintain crop yield in this region and is practiced on 75% of the agricultural land and consumes about 80% of the water resources available. Overall, 40% of the 130 x 10^6 ha of cultivated land in China is irrigated, but only 5% of this cultivated land adopt modern water-saving irrigation techniques such as spray and drip irrigation (China.org.cn, 2001). In Brazil, more than 50% of the corn production comes from Parana, Minas Gerais, and Sao Paulo states (USDA, 2007). Despite the statistics presented for corn production not being related to irrigation, these states are among those with larger irrigated areas and more efficient irrigation methods such as sprinkler systems (Loiola and de Souza, 2001).

2.4.2 Drainage

Drainage has been practiced long before recorded history, as evidenced by archeological finds (USBR, 1993). However, few of these ancient systems were successful and none exist at the present time due to neglect of the systems or lack of understanding of all the physical and technical problems involved. Drainage has now evolved to a more elaborate technical level due to advances in soil physics and hydraulics, but drainage engineering is still not an exact science because it remains largely a matter of experience, common sense, and judgment (USBR, 1993). Today, it is very difficult to precisely estimate the total drained area in the world. The Aquastat Database (FAO, 2011) estimates that 1.2×10^8 ha of cultivated land in the world are drained, while Smedema et al. (2004) estimate that $1.0\text{-}1.5 \times 10^8$ ha of rainfed land and $2\text{-}2.5 \times 10^7$ ha of irrigated land are drained, out of 1.5×10^9 ha of cropland in the world. However, these estimates should be used with caution since calculations usually involve actual, estimated, and modeled data (FAO, 2011).

Drainage can be defined as the removal of excess water and salt from the soil at a rate which will permit normal plant growth (USBR, 1993) by promoting essential soil aeration for plants and bacteria, and leaching deleterious levels of salt in the soil root zone (NRCS, 2001a). Besides waterlogging and salinity control, drainage also helps (i) *erosion control* by checking and controlling surface runoff, (ii) *flood control* by enhanced water management, (iii) *environmental protection* by reducing and intercepting phosphorus transport, (iv) *public health and rural sanitation* by preventing spread of diseases caused by water-born vectors, (v) *infrastructure protection* by preventing direct damage to roads and buildings, and (vi) *rural development and food security* by improving crop production (Smedema et al., 2004).

Agricultural drainage systems related to crop production are broadly classified as surface and subsurface drainage systems (King and Willardson, 2007). This classification is not based on the location of the components of the system but on its function. Thus, surface drainage systems remove excess water resulting from rainfall, snowmelt, and irrigation from the land surface, while subsurface drainage systems remove soil water to keep the water table below the bottom of the active root zone. Surface drains may be shallow or deep and are normally open ditches. Buried pipes with highly porous backfill may also be classified as surface systems depending on the source of water that is being drained. Subsurface drains are deeper and may be open ditches, but are usually buried perforated pipes. Since surface drainage is out of the scope of this study, the remainder of this section will focus on subsurface drainage.

Subsurface drains have evolved considerably since its first use about 300 years ago (Smedema et al., 2004). The early systems consisted of trenches filled at the bottom with stones or brushwood and backfilled with soil. Later, better conduits were made in the form of wooden box spouts, which evolved into clay-ware pipes and concrete pipes. Clay pipes (also called clay tiles) are typically 0.3-m pipe sections with internal diameter varying from 0.05-0.2 m (Smedema et al., 2004; King and Willardson, 2007). The imperfect fit between clay tile sections allowed for the water to seep in. Concrete pipes had the same length as clay tiles and internal diameters varying between 0.15-0.2 m. The water was admitted in by means of joints between concrete sections. Corrugated plastic drains became the industry standard after their advent in the 1960s. These plastic pipes have perforations to admit water (between 20-50 cm^2 of open area per meter length of tube), and are usually surrounded by an envelope, which can be coarse granular material (e.g. fine gravel or coarse sand) or synthetic fabrics called geotextiles (King and Willardson, 2007).

Design of subsurface drainage systems is the subject of several books and papers (Skaggs and Nassehzadeh-Tabrizi, 1986; USBR, 1993; ASABE Standards, 1998; NRCS, 2001a; Smedema et al., 2004; King and Willardson, 2007). It involves determination of soil parameters (hydraulic conductivity, which describes the capacity of the soil to conduct water, and drainable porosity, which is the volume of water released, per unit area of soil, due to a unit drop in the water table), environmental parameters (recharge by rainfall or irrigation, which will define the drainage coefficient or the depth of water to be removed by the drainage system), geological parameters (depth to impervious layer), and construction material (pipe diameter, envelope thickness, and resulting effective drain radius). During the design process, some criteria have to be defined *a priori*, such as the depth of the drains and the maximum allowable water table height above the drains. The designed drainage spacing can be calculated using steady flow or transient flow equations. The first one is used when a steady recharge occurs and the water table is to be maintained at the same level, while the second is used when the recharge varies with time and the water table is allowed to fluctuate. Despite this difference, the steady state method is normally used for both humid and arid conditions, whether the drainage process is steady or non-steady (Smedema et al., 2004; King and Willardson, 2007).

While subsurface drainage systems, by design, target keeping the water table at desired depths during wet periods, they may cause deficit water conditions during dry periods of the growing season (Fouss et al., 2007). Dry conditions may adversely affect yield if they occur during critical developmental stages of plant growth, as discussed in section 2.4.1. Doty et al. (1984), discussing different studies on the impact of over-draining, argue that drought stress may arise in drained areas. Soils with little water holding capacity (e.g. sandy soils), which are drained too rapidly or too deeply may develop drought stress within 4 to 7 days. For corn growing in sand, sandy loam, and silt clay loam soils, lowering the water table 0.8 m below the soil surface can reduce yields from 45 to 100% of potential yield. Given this concern, a concept of water control/management systems has emerged to conserve water resources, use natural rainfall effectively, reduce plant stresses from excess or deficient soil water, reduce energy costs, and maximize operating profits (Fouss and Reeve, 1987). These management strategies are referred to as water table management and include any combination of practices such as surface drainage, subsurface drainage, controlled drainage, or sub-irrigation that influence the level of the shallow water table (Evans et al., 1996). However, controlled drainage in particular has been designated as a Best Management Practice (BMP) for soils having drainage systems already installed.

Controlled drainage is accomplished by regulating drainage outflow with some water-level control device (Thomas et al., 1992; fig. 2.3). Structures for water level control normally use spillways fitted with stoplogs or gates to control the water level (NRCS, 2001a). While the design of water control structures can be found on specific guidelines for custom applications (NRCS, 2001b), pre-made control structures, such as the Agridrain® inlet water level control structure (Agri Drain Corporation, Adair, IA) and Innotag SCD control system (Innotag Distributions Inc., Beloeil, QC), are also readily available for PVC-pipe drainage systems.

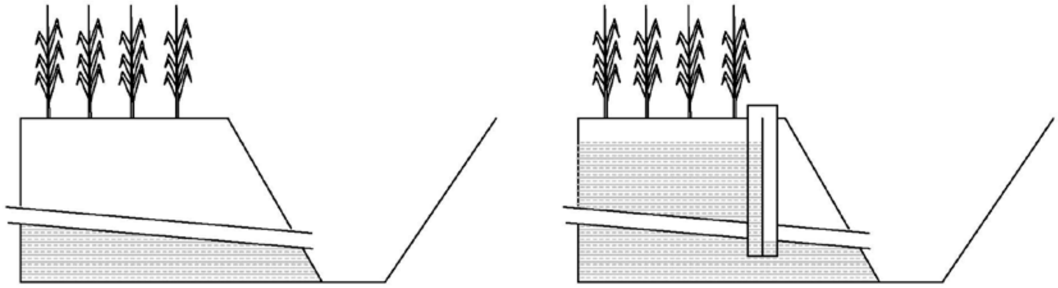

Figure 2.3. Water table height on conventional (left) and controlled drainage (right). Adapted from Busman and Sands, 2002).

Previous research has shown the positive effects of water table management on corn yield. Kalita and Kanwar (1992), keeping the water table at 0.3, 0.6, and 0.9 m, found that corn yields increased significantly with increasing water table depths from shallower to deeper. According to the authors, a shallow water-table depth of 0.2-0.3 m reduced oxygen supply to plant roots during the growing season, thus compromising yield. Tan et al. (1999), reported significant increases in corn yields from water table management (i.e. controlled drainage with sub-irrigation) compared to conventional drainage. Corn yields were 64% higher in the controlled drainage treatment. Ng et al. (2001) also report average corn yield 64% larger for controlled drainage with sub-irrigation than for free drainage. However, contradicting results have also been found. Doty and Parsons (1979) found that controlled drainage with sub-irrigation only gave good yields in dry years, compromising yields on wet years. Drury et al. (2009) also found that controlled drainage gave better results than free drainage only when additional N fertilizer (i.e. 200 kg N ha^{-1}) was applied. For regular N application (i.e. 150 kg N ha^{-1}), both controlled drainage and controlled drainage with sub-irrigation gave poorer results than unrestricted tile drainage. These findings indicate that water management alone cannot explain corn yield, but have to be taken into consideration with other variables such as weather patterns and agronomic practices.

2.5 Environmental Impacts of Nutrients from Drainage

2.5.1 Nitrate

Nitrate is a critical form of nitrogen for plants (Crawford, 1995). It is not only a nutrient, but also acts as an initiating signal for various processes. Skitt (1999), quoting several studies, mentions amino acid, protein, and phyto-hormone levels, carbon metabolism, root-to-shoot ratio, root architecture, flowering, and senescence among the mechanisms signaled by nitrate availability. Given the importance of these mechanisms, plants have developed uptake systems with distinct affinity for nitrate. High affinity systems are responsible for nitrate uptake at concentrations lower than one micromolar (µmoles L^{-1}; Crawford, 1995). However, the NO_3^- that is not taken up by plants can leach into groundwater and ultimately reach large water bodies. High nitrate concentrations in both ground and surface water can cause environmental problems. Nitrate has been reported to be the groundwater contaminant of major concern in the US (Fetter 1999), and it has also been linked to eutrophication of marine and freshwater ecosystems. Eutrophication in the Gulf of Mexico has been linked to nitrate fluxes originated from the Mississippi River by anthropogenic and natural processes (Justic et al., 2005), while early studies in the experimental lakes area in Ontario linked the eutrophication of pristine freshwater ecosystems to nitrate loads (Schindler et al., 1971).

Nitrate (NO_3^-) can be associated with a number of other ions to form different compounds (e.g. sodium nitrate, potassium nitrate, calcium nitrate). When dissolved in water, however, these compounds dissociate and the anions and cations become independent entities in the solution (Addiscott et al., 1991). Nitrate in solution is negatively charged, and this characteristic affects its retention in the soil because anions are repelled by the negatively charged clay particles (Hillel, 1998); nitrate is not positively adsorbed either and, thus, subject to the anion exclusion or negative adsorption (Tan, 1998). This phenomenon has been linked to transport velocities of dissolved anions larger than those of the accompanying water molecules (Gvirtzman and Gorelick, 1991), and renders NO_3^- freely mobile in most soils (Follet, 2008). Since nitrate is totally soluble at concentrations found in soils and is not adsorbed to soil particles, its mobility is mostly dependent on the soil-solution movement and on the mechanisms determining water transport.

Given the solubility of nitrate in water, drainage systems enhance nitrate mobilization with drainage water. While extensive tile drainage can prevent the nitrate problem in groundwater (Spalding and Exner, 1993), it may increase discharges to surface waters (Randall and Mulla, 2001). Research has shown that subsurface drainage is among the major factors contributing to nitrate export from the farmland (Keeney and DeLuca, 1993; David et al., 1997). For example, David et al. (1997), in a 6-year study in Illinois, showed that an average of 49% of the residual nitrate left in the soil after harvest was leached through drain tiles. Other common agricultural practices such as irrigation and cultivation, besides application of N fertilizer, further enhance the vertical movement of nitrate from crop land (Spalding and Exner, 1993), thus accelerating the nitrate transport when associated with drainage.

Controlled drainage is used to minimize the export of nitrate from tile discharge. Early studies have shown that controlled drainage was able to largely reduce nitrate export due to reduced effluent volume (Gilliam et al., 1979), despite no evidence of increased denitrification in the field, which would have minimized the nitrate concentration in the drainage water. However, Drury et al. (1996), comparing conventional to controlled drainage, found that, besides reducing the drainage volumes by 24%, controlled drainage also reduced the flow weighted mean NO_3^- concentration from 10.6 to 7.9 mg L^{-1} (i.e. 25% reduction). As a result, the average annual NO_3^- loss was reduced 43% from 25.8 kg N ha^{-1} for the conventional drainage treatment to 14.6 kg N ha^{-1} for the controlled drainage treatment. It is noteworthy that between 88% and 95% of the nitrate losses in all treatments occur during the non-crop period, where there is no nitrate uptake by plants. Elmi et al. (2000), assessing the nitrate loads and denitrification rates from conventional drainage versus controlled drainage with sub-irrigation in corn production under different N fertilization levels, found that overall NO_3^- concentrations in the sub-irrigation treatment were reduced by 42% and 16% in the two years of the study, respectively. They also showed that the water table depth had a strong influence on denitrification, with rates on the sub-irrigation treatment being higher than those on the conventional drainage. According to the authors, higher denitrification rates were associated with higher moisture content in the sub-irrigated plots.

2.5.2 Phosphorus

Adequate P supplies are necessary for seed and root formation, straw strength in cereals, and crop quality; consequently, P has experienced a large increase in use as fertilizer (Hart et al. 2004). Today, agriculture is among the major sources of phosphorus to water bodies. The P causes the development of algal blooms and consequent depletion of dissolved oxygen, increased suspended solids, decreased light penetration, and reduction in aquatic flora and fauna species (Eastman et al., 2010). The large accumulation of P in manure from animal feeding operations in localized areas has increased the potential for P export following land application (Sharpley and Moyer, 2000) because manure or compost application based on N needs of corn may result in soil accumulation of P since the manure or compost N/P ratio is usually smaller than the corn N/P uptake ratio (Eghball and Power, 1999). Despite this risk, manure is used extensively as a fertilizer due to its low cost and availability. Eghball and Power (1999), reviewing the literature on the effects of manure use as fertilizer, report that manure from beef cattle, dairy cattle, or poultry can increase yields if applied solely or in association with other synthetic fertilizers. In the US, the value of nitrogen, phosphorus, and potassium in cattle feedlot manure was estimated to be $461 million if purchased as fertilizers (Eghball and Power, 1994).

Phosphorus losses from agricultural landscapes occur primarily during surface runoff events (Eastman et al., 2010) because of the high P fixation capacity of soils (Heckrath et al., 1995). The loss of P from agricultural land occurs in sediment-bound and dissolved forms, but sediment P, which includes P associated with soil particles and organic material eroding during flow events, constitutes about 80% of P transported from most cultivated land (Sharpley et al., 2003). The soil particles in the sediment and their mineralogy play an important role on P transport by runoff. Clay particles comprise the largest fraction of the sediment transported by runoff because they are more easily transported by overland flow than bigger sand and silt particles (Lado et al., 2004). Also, the cations found in the clay's structure [i.e. aluminum (Al^{3+}), and manganese (Mg^{2+}); Hillel (1998)] result in P being strongly held within the clay lattice (Alam, 1999) and these ions are related to the soil's ability to retain P (Ulen and Snall, 2007).

Despite most of the transport of P from farm land being associated with overland flow, research has shown that subsurface drainage systems in agricultural fields also discharge considerable P quantities under a wide range of soil characteristics and management practices (Eastman et al., 2010). For example, a study on P discharges from tile drains in Nova Scotia, Canada, reported mean total P concentration above the USEPA guideline of 0.1 mg L^{-1} in 82% of the fields investigated, with 50-times-larger loads occurring, occasionally (Kinley et al., 2007). A critical factor for P transport through tile drains is the P concentration in the soil, which influences the change point, i.e. the concentration beyond which P can be leached through the soil profile. For example, Heckrath et al. (1995), working with a silty clay loam soil of the Batcombe series (Chromic Luvisol) having a high buffer capacity for P, found that this soil failed to retain P on the plots with concentrations exceeding 60 mg Olsen-P kg^{-1}. McDowell and Sharpley (2001) also found similar results when working with different soil types [i.e. Denbigh silt loams (Typic Dystrudept), Alvira (fine-loamy, mixed, Aeric Fragiaquult), Berks (loamy-skeletal, mixed, active, mesic Typic Dystrudept), Calvin (loamy-skeletal, mixed, mesic Typic Dystrudept) and Watson (fine-loamy, mixed, mesic Typic Fragiudult)]. Change points were found for Alvira and Berks soil, but no change point could be determined for Calvin, Watson, or Denbigh soils. The authors argue that this result may be due to the scatter in the data or simply because the soils were not sufficiently saturated with P to exhibit a change point. McDowell et al. (2001), working with a wide range of soils from the United Kingdom, New Zealand, and the United States, report that change points for Olsen P or Mehlic-3 P occurred in most soils. Where no change point was detected, it was found that the P saturation on the soil samples was either low or high and, therefore, grouped below or above the change point.

Beside the change point, other factors may also be involved in the P export through subsurface drainage. Sharpley et al. (2001) observed that P levels alone have little meaning for P loss potential unless considered with potential subsurface flow. However, factors controlling P losses through this mechanism are more complex than for surface runoff due to variable paths and time of water flow through a soil with tile drainage. In fact, Heckrath et al. (1995) noted that the rapid P transport within the soil profile may be associated with preferential flow through cracks and channels or movement of P forms less susceptible to sorption.

2.5.3 Salts

Salinity control is one of the purposes of agricultural drainage (Smedema et al., 2004). However, there are increasing restrictions on the export of salt from these drainage systems (Christen and Ayars, 2001). Accumulation of salts in water bodies is a potential problem affecting downstream users (Tedeschi et al., 2001). Salts in the drainage water may originate from both irrigation water and from the soil, where removal of salts from the profile is a natural process as water moves to streams and finally to the oceans (Skaggs et al. 1994).

A shift in salinity of both fresh and salt water can have ecological and chemical consequences. The ecological effects are a result of impacts of salinity on osmoregulation of aquatic organisms, and shifting salinity distributions can affect the distributions of macrobenthos, rooted vegetation, and sessile organisms (Boesch, 1977; Alber, 2002). Water salinity also affects the ability of the sediment to retain exchangeable ammonium (NH_4^+) (Rysgaard et al., 1999) and the concentration of metal ions in solution because ions compete for binding sites on clay-organic particle surfaces and this can interfere with the complexation and adsorption of metals (Elder, 1988).

The transport of salt from irrigated farmland can take place through different mechanisms. Duncan et al. (2008), revising the management of salt mobilization in the irrigated landscape in selected agricultural landscapes in Australia, United States, and Spain, found that different process can take place according to climate and agronomic practices adopted. For instance, they reported that subsurface drainage could have a varying effect on salt mobilization, being responsible from 29% to 94% of the total salt exported in Australia. For studies that did not considered subsurface drainage, groundwater seepage to streams was a prominent transport mechanism, responsible for almost 100% of the salt export. Since subsurface drainage can mine groundwater salts, it could have a considerable effect if present in these scenarios. However, salt export from subsurface drainage tends to decrease logarithmically from the time the drains are installed, which indicates gradual improvement of salinity of the groundwater (Pillsbury et al., 1965)

3. WATER TABLE CONTRIBUTION AND DIURNAL WATER REDISTRIBUTION WITHIN THE CORN ROOT ZONE

3.1 Abstract

Understanding the water redistribution pattern within the corn root zone will help determine the impact of this crop on water resources. The objective of this research was to observe the water redistribution pattern within the corn root zone in response to overhead irrigation and shallow groundwater contribution. Fifteen TDR (time-domain reflectometry) miniprobes were installed in each of the three replicate vertical planes, for measuring volumetric water content within the root zone of a cornfield located in Winkler, Manitoba, in 2009 and 2010. The probes were inserted at 0.1, 0.2, 0.4, 0.6, and 0.8 m depths from the ground surface and at 0.12, 0.24, and 0.36 m radial distances from the base of the corn plant. In 2010, the water table was automatically monitored by a water level-logger installed in an observation well. The soil was thoroughly wetted by applying 50 and 65 mm of water on the soil surface in 2009 and 2010, respectively, within the experimental site. The volumetric water content was measured prior to and at periodic intervals after the irrigation using TDR miniprobes. The results indicated a pattern of water redistribution within the root zone, where the soil became drier during periods of high ET demand and became wetter during periods of low ET in the evening and night. Poorly drained soils may show a delay in the drying/replenishment pattern in dry years due to low hydraulic conductivity and deeper water table. The results from 2010 indicated that 81% of the crop water requirement was from groundwater contribution during the measurement period. Simulations of soil water content and

upward flux using Hydrus-1D closely matched the observed values making this an effective tool for predicting changes in soil water content.

3.2 Introduction

The source, quantity, and quality of water available during a growing season will determine how water is managed on the farm. These factors also determine the impact of agriculture on natural resources. Water quality and quantity information is important for designing and scheduling irrigation (Jensen, 2007). This information helps to assess the environmental impacts of agriculture by allowing the calculation of sustainability indices such as the water use efficiency (WUE) and the water footprint (Howell, 2001; Hoekstra et al., 2009). Besides quantity, quality, and source of the water, the water redistribution pattern within the plant root zone is another important factor used to design efficient irrigation and drainage systems, and to assess the movement of nutrients within the soil.

The quantity of water used by the crop from different sources (e.g. rainfall, irrigation, and soil water) is difficult to determine precisely. In some instances, more complex water balance components have to be considered, such as crop interception or upward flow from groundwater into the root zone (Howell, 2001). The investigation of water redistribution within the soil, in turn, is complex because it involves processes that depend on the soil type and plant characteristics (Garrigues et al., 2006). Soil moisture content, root morphology, and plant physiological status strongly control water uptake at the root zone scale. An understanding of these processes is difficult due to the limited ability to non-destructively assess the water uptake from within the root zone (Ehleringer and Dawson, 1992). Therefore, minimally invasive techniques that do not affect the soil properties may be used to continually monitor the soil moisture, thus helping us understand both the quantity and source of water entering the root zone. Soil moisture measurement using the non-destructive time-domain reflectometry (TDR) technique can be successfully adapted for this purpose because most TDR systems are designed for long-term installation and continual monitoring at shallow depths (Schwartz et al., 2008). Different types of TDR probes are commonly used to measure soil water because of their ability to acquire data quickly, and their relative safety when compared to nuclear methods such as the Neutron Moisture Meter (Dalton, 1992; Zegelin et al., 1992).

An important consideration for specific uses of TDR systems is the type (i.e. number of rods) and size (i.e. rod spacing and length) of the probe. In field applications, the length of the probe has an influence since the soil water content measured is averaged over the entire probe length (Sri Ranjan and Domytrak, 1997). When assessing soil water re-distribution, point measurements of water content are necessary. In such cases, miniprobes having a length of 50 mm with outer rods spaced at 10 mm enabled the water content to be measured in a small volume of soil (Sri Ranjan and Domytrak, 1997). This allowed for the readings to be taken within the soil profile as point measurements at different depths and distances from the base of the plant. The smaller probe length also allowed easier insertion into the soil with minimal disturbance within the root zone (Kahimba et al, 2008). Kahimba et al. (2008) used miniprobes to obtain volumetric water content data at 0.1, 0.2, 0.4, 0.6, 0.8 m depths from the ground surface. Similarly, an array of miniprobes can be used to acquire a number of point-readings at different depths and different radial distances from the base of the plant, rather than having a single reading averaged over the entire profile.

The main objective of this research was to measure water content spatially and temporally to depict the water redistribution pattern within the root zone of corn after a thorough irrigation. The second objective was to determine the contribution of the water table to the soil moisture within the root zone. An array of TDR miniprobes was used to acquire soil moisture readings within the soil profile. The results of volumetric water content measurements at five different depths and three distances from the base of the plant as a function of elapsed time following an irrigation event are presented for two different years. The source of the water within the soil profile and the changes in redistribution pattern with time are also discussed. The soil water content and upward flux of water were also simulated using the Hydrus-1D model to verify the ability of the model to predict the changes in soil water status in response to crop water use.

3.3 Material and Methods

3.3.1 Study area

The study was carried out in Winkler, Manitoba, Canada, in 2009 and 2010. In 2009, readings were acquired between August 31 and September 4, at coordinates 49°07.094’ N and 97°57.548’W. During this period, the minimum daily temperature was 10.9° C on August 31 and the maximum daily temperature was 26.5° C on September 3; the average daily temperature was 18.7° C (Environment Canada, 2011). The soil in the area belongs to the Reinland Series, which is an imperfectly drained Gleyed Rego Black soil having loamy texture (Podolsky, 1991). In 2010, readings were acquired between August 16 and August 20, at coordinates 49°07.333’ N and 97°57.683’W. During this period, the minimum daily temperature was 5.2° C on August 17 and the maximum daily temperature was 31.8° C on August 20; the average daily temperature was 16.2° C

(Environment Canada, 2011). The soil in the second experimental area belongs to the Hochfeld Series, which is a moderately well drained Orthic Black soil, moderately calcareous, and having a loamy fine sand texture (Smith and Michalyna, 1973). The fields have been cultivated for several years and both locations in this study were under corn planted at a row spacing of 0.76 m (30 inches). Corn is usually rain-fed in this area, but overhead irrigation of corn is being currently considered as a way to increase yields. Due to shelterbelts and division of the quarter sections into smaller land parcels, irrigation is practiced mostly through travelling gun with application uniformities above 80%. Farmers tend to irrigate when the available moisture is depleted below the threshold defined for each crop. In addition, when irrigation equipment is limited and shared between different fields, the irrigation events may be adjusted based on equipment availability.

3.3.2 Soil water monitoring

Forty-five, 0.05 m long TDR miniprobes were custom made and individually calibrated in the Soil and Water Engineering laboratory at the University of Manitoba for each year of experiment. In 2009, the probes were installed at 0.1, 0.2, 0.4, 0.6, and 0.8 m from the ground surface, and at 0.12, 0.24, and 0.36 m from the base of the plant, forming an array of 15 probes (fig. 3.1) in each of three replicates.

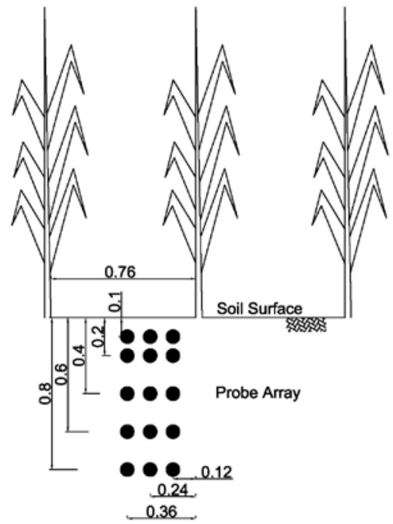

Figure 3.1. Scheme of the probe array installation (black circles), indicating the depths and distances from the plant in meters.

In 2010, a similar configuration was used but the distances from the base of the plant were changed to 0.07, 0.19, and 0.31 m allowing more detailed measurements closer to the plant. A new set of calibrated probes was installed prior to the irrigation experiment in each year, following the procedure described by Kahimba and Sri Ranjan (2007). In 2009, an area of about 5 m x 4 m enclosing the three replicates was bermed and the soil was thoroughly wetted by applying 50 mm of water using a hose. In 2010, the dimensions of the enclosed area were 4 m x 3 m, and the volume of water applied was 65 mm using the same method. Soil moisture readings were acquired using a Metallic Cable Tester 1502B (Tektronix, Inc., Beaverton, OR), which was connected to the 15 probes in each replicate via a 16-channel Vazec multiplexer (Vadose Zone Equipment Company, Amarillo, TX). WinTDR 6.1 software (Department of Plants, Soils and Biometeorology, Utah State University, Logan, UT) running in a laptop PC was used as the interface to control the TDR system to acquire the data. The readings were acquired for each probe before the irrigation event and at three times during each day (i.e., morning, between

10:30 and 11:30 h; afternoon, between 14:30 and 15:30 h; and evening, between 18:30 and 19:30 h) over four consecutive days. During the data analysis, the average of the point readings for the particular instant in time and location from the three replicates was used for testing the statistical significance of the difference between water content at different times of the day, depths, and distances from the base of the plant.

3.3.3 Ground water monitoring

Ground water level could not be monitored directly in the experimental sites in both years. In 2010, a well was installed in the same cornfield, about 150 m from the experimental site. A Levelogger® Junior (0.1% full-scale accuracy), placed inside a galvanized, pre-slotted, 2-inches diameter monitoring well, monitored the ground water level at 3 h intervals (Solinst Canada Ltd., Georgetown, ON). This well was not affected by the irrigation done in the experimental site, and its data were used to calculate the upward water flux under cornfield conditions.

3.3.4 Ground water contribution

The weather variables collected were minimum, maximum, and average daily temperature, relative humidity, solar radiation, wind speed and direction, and rainfall obtained from the MAFRI Ag Weather Program (MAFRI, 2011). The accuracy of the anemometer was 1.5%, solar radiation sensor was < 1.0%, and temperature sensor was < 0.5%. Both hourly and daily reference evapotranspiration (ET0) were calculated using the REF-ET calculator (Kimberly R&E Center, University of Idaho, Kimberly, ID). The potential contribution from dew condensation (mm) was calculated on an hourly basis using the psychrometric relationships (ASHRAE, 2009) and weather data. Whenever the minimum hourly air temperature was below the dew point temperature, it was assumed that the moisture in the air mass within the corn canopy would condense on to the leaves and drip down to the soil surface as stem flow. The condensed volume was calculated from the difference in humidity ratio corresponding to the dew point temperature and the minimum temperature, during the hour. The volume of air mass was calculated using the corn canopy height of 2.5 m and the bermed area of the plot where the TDR measurements were carried out. The same bermed area was used to convert the dew condensation from volume units to depth units. Crop coefficients based on fraction of season derived from growing degree-days were calculated using the methodology presented by Stegman (1988). Daily crop evapotranspiration (ET_c) was calculated by:

$$ET_c = K_c \, ET_0 \tag{1}$$

where ET_c is the crop evapotranspiration (mm), Kc is the crop coefficient for corn, and ET_0 is reference evapotranspiration (mm). The field was seeded to corn hybrid 'Pioneer 39B94' on April 28 at 69,000 plants ha-1. The corn plants were at physiological maturity stage during the experiment.

Bulk density and field capacity were measured using a methodology adapted from Mkhabela and Bullock (2012) for three different random locations in the field at 0.15, 0.30, 0.60, 0.90, and 1.2 m depths. Porosity was calculated using:

$$\phi = 1 - \frac{\rho_{bulk}}{\rho_{particle}} \tag{2}$$

where ø is the soil porosity (dimensionless), ρ_{bulk} is the soil dry bulk density (kg m^{-3}), and $\rho_{particle}$ is soil particle density (assumed to be 2650 kg m^{-3}). The drainable porosity of the soil was calculated as the difference between porosity and field capacity. Values of calculated bulk density, field capacity, and porosity, and drainable porosity at depths are presented in Table 3.1. Due to soil disturbances caused by soil cultivation, the bulk density at 0.15 m depth was very low and, consequently, porosity was large (58%). This value was above the range normally found for surface sandy soils (i.e. 35-50%; Hao et al., 2007), and lead to a large value of drainable porosity (25%). Due to the inconsistent porosity value at 0.15 m, this layer was excluded from the calculation of the average drainable porosity, which was found to be 14.1%. The moisture entering the root zone from the water table by means of upward movement was calculated by multiplying the daily water table variation in mm by the average drainable porosity. Upward movement of water mainly drove the water table depletion during the experimental period. This assumption is supported by the negligible seepage observed in imperfectly drained soils (Skaggs et al., 2012). Since no further additional recharge by either precipitation or irrigation occurred during the measurement period, the ET_c demand was assumed to be met by groundwater contribution, calculated based on the drop in water table depth. Therefore, the relative contribution of the groundwater is presented as a percent of the ET_c in this paper.

Table 3.1. Soil bulk density, field capacity, and porosity at depths.

Depth (m)	Bulk Density (kg m^{-3})	Field Capacity (m^3 m^{-3})	Porosity (%)	Drainable Porosity (%)
0.15	1121	0.32	58	25.3
0.3	1353	0.32	49	16.5
0.6	1535	0.32	42	9.9
0.9	1501	0.30	43	13.7
1.2	1408	0.30	47	16.5

3.3.5 Data analysis

The average volumetric water content data from the three replicates as a function of depth and distance from the base of the plant was plotted at successive times as contour plots using SigmaPlot 2000 (Systat Software Inc., San Jose, CA), showing the vertical and horizontal distribution of water content within the soil profile. These snapshots of soil water distribution at different times of the day showed a pattern of redistribution within the root zone. The soil water content was also statistically compared between different periods of the day for the same position using analysis of variance in JMP 8.0 software (SAS Institute Inc., Cary, NC). The standard deviation of the TDR readings between the three replicates for the different depths, distances from the base of the plant, and time of the day was 0.03 and 0.02 m^3 m^{-3} in 2009 and 2010, respectively.

3.3.6 Modeling of soil water content and upward flux

Soil moisture and upward flux were modeled for 2010 using Hydrus-1D (Šimůnek et al., 2008) in order to assess the usefulness of this model to predict soil water status and the groundwater contribution to root zone. The model was set to simulate water flow and water root uptake using the van Genuchten–Mualem single porosity model. The air-entry pressure value of –2 cm and the no hysteresis options were selected in this model. The depth of the model space was set to 2.5 m, and two soil materials were used in the simulations: the first one from soil surface to 0.4-m depth, and the second from 0.4-m to 2.5-m depth. These two layers allowed for simulating different conditions at the shallow layers (disturbed by farm operations) and deeper layers. Initial values of the water flow parameters (i.e. soil variables) in the model were obtained from the Rosetta Model (Schaap et al., 2001). The parameters used for calibration were α, n, and Ks, which were previously calibrated and validated for the experimental area in a different modeling exercise (Cordeiro and Sri Ranjan, 2013) The following dimensionless water flow parameters had the same values for both layers: residual soil water content (Qr = 0.049), saturated soil water content (Qs = 0.39), parameter n in the soil water retention curve (n = 1.75), and tortuosity (l = –0.83187). The parameter alpha in the soil retention curve (α) and the saturated hydraulic conductivity (K_s) had different values for each layer. The parameter α was set to 0.0014 and 0.0012 mm^{-1} for the first and second layers, respectively. The parameter Ks was set to 62.5 and 25 mm h^{-1} for the first and second layers, respectively. The upper boundary condition was set to atmospheric with surface layer, while the lower boundary condition was set to constant pressure head. This condition was assumed because water table data was not available at close proximity of the TDR probes, and because the simulation was run over a short period of time. The reference ET calculated above (Section 2.4) was used as the model input potential evapotranspiration (PET). The leaf area index (LAI) value of 3.0 was used for the entire simulation based on good ground cover, which is not dissimilar to values presented by Flesch and Dale (1987). An extinction coefficient of 0.7 was used based on values presented by Lindquist et al. (2005). The Feddes' model was selected for water uptake reduction, using the model parameters for corn during ripening, available within Hydrus-1D. The model space was dived into 251 nodes having a density of 0.1. The root distribution was assumed to decrease linearly from 100% to 0%, starting at the soil surface down to 0.45 m depth. The initial condition in the model space was set in pressure head, which was set to zero at the water table depth. Pressure heads decreased linearly toward the soil surface (i.e. became increasingly negative above the water table) and increased linearly toward the bottom of the model space (i.e. became increasingly positive below the water table). This condition represents a soil profile where pressure heads are in equilibrium with the water table (Radcliffe and Šimůnek, 2010). For the soil moisture simulations, five observation notes were inserted at the same depths of the TDR probes (i.e. 0.1, 0.2, 0.4, 0.6, and 0.8 m from the ground surface). Also, 21.8 mm of rainfall per hour over a period of three hours was used to simulate the irrigation applied to the experimental area. For upward flux simulations, only the node at 0.8 m was used to account for the moisture entering the root zone. No rainfall was used in the upward flux simulation. The simulation period started on August 16, 2010, at 3:00 h, and completed on August 20, 2010, at 23:00 h. The model accuracy for soil water was assessed by means of i) graphical comparison of both simulated and observed values, ii) the coefficient of determination (R^2), iii) the root mean square error (RMSE), and iv) the Nash–Sutcliffe modeling efficiency coefficient, which is calculated by (Van Liew and Garbrecht, 2003):

$$ME = 1 - \left[\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - O_{mean} \right)^2} \right], \qquad (3)$$

where ME is the Nash–Sutcliffe modeling efficiency coefficient, n is number of pairs of observed and predicted values, O_i is the i-th observed value, P_i is the i-th predicted value, and O_{mean} is the observed mean. Simulations were considered good for high R^2 values (i.e. $R^2 \sim 0.8$) and low RMSE values (RMSE close to zero). Results were considered to be good if ME ≥ 0.75, and satisfactory for 0.36 ≤ ME ≤ 0.75 (Van Liew and Garbrecht, 2003).

3.4 Results

3.4.1 The 2009 growing season

During the 2009 season, the weather forecast was used to select a rain-free period to conduct the experiment to avoid any further addition of water from the rain event. The soil water distributions in the soil profile during the morning, afternoon, and evening are shown in figure 3.2 as snapshots for each time. The average water content for all depths and distances from the plant within the root zone before wetting was 0.22 $m^3\ m^{-3}$, but the depths closer to the surface had water content of about 0.20 $m^3\ m^{-3}$. At 0.8 m depth and at 0.36 m distance from the base of the plant, the water content was found to be as high as 0.30 $m^3\ m^{-3}$ (fig. 3.2a).

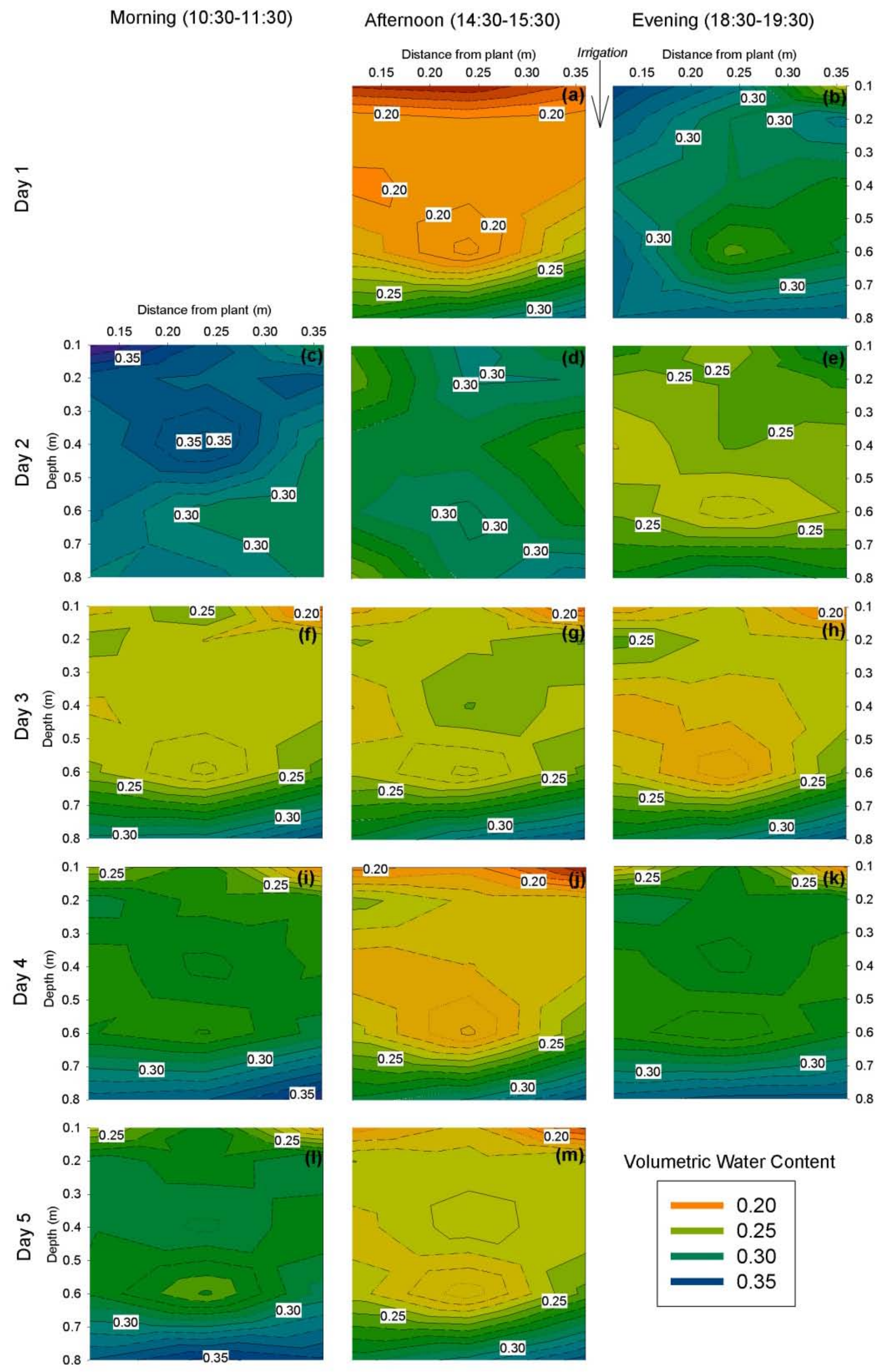

Figure 3.2. Volumetric moisture content as a function of distance and depth in the root zone of corn during the 4 days of monitoring during the 2009 growing season. Letters (a) through (m) indicate different snapshots in time. Contour interval in the diagram represents a change of 0.05 m^3/m^3.

After a thorough wetting of the surface, by the application of 50 mm of water, the average soil water content within the root zone increased to 0.30 $m^3 m^{-3}$. The highest water content in the profile was observed in the morning of Day 2 with values as high as 0.35 $m^3 m^{-3}$ at depths ranging from 0.1 to 0.5 m. However, these values decreased during the day reaching an average over the sampling volume of 0.25 $m^3 m^{-3}$ by the evening (fig. 3.2c-e). The water content started to decline as the days progressed. During Day 3 morning, the profile was drier at the surface, uniform between 0.2 and 0.6 m, and wetter at 0.8 m depth. By the evening of Day 3, the water content in the profile was less than in the morning. In the morning of Day 4, the water content seemed to have increased in the entire soil profile indicating upward migration of water into the root zone since there was no surface recharge from any rain event. From this time on, the pattern was drier in the afternoon, showing some replenishment in the evening that persisted until the following morning. The afternoons are characterized by the low water contents, while mornings are characterized by high water contents indicating upward moisture migration from below the root zone. The moisture in this case seemed to be coming from the wetter part of the profile at 0.8 m depth, in which soil moisture remained stable between 0.30 – 0.35 $m^3 m^{-3}$ (fig. 3.2j-m). The rationale for the upward migration happening after the Day 3 is explained in the discussion section.

The analysis of variance indicated that the variation of water content as a function of time of the day ($p = 0.015$) and depth ($p<0.01$) were statistically significant while the distance away from the plant did not have an effect. As seen in Table 3.2, the soil water content was higher in the morning and lower in the afternoon, with intermediate values in the evening. Table 3.2 also shows the difference in soil moisture as a function of depth, indicating upward movement of water from wetter to drier layers.

Table 3.2. Comparison of average volumetric soil water content for different times of the day at the same distance from plant and depth in 2009†.

	0.12 m			0.24 m			0.36 m		
Depth (m)	Morning	Afternoon	Evening	Morning	Afternoon	Evening	Morning	Afternoon	Evening
0.1	0.268	0.220	0.262	0.283	0.243	0.266	0.222	0.199	0.228
0.2	0.288	0.245	0.280	0.274	0.250	0.263	0.283	0.254	0.271
0.4	0.273	0.236	0.252	0.293	0.250	0.262	0.268	0.238	0.254
0.6	0.279	0.249	0.268	0.255	0.230	0.233	0.281	0.257	0.263
0.8	0.308	0.281	0.297	0.326	0.304	0.314	0.334	0.331	0.319

† Values are averages of the three replicates; times are considered after the irrigation event.

3.4.2 The 2010 growing season

As in 2009, a rain-free period was selected in 2010 based on weather forecast. A set of water content measurements was done prior to the irrigation event. Following this, 65 mm of water was applied on the surface in the morning and the first set of TDR readings after irrigation was taken 24 hours later. Since the area received over 30 mm of rainfall in the previous four days, the soil water status prior to irrigation (fig. 3.3a) was not as dry as in 2009 (fig. 3.2a). The irrigation does not seem to have affected the soil water content distribution during the following day. The soil profile was already wet at the time of irrigation resulting in water moving faster through the soil profile due to the higher unsaturated hydraulic conductivity.

Table 3.3 shows the comparison of the soil water content for different times of the day at the same distances from the plant, respectively. This table shows the soil water content being higher in the afternoon and lower in the evening, with intermediate values in the morning. This difference, however, was more pronounced in the top layer for the three different distances from the plant. Table 3.3 shows the soil water content being lower closer to the plant, indicating higher plant water uptake at this location (fig. 3.3f-i). This difference in water content at distances from the plant also decreased with depth, probably due to reduced plant uptake from these regions.

Table 3.3. Comparison of average volumetric soil water content for different times of the day at the same distance from plant and depth in 2010[†].

	0.12 m			0.24 m			0.36 m		
Depth (m)	Morning	Afternoon	Evening	Morning	Afternoon	Evening	Morning	Afternoon	Evening
0.1	0.208	0.235	0.173	0.239	0.265	0.195	0.214	0.243	0.178
0.2	0.201	0.217	0.163	0.211	0.227	0.170	0.211	0.227	0.170
0.4	0.232	0.237	0.176	0.239	0.245	0.181	0.233	0.237	0.175
0.6	0.268	0.270	0.202	0.270	0.272	0.202	0.293	0.325	0.251
0.8	0.302	0.304	0.227	0.320	0.323	0.241	0.301	0.304	0.228

[†] Values are averages of the three replicates; times are considered after the irrigation event.

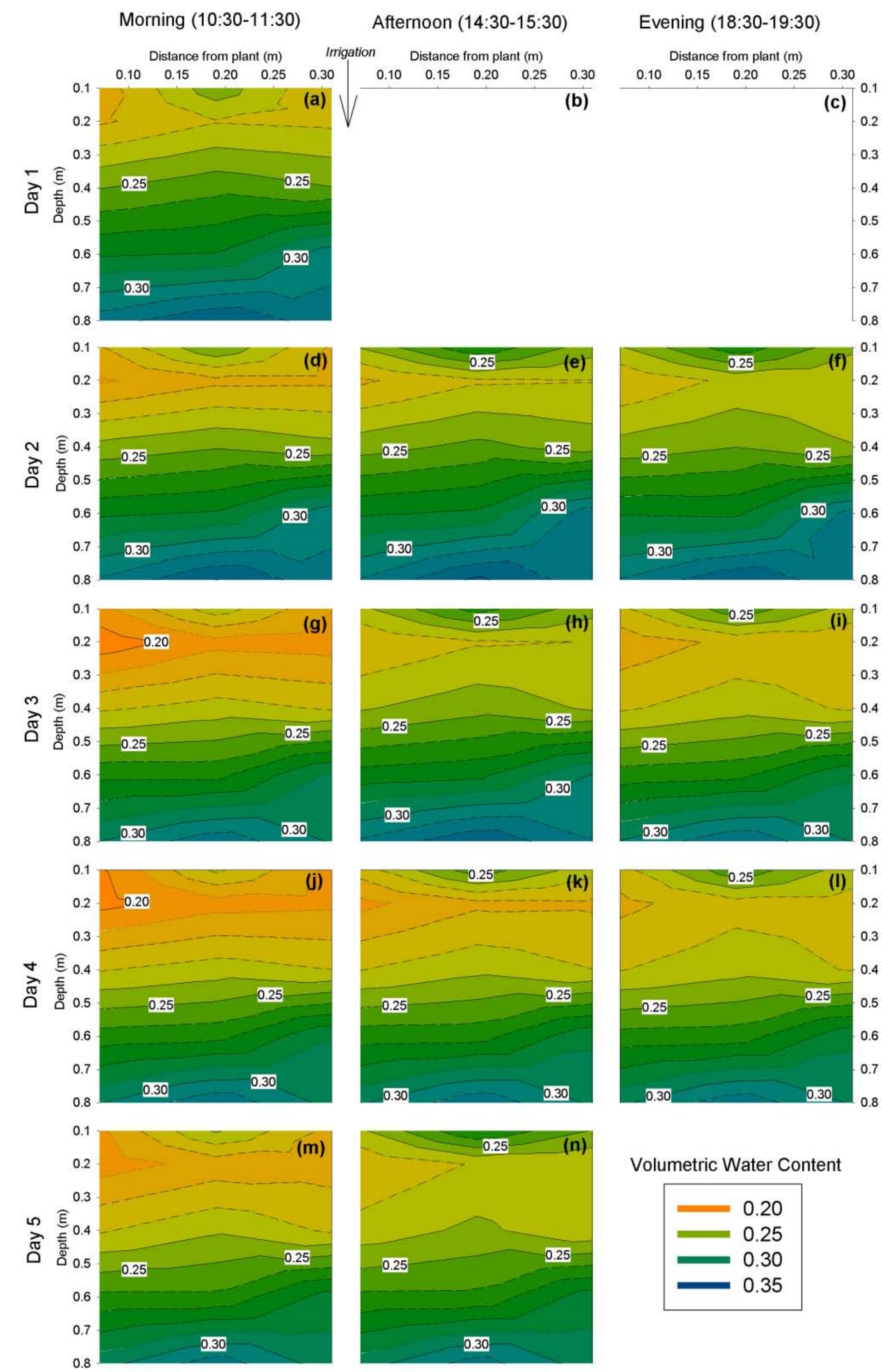

Figure 3.3. Volumetric moisture content as a function of distance and depth in the root zone of corn during the 4 days of monitoring during the 2010 growing season. Letters (a) through (n) indicate different snapshots in time. Contour interval in the diagram represents a change of 0.05 m^3/m^3.

The water table variation and the crop ET during the 2010 experiment are shown in figure 3.4. This figure shows the water table falling during the experiment following a diurnal pattern where it remained reasonably constant during the evening/night/morning period (i.e. between 18:00 and 12:00 h next day) but dropped during the hot hours of the day (i.e. between 12:00 and 18:00 h). The water table starts to drop as hourly ET reaches values above 0.4 mm h^{-1}. This water table variation is also approximately proportional to both the hourly and daily crop ET, with larger water table variations occurring with higher crop ET.

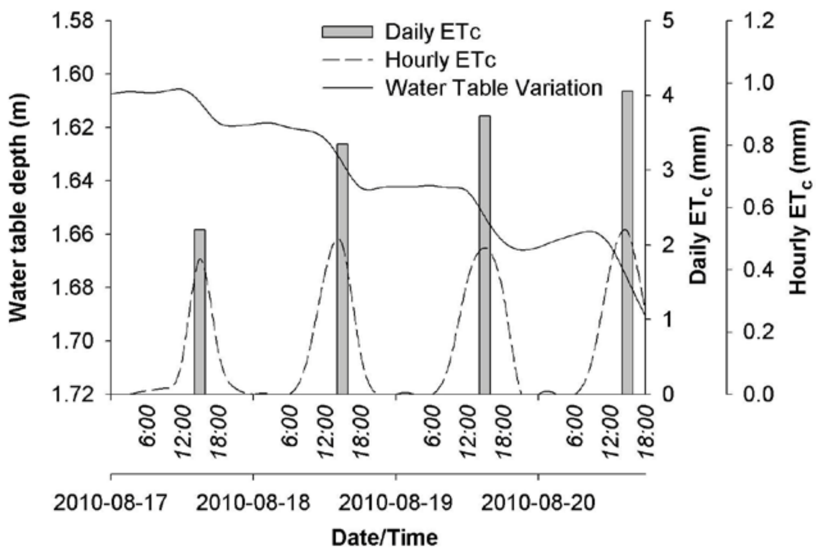

Figure 3.4. Water table variation (solid line), hourly crop evapotranspiration (dashed line), and daily crop evapotranspiration (bars) during the 2010 experiment.

In 2010, a wetter-than-normal growing season (fig. 3.5) may have had an influence on the root distribution due to waterlogged conditions, restricting the roots to the upper layers of the soil profile. Unfortunately, root depth was not studied in this research. In addition, Raes and Deproost (2003) state that the root extraction rate decreases exponentially from the top to the bottom of the root zone. These factors seemed to have influenced the water uptake pattern, resulting in drier soils at shallower depths. However, the soil allowed upward movement of water from the layers below 0.4 m to continuously replenish the soil layers up to 0.4-m depth (fig. 3.3g-n). The analysis of variance showed that the difference in soil moisture at different time of the day ($p<0.01$) and distance from the plant ($p<0.01$) were statistically significant.

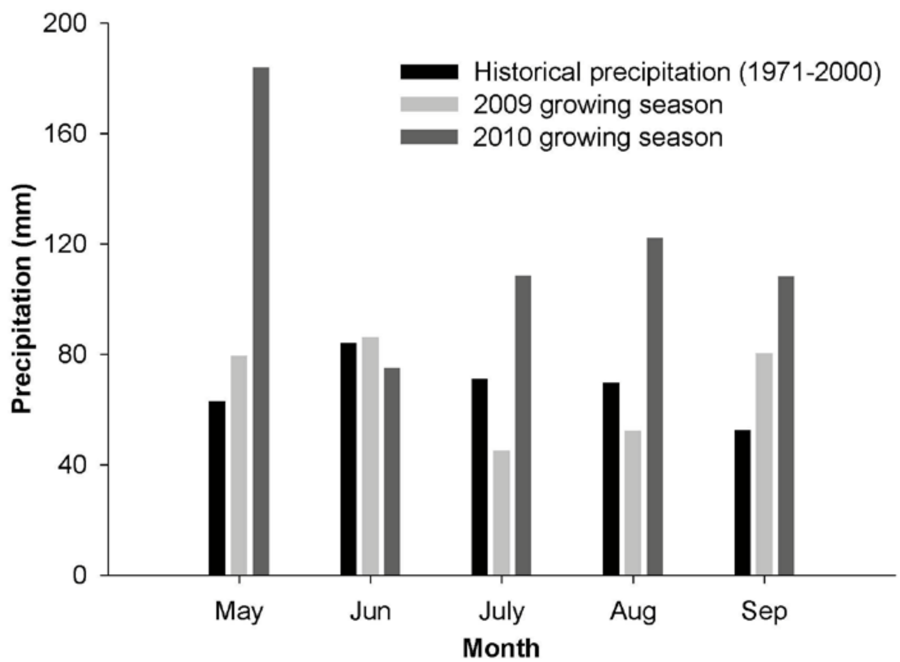

Figure 3.5. Comparison between historical, 2009 and 2010 growing seasons precipitation.

3.4.3 Soil water content and upward flux simulations

The Hydrus-1D simulations of soil water content in 2010 showed good agreement with observed values at 0.1, 0.6, and 0.8 m (fig. 3.6a, d, and e), but slightly overestimated at 0.4 and 0.6 m (fig. 3.6b and c). This lack of agreement occurs mainly at the beginning of the period, after the irrigation event. When the entire soil profile is taken into consideration and the soil water content is averaged, the overall agreement is very good, especially towards the end of the experiment (fig. 3.6f). The correlation between observed and simulated values over the entire experiment was very good (R^2 = 0.83) with a small root mean square error (RMSE = 0.018). The model efficiency as defined in Eq. 3 was also high (ME = 0.76), indicating good agreement between simulate and observed data. The total calculated upward flux was 11.5 mm, while the simulated total was 12.4 mm. The values for the four days of experiment were also similar. Observed fluxes during the four days were 1.6, 2.7, 3.2, and 4.0 mm, while simulated values were 2.6, 2.8, 3.3, and 3.7 mm, respectively. The calculated upward flux and Hydrus-1D simulated flux were in good agreement with an R^2 = 0.92, RMSE = 0.51, and ME = 0.66.

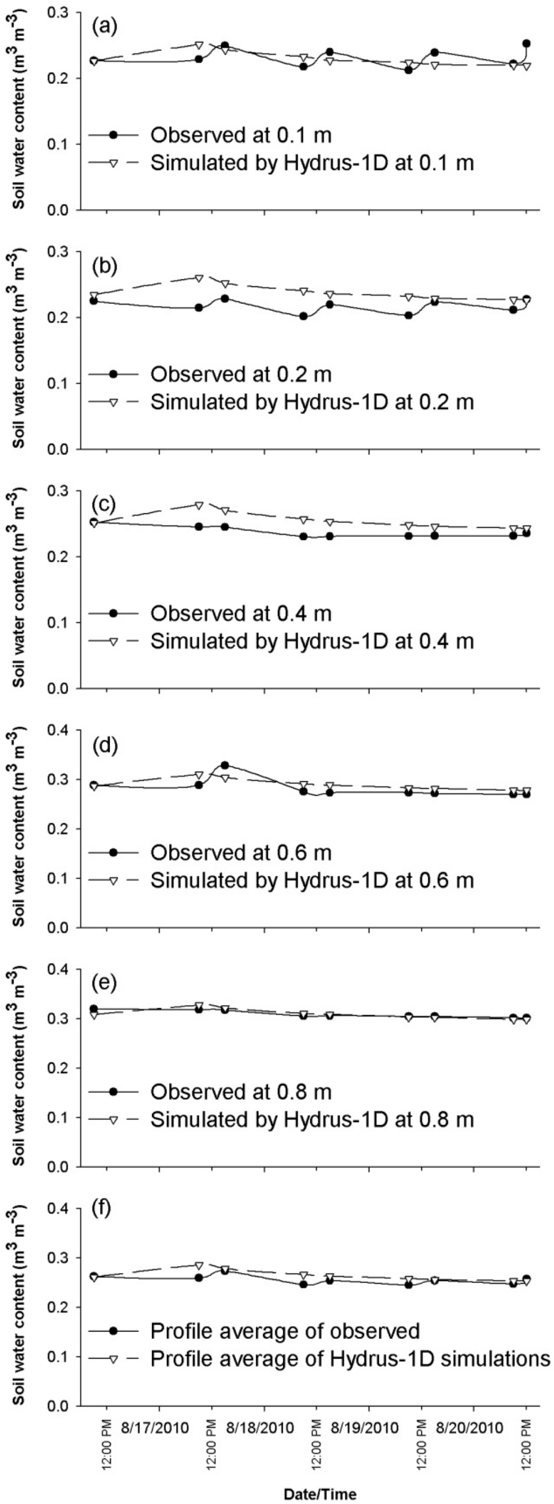

Figure 3.6. Observed and simulated values of soil water content at 0.1 m, 0.2 m, 0.4 m, 0.6 m, 0.8 m, and profile average during the experiment in 2010.

3.5 Discussion

The replicated data collected in each of the two years indicate a dynamic water distribution within the soil profile during the day, with water being replenished in the root zone from the water table below during the night. In the absence of further surface recharge after the initial irrigation event (in both years) the source of water for replenishing the root zone could be attributed to the upward flux from the groundwater table. In 2010, the decline in water table elevation corresponded with periods of high crop ET further supporting the upward flux. The difference in water content at different times of the day, which was statistically significant ($p < 0.05$), confirmed replenishment by upward flux (Table 3.2 and 3.3; fig. 3.2 and 3.3). The water table contribution in 2010 was indicated by a decline in water table elevation corresponding to the period of high crop ET (fig. 3.4). The contribution of groundwater to agricultural water requirements has been identified in other arid regions of the world (Kahlown et al., 2005). Water table contribution to supply plant water demand was also observed by Follett et al. (1974) for conditions similar to those of the present study. The authors, working in North Dakota with soils having textures ranging from sandy loams to loamy sands, found that corn grown with no irrigation benefitted from a shallower water table (around 2.0 m) compared to deeper water table (around 2.3 m). They concluded that shallow water tables could produce maximum yields without irrigation. In fact, the fields in Winkler have comparable conditions as those described by Follett et al. (1974), i.e., similar soil texture and a shallow water table that declines during the growing season. These conditions suggest a reason for good corn yields in the study area in the absence of supplemental irrigation. Corn is grown in Winkler with no irrigation, suggesting that the contribution from the water table to meet the plant water demand during dry years or in periods when water supply by rainfall does not suffice.

An analysis of the water table decline during the 2010 experiment revealed the partial contribution of the ground water to crop ET. Table 3.4 shows the amount of water entering the root zone during the 2010 experiment. The 14% drainable porosity used in the calculation is within the range presented by Johnson (1966) for soils having fine sand texture. Table 3.5 shows the weather variables measured during the 2010 experiment. Dew condensation was assumed to occur whenever the minimum hourly temperature became lower than the dew point temperature. Figure 3.7 shows the dew contribution was minimal and only occurred during the cold hours of the early morning period. There was no dew condensation on Day 1 of the experiment because the dew point temperature was lower than the minimum temperature. The total dew condensation on Days 2, 3, and 4 was 0.003, 0.004, and 0.001 mm, respectively.

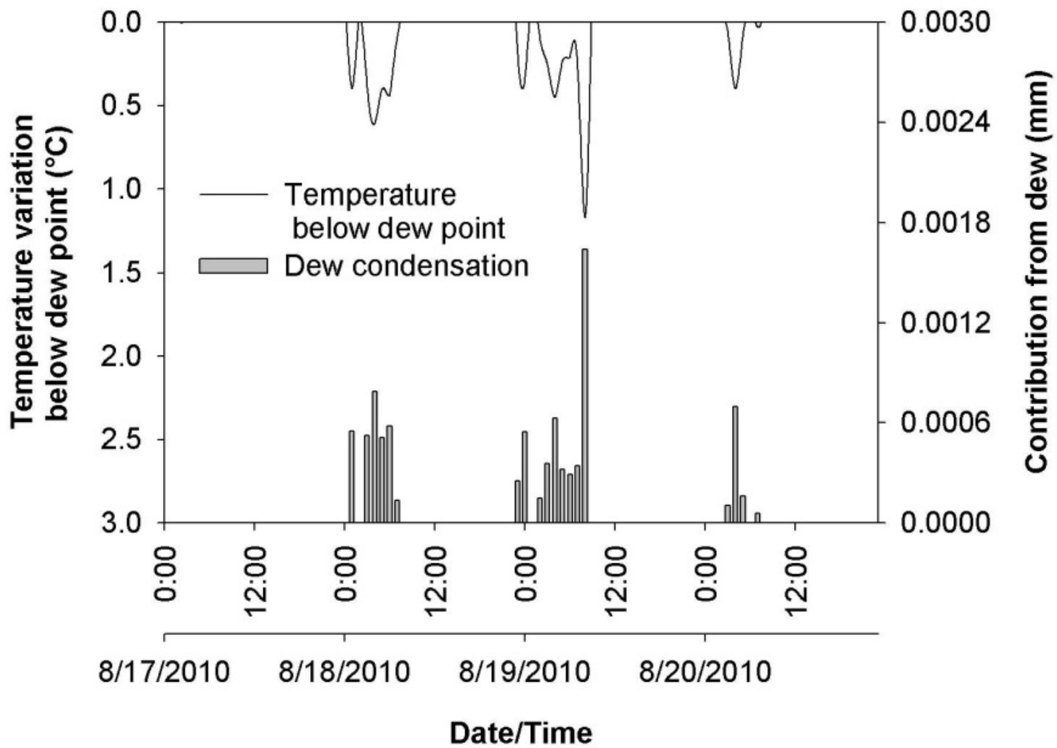

Figure 3.7. Temperature variation below the dew point temperature and the potential dew condensation contributing to variations in soil water content.

Given the negligible contribution from dew and the absence of rain and irrigation during the period under consideration, the only source of moisture to the root zone was the upward flux from the water table. The relative contribution of the water table to daily crop ET averaged 81% during the experimental period, which is characterized by large crop ET rates. Comparison of the water table drop and daily crop ET in Table 3.4 and the weather variables in Table 3.5 indicates that the water table depletion was mainly driven by the crop water demand, which was determined by the weather conditions. In Day 1 of the experiment, the solar radiation was the lowest observed, while the relative humidity was the highest (Table 3.5). These conditions led to the lowest ET_c and, as a result, to the lowest water table drop (Table 3.4), despite the highest average wind speed recorded (Table 3.4).

Table 3.4. Water table contribution to daily crop ET during the 2010 experiment.

Day of experiment	Water table drop (mm)	Water entering the root zone† (mm)	Daily crop ET (mm)	Water table contribution to ET (%)
1	11.4	1.6	2.3	70
2	23.3	2.7	3.5	77
3	22.7	3.2	3.9	82
4	28.7	4.0	4.2	95

† Calculated using a drainable porosity of 14 %.

Table 3.5. Weather variables and crop coefficients during the 2010 experiment.

	Weather variables†					
Day of experiment	Tmax (°C)	Tmin (°C)	RH (%)	Wind Speed (m sec^{-1})	Solar Radiation (MJ m^{-2})	Kc
1	21.4	5.2	80.3	2.0	13.9	0.99
2	22.2	6.0	72.1	0.9	20.8	0.99
3	24.4	7.1	73.7	2.0	20.3	0.98
4	31.8	11.7	75.4	1.9	20.3	0.98

† Tmax = maximum air temperature, Tmin = minimum air temperature, RH = average relative humidity, and Kc = crop coefficient.

In contrast, Day 4 had the largest maximum air temperature (Table 3.5), which led to the largest ET_c of the experiment with a corresponding larger drop in water table elevation (Table 3.4). It is important to highlight that the plant characteristics (i.e. developmental stage) and weather conditions (i.e. solar radiation, wind speed, maximum and minimum air temperature, and relative humidity) that affect ET were taken into account in the present study. The corn crop coefficients (Table 3.5) used to calculate the ET_c corresponding to the stage of growth (Table 3.4) were based on the growing-degree-days accumulated by the crop at that stage. As the corn plants developed, the crop coefficients used in the calculations of ET_c also changed according to the accumulated heat units for this location. The reference ET was calculated using weather variables discussed previously (i.e. solar radiation, wind speed, maximum and minimum air temperature, and relative humidity) and reflects their effect on ET_c. It should be noted, however, that the contribution from groundwater to ET_c obtained in this study (i.e. 81%) is limited to the period of measurement for which ET was calculated. The water sources available to the crop may change over the growing season based on precipitation and irrigation, which may decrease the need for contribution from the groundwater. During the early part of the season, the crop can rely on high soil water content, shallow water table, and frequent rainfall events to meet the crop water demand. If the growing season is dry, especially during periods of large ET, the relative importance of groundwater contribution to plant evaporative demand may be significant. Given the wet weather conditions in 2010, where the soil moisture within the root zone was replenished by frequent rainfalls, the water table contribution to crop ET could be smaller than that observed in a dry year. The largest ground water contribution tends to occur towards the end of the growing season, when the roots are fully developed and the soil water in the root zone is being rapidly depleted. That was the case for Soppe and Ayars (2003) when characterizing ground water use by safflower using weighing lysimeters in San Joaquim Valley, California. Considering the growing season as a whole, the groundwater contribution is likely to be much smaller than the 81% observed during the measurement period of this study. For instance, Cameira et al. (2003) found a 45% relative contribution from groundwater to crop ET for the hot and dry conditions of their study area with silt loam soils receiving 706 mm of rainfall as the average precipitation.

Ayars et al. (2006) reported that the factors affecting crop water use from shallow groundwater are: i) soil water flux, where the distance between the groundwater surface or the nearly saturated zone and the bottom of the root zone plays the most important role; ii) the root system, including developmental stage and depth; iii) crop, which influences the tolerance to groundwater salinity and the length of the growing season; iv) the presence of drainage system, which affects the soil water content; and v) the irrigation systems and management, which has direct impact on crop water use. Moreover, Sepaskhah et al. (2003) stressed that irrigation and drainage design usually does not consider the effects of shallow water table on crop growth and performance of drainage systems. In fact, in areas where irrigated corn production is practiced, the depth of irrigation will be over-estimated if the calculation is only based on ET and precipitation data while neglecting the contribution from the water table. In addition, the peak drain outflow in subsurface tile networks will also be affected. For example, an increase in soil moisture content by 0.02 m^3 m^{-3} between the soil surface and a drainage base at 1.0 m is equivalent to a rainfall of 20 mm. This extra moisture decreases the water storage capacity in the soil leading to a faster tile response in soils having poor drainage (Reid and Parkinson, 1984).

Despite the upward contribution from the water table, the soil water distribution within the root zone can differ according to the physiographic and weather conditions. In 2009, a delay between plant water uptake and replenishment was observed, where the soil became drier in the afternoon and wetter in the evening and morning. This phenomenon can be explained by the decrease in unsaturated hydraulic conductivity arising from higher ET in the afternoon, which lowers the water content of the soil within the root zone. During the evening and night the upward flux driven by the capillary gradient leads to an increase in water content in the root zone, which also increases the unsaturated hydraulic conductivity of the soil. This dynamic could be related to the drier-than-normal months of July and August (fig. 3.5), which combined, had a rainfall deficit of 43 mm. This condition may have driven the water table deeper, increasing the vertical distance between the root and saturated zones and making it more difficult for the upward migration of water from the water table. Another factor delaying the soil water replenishment in 2009 could have been the texture of the soil, which is imperfectly drained. The hydraulic conductivity of loamy soils varies from 10^{-4} to 10^{-7} m s^{-1}, but it would be even smaller (i.e. 10^{-10} to 10^{-12} m s^{-1}) under unsaturated conditions (Marshall et al., 1996), thus hindering the upward water flux within the soil matrix. In 2010, the drying pattern was observed to start during the morning, which was earlier than that observed in 2009. A reason for this could be a shallower root system caused by the excessive rainfall in May and resulting in shallow water table during the early season, which had detrimental effects on root proliferation in the deeper layers (Klepper et al., 1983). This resulted in a limited area of direct influence of the root system, depleting the soil water more rapidly in the top 0.3 m of the soil in 2010, as opposed to the more extensive depletion up to 0.7 m deep as observed in 2009 (fig. 3.2 and 3.3). The reasonably constant water content between 0.4 and 0.8 m in 2010 (fig. 3.3g-n) is an indication of the limited influence of the root system in this layer. The significant change in water content at radial distances from the plant (Table 3.3) also supports this claim, where the limited depth was compensated by the water available at greater distances away from the base of the plant. In addition, the frequent rainfall events in 2010 probably helped keep the soil moisture more stable at deeper layers of the soil profile allowing higher unsaturated hydraulic conductivity. The soil water replenishing time in 2010 seemed to be comparable to that observed in 2009, despite the better drainage of this soil.

Simulated soil water content and upward flux using Hydrus-1D showed good agreement with observed values, based on the evaluation criteria. The model proved useful for an overall assessment of soil water status and upward flux for irrigation purposes. Simulated water content seems to depart from observed values during recharge events at discrete depths; however, if the entire soil profile is considered, which is usually the case for calculation of available soil water in the root zone, the simulation performance is greatly enhanced. Simulation of upward flux was found to be comparable to the calculated values, making Hydrus-1D a valuable tool for estimating groundwater contribution to crop ET. It should be noted that the model in this study was set to have a constant boundary condition at the bottom of the model space, which assumes a stationary water table. As a result, simulations such as the ones above should only consider short periods of time. However, this assumption is still valid under practical conditions since irrigation forecast is usually done for short periods. It also brings the benefit of reducing the amount of information necessary to run simulations. An estimation of the soil bulk density and field capacity, weather variables for calculation of crop ET, and a single reading of water table elevation for defining the initial condition were sufficient to simulate the soil water status and ground water contribution during the next few days. These variables are readily available for most soils and locations from databases, making the use of Hydrus-1D a practical option for improving water use efficiency and scheduling irrigation.

The results reported in the present study have important implications to agricultural water management of corn under conditions prevailing in the Canadian Prairies. The first implication, which has been discussed previously, pertains to contribution of groundwater to crop water demand and, consequently, to yields. For instance, Cordeiro and Sri Ranjan (2012), working in the same area, compared the agronomic performance of corn under different water management strategies including overhead irrigation, sub-irrigation, and subsurface drainage. In both years of the study, they found no statistical difference between yields from the control treatment and treatments receiving overhead irrigation applied through a travelling gun. In this case, the yields of the treatments not receiving irrigation could have been positively influenced by groundwater contribution, especially if this contribution occurred during critical periods in the phenology that affect corn yield. According to Larson and Hanway (1977), corn yields are particularly susceptible to water stress between tasseling and silking because low available water could delay silking and reduce seed set due to inadequate pollination. However, from silking to maturity, corn yield is not as affected by water stress as it is during the silking phase. Contribution of groundwater could also explain good yields even in dry years without irrigation in this area where the study was conducted. For instance, MASC (2013) reports good crops in 2012 despite the dry weather conditions in southern Manitoba. In fact, corn yields in 2012 were the largest since 2009 across different hybrids in the risk area 12 of Manitoba, where Winkler is located and where corn is grown without irrigation input.

High yields under dry conditions highlight the upward flux from groundwater as an important process contributing to crop production in the Canadian Prairies. More importantly, it suggests that groundwater resources, which are replenished by recharge through rainfall and snowfall, should be managed properly for crop production. Snowfall, which accounts for 20% to 30% of the total annual precipitation in the Canadian Prairies (Tiessen et al., 2010; Li et al., 2011), should be managed to increase infiltration during the snowmelt period and replenish the shallow groundwater for later use by crops. Snowmelt runoff has been reported to decrease dramatically with low soil moisture due to substantial infiltration into the unsaturated frozen soil (Fang and Pomeroy, 2007). Thus, subsurface drainage, which is rapidly expanding in the Canadian Prairies (Cordeiro and Sri Ranjan, 2012), can be used to lower the water table in the fall and create the air-filled pore volume to accommodate the infiltration during the spring snowmelt. Besides water management benefits, approaches to enhance snowmelt infiltration would also have positive impacts to the environment, such as reduced runoff volumes, which is the major contributor to nitrogen and phosphorus export from agricultural watersheds in the context of the Canadian Prairies (Liu et al., 2013).

3.6 Conclusion

The contribution of the water table to the crop water requirements and the redistribution of soil moisture within the soil profile are important considerations for designing irrigation and drainage systems. However, monitoring these changes requires a system that acquires data quickly and at regular intervals as point measurements spatially and temporally. Such a monitoring system consisting of TDR miniprobes was used to monitor water redistribution within the root zone of corn after a thorough wetting event in a farm in Winkler, MB, Canada. The results indicated that the contribution of the water table is a significant factor in the study area where corn is produced with no input from irrigation. The water table contribution to crop ET was found to be 81% during the period of the experiment, characterized by large crop ET. The depletion of the ground water was mostly restricted to the hot hours of the day. The analysis of contour plots and statistical tests indicated that if the soil water content is high enough to support higher unsaturated hydraulic conductivity, it will allow for upward movement of moisture. Under these conditions, the water status of the soil profile tends to follow a pattern in which the soil dries out during the hours of high ET demand but is replenished when the evapotranspiration decreases. Simulations using Hydrus-1D indicated that this model can satisfactorily predict soil water content and upward fluxes, rendering this model a useful tool for water management and irrigation scheduling.

4. CORN YIELD RESPONSE TO DRAINAGE AND SUB-IRRIGATION IN THE CANADIAN PRAIRIES

4.1 Abstract

Subsurface drains are commonly used in humid regions to deal with high water tables. However, corn (*Zea mays* L.) could benefit from subsurface drainage even under semi-arid conditions where the high intensity rainfall causes the water table to rise within the rootzone for short periods. In southern Manitoba, seasonally high water table with high salinity has led to salinization of the rootzone, making subsurface drainage an attractive option to increase yields. The objective of this research was to evaluate agronomic performance of corn under water table management using sub-irrigation/tile-drainage. Four treatments were tested in this experiment: (i) controlled drainage with sub-irrigation (CDSI), (ii) no drainage with overhead irrigation (NDIR), (iii) free drainage with overhead irrigation (FDIR), and (iv) no drainage with no irrigation (NDNI) as control. The impact of these treatments on crop performance, measured by yield, kernel quality, plant biomass, and plant height, were evaluated over two growing seasons. In the first year, which was 57% wetter than the 30-year average, yields were 8.48 (NDNI), 10.36 (NDIR), 10.10 (FDIR), and 9.22 (CDSI) Mg ha^{-1} with only the mean yield difference for the NDIR and the CDSI treatments being statistically significant ($P = 0.014$). In the second year, which was 16% drier-than-normal, yields were 9.25 (NDNI), 10.47 (NDIR), 11.28 (FDIR), and 9.49 (CDSI) Mg ha^{-1} with no statistically significant difference in the yield.

4.2 Introduction

Worldwide, it is estimated that 100-150 million ha of irrigated land and 250-300 million ha of rainfed land are in need of improved drainage (Smedema et al., 2004). Traditionally, drainage has been used in humid regions to maintain the water table well below the root zone. In Canada, subsurface drainage of agricultural land is more common in humid regions as a management practice for maintaining the water table below the root zone while it is seldom used in the arid regions for this purpose (De Jong et al., 2009). In the Canadian Prairies, the high water table due to spring snowmelt infiltration needs to be lowered quickly to allow early field operations and soil warming. In addition, high-intensity, short-duration rainfalls in this region result in frequent high water tables that need to be lowered rapidly to maintain soil aeration during the growing season. Therefore, subsurface drainage is becoming a common practice in areas with intensive agriculture, which have only seasonally high water tables (Kladivko et al., 2004). In the Midwestern U.S., subsurface drainage was initially installed to provide suitable soil conditions for seedbed preparation in the spring, and to extend the growing season by advancing the spring operations (Grigg et al., 2003).

Besides preventing waterlogging, providing aeration to the root zone, and enhancing the trafficability of soil, drainage in arid regions provides leaching capability to control salinity build-up within the crop root zone and soil profile (Ayars et al., 2006). Subsurface drainage also reduces surface runoff, sediment losses, and the movement of contaminants attached to the sediment (Skaggs et al., 2010). However, subsurface drainage may act as a conduit for nutrients and herbicides which are hazardous to both the environment and public health (Kalita et al., 2006).

Much research dealing with drainage impact on crop yield and the environment has been done in areas such as the humid regions of the USA, where subsurface drainage is more common (Wright and Adamsen, 1993; Hofmann et al., 2004; Kladivko et al., 2005; Skaggs et al., 2006; Lang et al., 2010; Luo et al., 2010; Skaggs et al., 2010). In the Canadian Prairies, where subsurface drainage is gaining acceptance, very little research on this subject has been reported (Farming for Tomorrow, 2011). Many of the available design parameters such as drainage base depth and spacing are available for steady state conditions for other regions. The Canadian Prairies, which experience high intensity storms, which require solutions for unsteady state conditions, do not have clearly defined design parameters. In addition, topography, soil compaction, surface infiltration characteristics, and soil type need to be considered in the design process.

Given the lack of research on subsurface drainage systems in the Canadian Prairies, there is no information available about the impact of these systems on crop performance for this region. Research done in humid regions of Canada has shown that a combination of controlled drainage with sub-irrigation was able to increase crop yields (Liu et al., 2011). For instance, corn yield in Ontario increased by 22% in wet years and 91% in dry years due to supplemental irrigation provided through sub-irrigation (Tan et al., 2007). Contradictory results have also been observed, where sub-irrigation did not always show an increase in corn yields (Drury et al., 2009). Since the conditions between the humid and semi-arid regions of Canada are essentially different, the results of research conducted in the former do not directly apply to the latter. Thus, research in the Canadian Prairies is required not only to establish short-term effects of drainage on crop production, but also to create datasets that will allow for long-term crop yield simulations by means of modeling exercises.

A number of crops are available for drainage studies in the semi-arid conditions of the Canadian Prairies. For example, potato, canola, corn, sunflower, flax, and soybeans, are among the high-value crops produced in southern Manitoba besides wheat, oat, barley, and alfalfa, which are generally grown under rainfed conditions. Corn is commonly in rotation with potatoes to prevent the spread of disease and reduce the impact of insects (MAFRI, 2011a). Corn is also grown for human consumption and as silage in livestock production (MAFRI, 2011b). Corn is fed to dairy and beef cattle, while it is also processed and used as hog and poultry feed. In Canada, corn was ranked as the fourth largest crop produced in 2009 (1.06×10^7 metric tonnes), following wheat (2.86×10^7 metric tonnes), canola (1.26×10^7 metric tonnes), and barley (1.18×10^7 metric tonnes) (Statistics Canada, 2009). Canadian corn production area reached 1.25 million ha in 2000, driven by demand from the hog and ethanol industries (Statistics Canada, 2002).

The objectives of this research were to assess how different water management treatments affect corn performance in terms of yield and grain quality under Canadian Prairie conditions. The experiment tested the agronomic and hydrologic responses for different combinations of irrigation (overhead and sub-irrigation) and subsurface drainage (free and controlled drainage). The corn responses under unusually wet conditions prevalent during the first year of experiment and drier-than-normal conditions in the second year are discussed.

4.3 Material and Methods

4.3.1 Site characterization

The experiment was carried out at Hespler Farms, Winkler, Manitoba (NAD 1983 UTM 14N 575905.735E 5441331. 527N). The soil in the area belongs to the Reinland Series, which is an imperfectly drained soil having loam texture (Podolsky, 1991; Manitoba Soil Survey, 1973). This soil series consists of Gleyed Rego Black Chernozem soils (MAFRI, 2010), which corresponds to Udic Boroll subgroups in the US soil taxonomy (Soil Classification Working Group, 1998). The textural percentages are 69, 20, and 11% for the sand, silt, and clay fractions, respectively. The research site belongs to a commercial farm and was selected due to its homogeneous soils and farming practices, which minimizes extraneous interference in the treatments' performance. The four north-most plots in the study area (fig. 4.1) are at the interface between soils in the Reinland and Hochfeld series. The latter series is very similar to the former, also having a fine sandy loam texture (Manitoba Soil Survey, 1973). Table 4.1 shows the calcium carbonate equivalent (CCE), the total organic carbon (TOC, as a measure of organic matter), and electrical conductivity for all the research plots. The long-term averaged weather data (1971-2000) for the area, as collected at the Morden CDA (Canadian Department of Agriculture) weather station (Environment Canada, 2010), is shown in Table 4.2 for the growing season months.

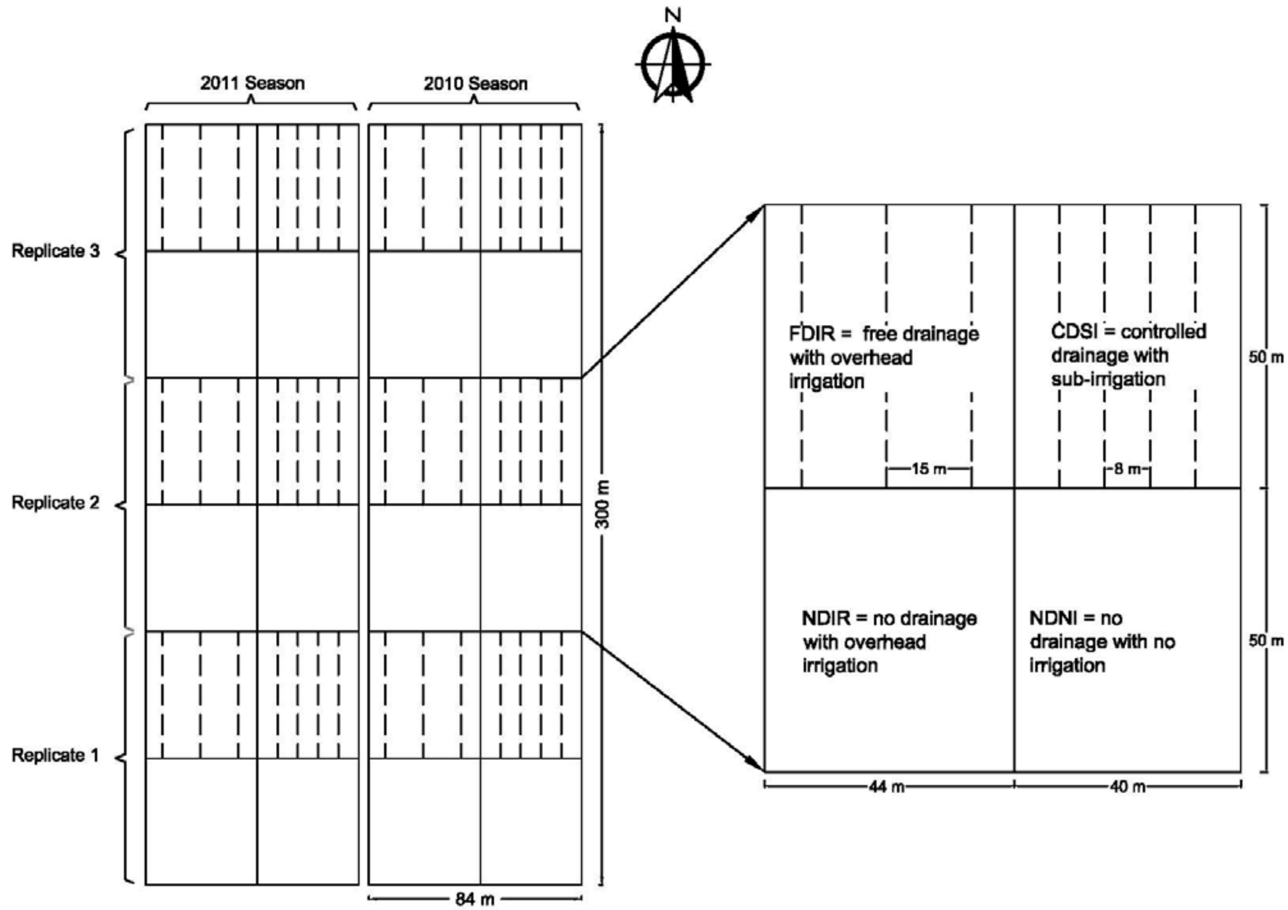

Figure 4.1. Plot layout for the 2010 and 2011 growing seasons showing the tile arrangement for each plot, and the details of each treatment within Replicate 2 in 2010.

Table 4.1. Soil parameters in the research plots averaged over a 1.2 m soil profile.

	Soil parameters		
Plot	CCE (%)	TOC (%)	EC (dS m^{-1})
NDNI Rep 1 2010	2.9	1.4	1.0
CDSI Rep 1 2010	3.4	1.5	0.5
NDNI Rep 2 2010	2.8	1.4	0.7
CDSI Rep 2 2010	3.5	1.5	0.4
NDNI Rep 3 2010	3.7	1.3	0.5
CDSI Rep 3 2010	2.8	1.3	0.4
NDIR Rep 1 2010	1.6	1.2	0.5
FDIR Rep 1 2010	2.5	1.2	0.4
NDIR Rep 2 2010	1.1	1.6	0.7
FDIR Rep 2 2010	3.0	1.4	0.8
NDIR Rep 3 2010	1.1	1.8	0.5
FDIR Rep 3 2010	3.0	1.4	0.6
NDIR Rep 1 2011	5.7	1.1	0.7
FDIR Rep 1 2011	4.9	1.2	0.6
NDIR Rep 2 2011	3.0	1.7	0.6
FDIR Rep 2 2011	2.6	1.8	0.7
NDIR Rep 3 2011	3.7	1.6	0.6
FDIR Rep 3 2011	1.6	1.2	0.4
NDNI Rep 1 2011	4.6	1.3	0.7
CDSI Rep 1 2011	5.1	1.4	0.6
NDNI Rep 2 2011	1.9	1.4	0.6
CDSI Rep 2 2011	4.7	1.5	0.7
NDNI Rep 3 2011	5.5	1.6	0.8
CDSI Rep 3 2011	2.9	1.4	0.6

Table 4.2. Historical weather data for the experimental site during the growing season months (averaged data from 1971 to 2000).

	Month						
Weather Variable	Apr	May	Jun	Jul	Aug	Sep	Oct
Daily Temp (°C)	4.7	12.9	17.7	20.1	19.1	13.3	6.2
Daily Maximum Temp (°C)	10.4	19.4	23.6	25.9	25.3	19.1	11.2
Daily Minimum Temp (°C)	-1.0	6.2	11.8	14.2	12.9	7.6	1.3
Rainfall (mm)	24.5	61.6	84.4	71.2	69.9	52.5	37.8
Snowfall (mm)	11.1	1.7	0.0	0.0	0.0	0.3	7.0
Wind Speed (km h-1)	13.9	13.8	12.8	10.9	10.5	12.7	13.4
Sunshine (h)	218.2	266.3	272.1	308.3	280.1	186.5	149.8

4.3.2 Experiment

The study area was divided into two sections for the 2-year experiment (fig. 4.1). In 2010, the experiment was done in the east section; in 2011, the experiment was done in the west section. The dimensions of each section were 300 m by 84 m, which comprised two rows of six plots. Four combinations of water management treatments were tested in this experiment: (i) no subsurface drainage with no irrigation (NDNI; control), (ii) no subsurface drainage with overhead irrigation (NDIR), (iii) free subsurface drainage with overhead irrigation (FDIR), and (iv) controlled subsurface drainage with sub-irrigation (CDSI). There were three replicates for each treatment. Overhead irrigation was done with a travelling gun, which was operated through a central alleyway between the two sections. The target for overhead irrigation was to keep the soil moisture within the readily available water content range, which corresponds to a volumetric water content not below 20%. Since the travelling gun system was operated by the farmer and used in other fields, the overhead irrigation scheduling in the field had to accommodate these off-site operations. Sub-irrigation was done through the same drains that were used to drain the land when the water table was high. The target was to keep the water table constantly at 0.75 m below the soil surface. The irrigation water used in the experiment came from a reservoir 3 km west of the field, which is operated by a consortium of farmers. The snowmelt is pumped into the reservoir during early spring and is used during the growing season for irrigation.

The experimental plots were part of a commercial operation managed by the farmer. The individual plots were very large which made farming operations easier with existing farm equipment and also providing an opportunity to use the plots for agricultural extension demonstration. In addition, the large size of the plot provided a buffer effect for the monitored locations which were located closer to the center of each plot (monitoring protocol described in the next subsection). Also, a small dike approximately 0.3 m high was built around the plots to isolate them hydrologically from each other. The installation of the drainage system and the operation of the overhead irrigation system dictated the assignment of treatments to the plots. The plots with NDNI and CDSI treatments with 8 m drain spacing were 40 m by 50 m. The plots with NDIR and FDIR with 15 m drain spacing were 44 m by 50 m. Although drain tiles were installed in the NDIR plots, they were capped off to simulate a non-drained condition for this study.

The subsurface drains were installed at 0.9-m depth during the fall 2009 using a Wolfe self-propelled drainage plow controlled by GPS. The drain laterals consisted of 100-mm diameter corrugated, perforated pipe. A drainage coefficient of 6 mm d^{-1} was used and the installation slope was 0.05%. The impermeable layer is located 6 m below the ground surface. Each drained plot had its own dedicated sub-main draining into the manholes installed just east of the field. The dedicated sub-mains collected drainage water from each plot separately. Control structures (Agri Drain Corporation, Adair, IA) were used in the sub-irrigated plots in order to control water table elevation. Each control structure was installed outside the plot close to the manhole inline with the sub-main. Water table was managed by using different combinations of stoplogs in the control structures. Interceptor drains were installed around the sub-irrigated plots on three sides to hydrologically isolate them from the other plots. These interceptor drains prevented the sub-irrigation water from entering the adjacent plots (Forrester, 2000).

In the fall prior to corn planting, the field was tilled to 0.08-m depth using a super coulter (Summers Manufacturing Company, Inc., Devils Lake, ND) to cut up vines from the previous season potato crop. At planting, 130 kg N ha^{-1} were applied as urea (46-0-0) and incorporated with a field cultivator to 0.1 m depth, which was followed by the corn planter. Also, 18 kg N ha^{-1} and 60 kg P ha^{-1} were banded during seeding as ammonium polyphosphate (10-34-0). In 2010, the field was seeded to corn hybrid ‘Pioneer 39B94’ on April 28th at 69,000 plants ha^{-1}. In 2011, the field was seeded to corn hybrid ‘Pioneer 39D97’ on May 16 at 74,000 plants ha^{-1}. Both hybrids are rated at 2250 heat units have similar agronomic performance, making the comparison of the results possible. The spacing between rows for both years was 0.76 m.

4.3.3 Monitoring

Weather parameters were measured using an on-site WatchDog 2900ET weather station (Spectrum Technologies, Inc., Plainfield, IL). The weather variables measured were minimum, maximum, and average daily temperature, relative humidity, solar radiation, wind speed and direction, rainfall, and reference evapotranspitation (ET) was calculated by the data logger based on the weather data using the Penman-Monteith method (Spectrum Technologies, 2009).

The water application rate by the overhead irrigation system was measured using IrriGages catch cans (K-State Mobile Irrigation Lab, Manhattan, KS) positioned across the plots. The standard IrriGage has a 100-mm diameter opening, a 200-mm long collector barrel, and an attached storage bottle for collected water (Clark et al. 2006). The irrigation uniformity calculated using Chrisitansen's uniformity coefficient (CU_C; Heermann and Kohl, 1980) was 89%, which could be achieved due to the presence of wind breaks (shelter belts) along the east and west sides of the field. In the sub-irrigation plots, MJR-100-1G water meters (Seametrics Inc., Kent, WA) were installed in the inlet line to measure the flow when running in 'irrigation' mode. The water outflow from drained plots was recorded by automated flow monitoring systems, which comprised of Leveloggers® Gold (Solinst Canada Ltd., Georgetwon, ON) and V-notch weirs, which were used to continuously monitor the drainage outflow rates. The weir and level logger system to measure the drainage discharge was calibrated in the Hydraulics Laboratory at the University of Manitoba, Winnipeg, Manitoba. In addition, periodic field verifications were done using a volumetric cylinder and stopwatch. For FDIR treatment, the sub-mains draining into the manholes flowed over a sharp-crested V-notch weir. The invert of the pipe close to the weir was connected to the bottom of a stilling pipe holding the Levelogger®, so that the height of the water column in the stilling pipe would be the same as the height of the water flowing over the weir. The elevation of the bottom of the V-notch was also determined and used to calculate the height of the water column above the V-notch. The variation in water column data (i.e. the height of the water column above the bottom of the V-notch) was translated into flow rate from the sub-main outlet using a weir equation. Leveloggers® were also used in the control structures to monitor the outflow from the sub-irrigated plots during the ‘drainage’ mode. A V-notch weir was placed on top of the last stop-log and a stilling pipe holding a Levelogger® was installed on the upstream side of the control structure.

Ground water levels were monitored by Leveloggers® installed inside galvanized, pre-slotted, 50-mm diameter observation wells. The wells were 2.4-m long, with the top 0.2 m above the ground surface. Three wells were installed in each drained plot (i.e. FDIR and CDSI treatments), with the first one close to the drain, the second one at mid-spacing between two adjacent drains, and the third one in between the other two wells (i.e. ¼ spacing). The water table elevations reported in the results section refer to the wells located at mid-spacing between drains unless indicated otherwise. Only one well was installed in each of the non-drained plots (i.e. NDNI and NDIR treatments), and was aligned with the well close to the drains in the drained plots. Levelloggers® were used in each well to collect the water table depth at 3-h intervals for the duration of the growing season.

Soil moisture and soil salinity were measured using 50 mm-long TDR miniprobes installed at five different depths (i.e. 0.2, 0.4, 0.6, 0.8 and 1.0 m) adjacent to the observation well located at mid-spacing between drains. Thermocouples were attached to the TDR probes in order to collect temperature at different soil depths to enable soil temperature correction of the TDR readings (Kahimba and Sri Ranjan, 2007). The TDR miniprobes were installed after planting and removed before harvest to allow for field operations. The software WinTDR (Utah State University, Logan, UT) and 16-channel VAZEC TR-200 multiplexers (Vadose Zone Equipment Company, Amarillo, TX) were used to collect data from the TDR probes and a Fluke 51 thermocouple thermometer (Fluke Electronics Canada LP, Mississauga, ON) was used to measure the soil temperature once a week. The TDR readings were temperature corrected before data analysis (Kahimba and Sri Ranjan, 2007). A topographic survey was done in the fall 2010 after harvest using a survey-grade GPS mounted on an all-terrain vehicle (ATV).

Plant growth monitoring was done by measuring above-ground plant dry biomass and plant height. Both measurements were done bi-weekly during the entire season by randomly collecting two plants from each plot, outside the designated rows for harvesting. The plants were cut at the ground surface and their height was measured. Then, they were transported in large paper bags to a walk-in oven in the Department of Plant Science at the University of Manitoba. The plants were allowed to dry for three days at 65°C, after which the dry biomass was obtained by weighing.

Yield was measured by hand harvesting 12-m long portion of the row closest to each well in the plot, parallel to the drains. The yields were standardized to 15% moisture content. Corn quality was assessed using the test weight procedure, which is a standard method for grain grading. Test weight is the measure of grain density determined by weighing a known volume (0.5 L) of grain (CGC, 2009). The detailed procedure used in this study followed the methodology described in the Official Grain Grade Guide (CGC, 2004).

4.3.4 Data analysis

The data collected during the experiment were tabulated and statistically analyzed in order to compare the output of each treatment in terms of agronomic response (i.e. yield, test weight, plant height, and plant biomass). The agronomic parameters were analyzed by replicate using matched-pair *t-test* procedure in JMP 8.0 software (SAS Institute Inc., Cary, NC). The treatment comparison was done by replicates, assuming the treatments within a replicate to be correlated due to their proximity. The paired *t-test* takes the correlation between the responses into consideration (SAS, 2009). Analysis of variance (ANOVA) was used to compare the water table depth and the drainage outflow.

4.4 Results and Discussion

In the Canadian Prairies, much of the growing-season precipitation occurs as high-intensity rainfall events. According to Akinremi et al. (1999), rainfall events in classes 4 (10-25 mm) and 5 (> 25 mm) account for 52% of the total precipitation in the Canadian Prairies. Figure 4.2 shows the comparison between the long-term average and the measured precipitation for 2010 and 2011 growing seasons on a monthly basis. The long-term average precipitation (1971-2000) between May and September for the study area was 341.6 mm (Environment Canada, 2010), while the precipitation for the same period in 2010 totalled 598.8 mm. Except for June, 2010, the experimental site received much greater rainfall amounts compared to the long-term monthly average precipitation. For May, July, August, and September, the rainfall was 191%, 53%, 75%, and 105% above average. Overall, the 2010 growing season turned out to be much wetter than normal, with 257 mm above average (75% above the long-term average). In 2011, despite the excess precipitation in May and June, there were drought conditions in July to

August, which is the period of higher ET. In July and August the precipitation was 15% and 12% below average, respectively. September was also dry during the first two weeks with precipitation 90% below average, but there was a large rainfall (i.e. > 70 mm) on 20 September. As a result, the total monthly precipitation in September was above the long-term average. However, this excess moisture had no effect on yields at this point in the growing season.

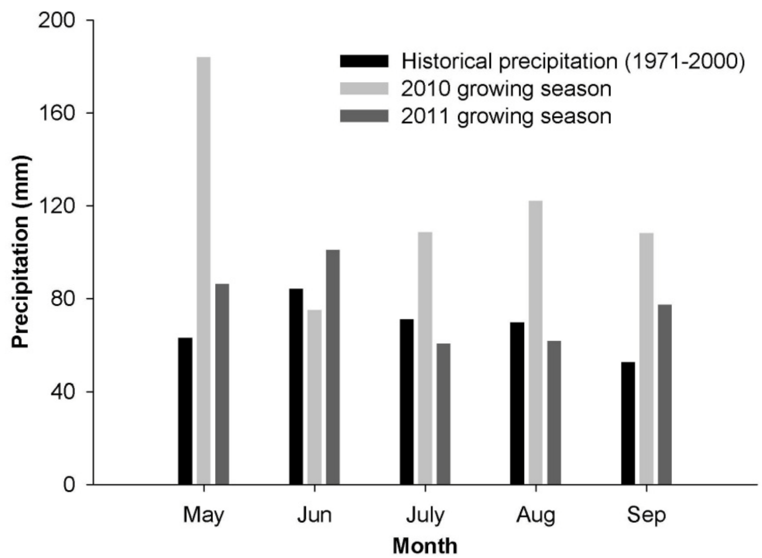

Figure 4.2. Comparison of precipitation between historical, 2010, and 2011 growing seasons.

4.4.1 Yield and grain quality

In 2010, the average yields were 8.48 (NDNI), 10.36 (NDIR), 10.10 (FDIR), and 9.22(CDSI) Mg ha^{-1}. These values are consistently higher than Manitoba's 10-yr average (4.80 Mg ha^{-1}; Manitoba Agricultural Services Corporation, 2009) and the 2010 Manitoba yield for the corn variety Pioneer 39B94 (6.37 Mg ha^{-1}; Manitoba Agricultural Services Corporation, 2011). The better agronomic performance of the study site in comparison to other parts of the Province of Manitoba is due to the better agricultural suitability classification of the soil. A trend in higher yields was observed in the plots with overhead irrigation either with (FDIR) or without (NDIR) subsurface drainage compared to the plots without overhead irrigation (fig.4.3). Despite differences in absolute values, the differences in yields were not statistically significant for most treatments ($P>0.05$) due to the high variability observed between the replicates. Only the mean yield difference for the NDIR and the CDSI treatments were statistically significant ($P = 0.014$), as indicated by the error bars in figure 4.3 (whiskers are only shown for means of treatments with statistically significant differences). Due to the heavy rainfall, overhead irrigation was only done twice during the 2010 growing season, with 6 mm and 20 mm being applied on 09 July and 09 August, respectively. Sub-irrigation was begun on 12 July and a total of 147 mm was applied over the next 50 days.

In 2011, the average yields were 9.25 (NDNI), 10.47 (NDIR), 11.28 (FDIR), and 9.49 (CDSI) Mg ha^{-1}. There was an overall increase in yield from 2010 to 2011 for all treatments (fig. 4.3), but there was no statistically significant difference ($P>0.05$) between the treatments in 2011. Under drier-than-normal conditions, overhead irrigation seemed to have more impact on yield than sub-irrigation, since the two treatments with overhead irrigation (i.e. FDIR and NDIR) showed an increasing trend in yields than CDSI. Drainage seems to give an additional advantage in the early part of the season to the FDIR treatment, resulting in the increasing-yield trend among all the treatments. Overhead irrigation was done on 20 July (13 mm), 29 July (13 mm), 11 August (9 mm), 24 August (5 mm), and 30 August (14 mm), totalling 54 mm applied. A total of 290 mm (standard deviation ± 4.32 mm) of water were applied through sub-irrigation from 10 July to 4 September.

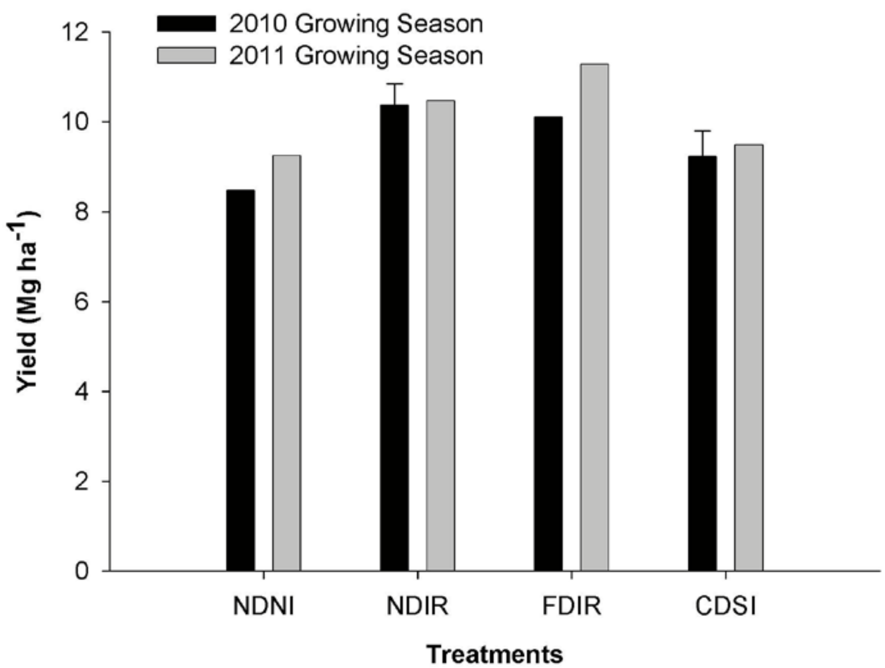

Figure 4.3. Average yield (Mg ha^{-1}) for the different irrigation/drainage treatments: NDNI (no subsurface drainage with no irrigation), NDIR (no subsurface drainage with overhead irrigation), FDIR (free subsurface drainage with overhead irrigation), and CDSI (controlled subsurface drainage with sub-irrigation). Error bars shown for means with statistically significant difference ($P<0.05$).

In 2010, the test weights, which are based on kernel bulk density and used as a measure of the kernel quality, were 74.5, 74.3, 74.7, and 74.5 kg hL^{-1} (i.e. kilograms per hectolitre) for NDNI, NDIR, FDIR, and CDSI treatments, respectively. The test weights were not statistically significantly different ($P>0.05$) and the trend in kernel quality did not mirror that of the yield, where the treatment with higher yield (NDIR) showed the smaller test weight. The dry-basis biomass yield and plant height measurements done throughout the growing season were not statistically significantly different ($P>0.05$; data not shown).

The test weights in 2011 were 72.0, 72.0, 72.8, and 73.5 kg hL^{-1} for NDNI, NDIR, FDIR, and CDSI treatments, respectively. Although not statistically significantly different (P>0.05), these values showed a different trend than that observed in 2010. The treatment with higher kernel density was CDSI, despite performing third best in terms of yield. Conversely, the best treatment in terms of yield (FDIR) had the second best test weight. As for 2010, the dry-basis biomass yield and plant height measurements in 2011 were not statistically significantly different (P>0.05; data not shown).

Comparison of the results for the two years seems to indicate that, under the conditions of the experiment, excess moisture was detrimental to yields but beneficial to kernel quality as the yields increased as test weight decreased from 2010 to 2011. Also, in dry years, the continuous sub-irrigation supply seems to provide moisture during a sensitive period for kernel quality as indicated by the higher test weight observed for CDSI. A mismatch between overhead irrigation dates and periods of increased sensitivity to water stress may have caused the test weights to be smaller for FDIR.

These agronomic results agree with those found in the literature for more humid regions in the United States and Canada. Grigg et al. (2003), studying the effect of drainage on corn yield in Louisiana, found that controlled drainage and controlled drainage with sub-irrigation did not show statistically significant difference when compared to surface drainage. The authors suggest that the effects of drainage would have been significant if rainfall was in excess of the 30-year annual average (i.e. 1540 mm). Their results show no difference under drier-than-average conditions, thus agreeing with the results found in this study for 2011. More recently, in Ontario, Drury et al. (2009) compared the agronomic performance of a corn-soybean rotation receiving different nitrogen fertilization rates under three water management treatments: controlled drainage (CD), controlled drainage with sub-irrigation (CDS), and unrestricted tile drainage (UTD). Their results showed, under excess N fertilization, CDS increased crop yields by 2.8% only when compared to UTD. However, under regular N application rates, the crop yields under CDS were 6.5% lower than those for UTD. For corn, the yield was significantly lower for CD than for UTD during the first year, while there was no difference between treatments during the second year of their study. The authors suggest that lower yields for CDS occurred due to reduced soil aeration and enhanced N losses caused by wet conditions in August (128 mm). These wet conditions agree with the conditions found for the present study during July and August of 2010, with precipitation larger than usual. The authors also argue that the tile spacing (7.5m) and/or tile depth (0.6 m) could have been too great to transfer water horizontally through the soil to dry areas between tiles. Slow lateral movement of water seems to be the case in the present study, as evidenced by difference in water table depth among the wells in the sub-irrigated plots, which is discussed in the next session. If this is the case, the design parameters used in the present study (i.e. 8.0 m drain spacing and 0.9 m drain depth) would have compromised the water supply to the sub-irrigation plots during the dry months of the 2011 growing season. Such information is quite important for adapting the design of sub-irrigation systems for the Canadian Prairies because it reveals that soil textures would play an important role in allowing sufficient lateral water movement to the drier zone between tile in order to meet plant water demand.

4.4.2 Water table

The agronomic results were assessed with respect to water table depth in order to verify its influence. Figure 4.4 shows the variation in water table depth below the ground surface for 2010 as an average for the three replicates. The depth to the water table was shallower for the treatments with no drainage (i.e. NDNI and NDIR) during the beginning of the growing season when higher than average rainfall was received.

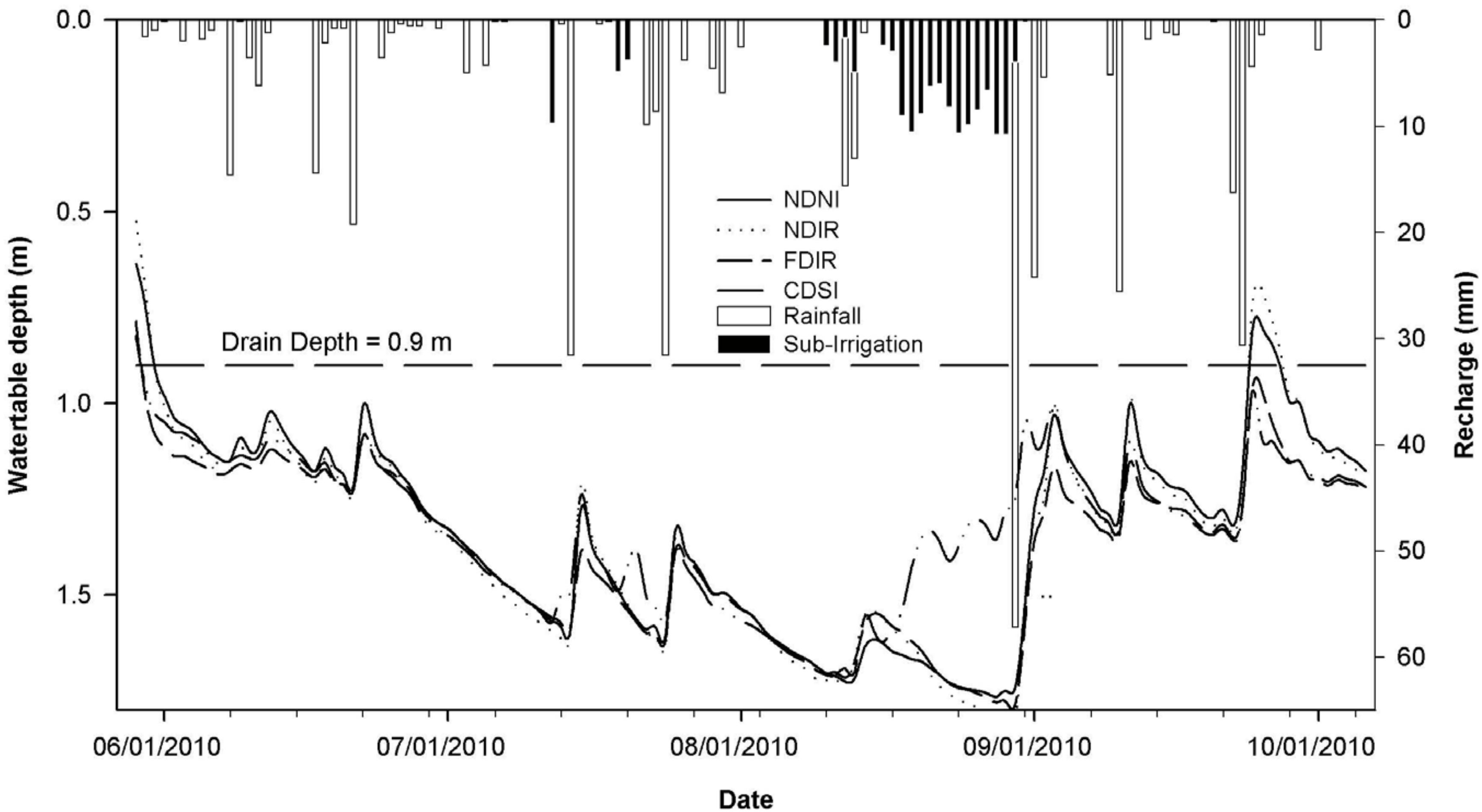

Figure 4.4. Variation in water table depth during the 2010 growing season for the different treatments (average of 3 replicates). White and black bars represent rainfall and sub-irrigation, respectively.

Differences of up to 0.3 m in water table depth were observed between drained and non-drained plots during the last week of May. However, differences during this period do not seem to have affected yields since FDIR and CDSI would have performed better if yields were particularly sensitive to shallow water table at the beginning of the growing season. Nonetheless, shallow water table can hinder root development, thus compromising the ability of the plant to draw water efficiently from the soil profile during the latter part of the season. Towards the end of June, which was drier than normal (fig. 4.2), the water tables started to decline. The difference in water table depth between the different treatments decreased as the water table dropped below the drainage base depth (i.e. 0.9 m). Below this depth, drainage no longer influenced the water table behaviour. Although the sub-irrigation was supposed to begin during the last week of June, to maintain the water table elevation above the drainage base depth, it was delayed until 12 July due to operational difficulties arising from a malfunctioning in-line sand filter that was used to remove suspended materials from the water. When the sub-irrigation was initiated on 12 July (first black bar in the recharge graph), it had to be stopped in response to the large rainfall events that occurred during the subsequent days. The sub-irrigation was resumed on 7 August and the water table began to rise. The difference in water table depth between the different treatments disappeared due to the large rainfalls towards the end of August. The delay in operation of the sub-irrigation may have contributed to the relatively lower yield from the CDSI treatment. Despite the steep water table rise, it never reached the designed operating depth of 0.75 m. Towards the end of the season, as evapotranspiration was much lower, the water table rose once again and the non-drained plots were the ones most responsive to rainfall.

Over the growing season, the average water table depth for the NDNI, NDIR, FDIR, and CDSI treatments were 1.33, 1.34, 1.37, and 1.31 m, respectively. The analysis of variance showed no difference in water table depth among the four treatments in 2010 ($P>0.05$). Statistically significant differences were not observed probably because the water table was below 0.9 m depth during most of the season, where the subsurface drainage did not play a role. The impact of the sub-irrigation on the water table seems to have been masked by i) the short period sub-irrigated, and ii) by the shallow water table for all treatments at the beginning and ending of the season and deep water table during the mid season (fig. 4.4). This large variability has a direct influence on the results of ANOVA.

At the beginning of 2011, the water table variation was similar to that observed for the same period of 2010 (fig. 4.5). The water table was fluctuating around 1.0 m depth during the first week of June and started to decline towards the end of the month. A 50-mm rainfall on 23 June brought the water table nearly to the soil surface, from which point it started to decline.

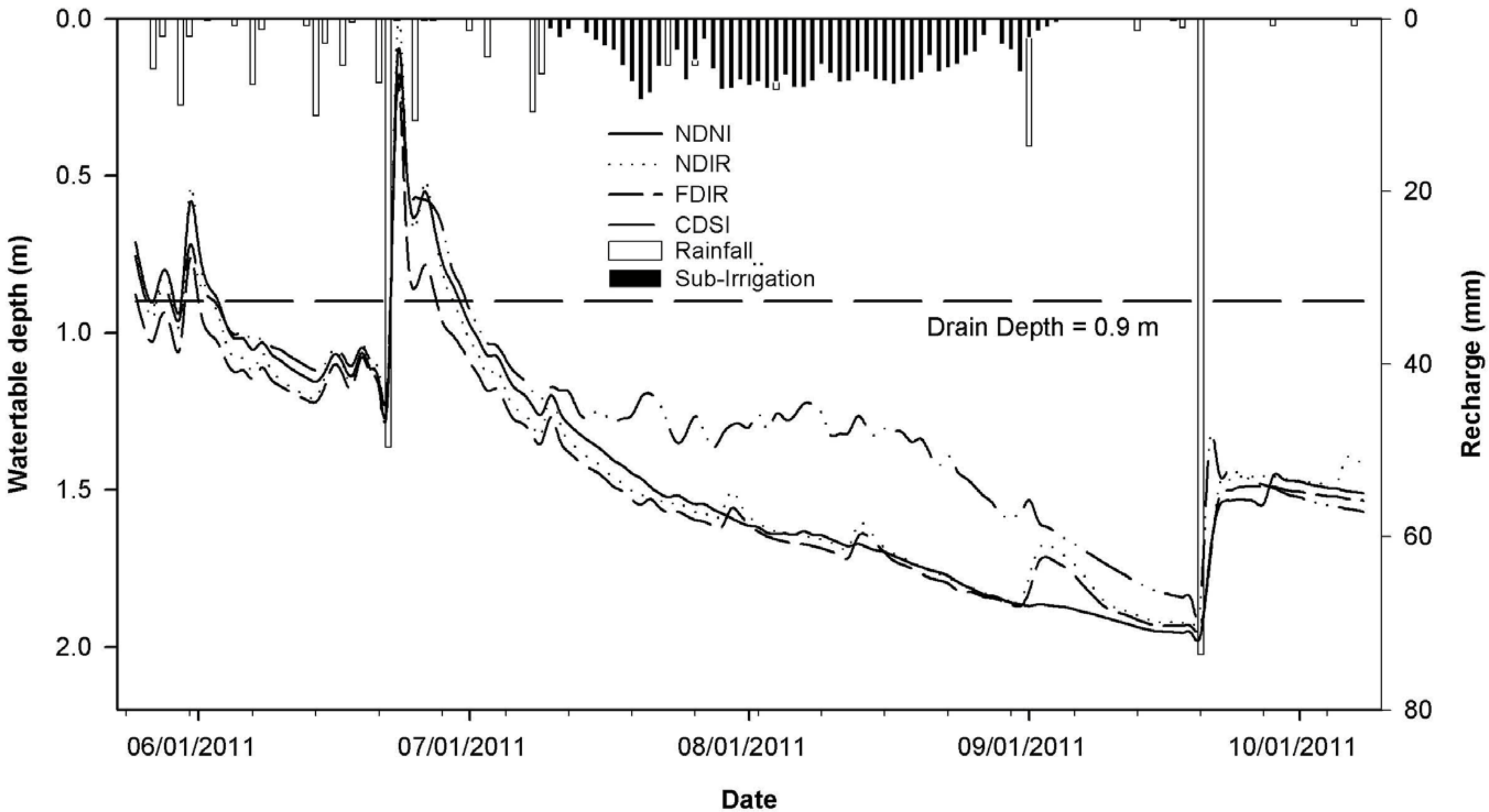

Figure 4.5. Variation in water table depth during the 2011 growing season for the different treatments (average of 3 replicates). White and black bars represent rainfall and sub-irrigation, respectively.

The water table declined faster for the plots with drainage. The water table for CDSI was held around 1.2 m by means of sub-irrigation started on 10 July. The maximum sub-irrigation rate achieved was 9 mm/d using a head of 0.5-m of water (i.e. difference between the water table at mid drain spacing and the water level in the control structure). As the water table rose, the height of the control structure did not allow for a larger head, thus limiting the ability of the system to raise the water table and achieve the design depth of 0.75 m. In order to reach this depth, a larger rate should be applied to offset the daily ET and cause a net raise of the water table. Despite the higher water table in the CDSI treatment, the two treatments with overhead irrigation had the highest yields probably because of the water applied above the ground surface was readily available for plant uptake. These results indicated that the water table depth alone is not the determining factor for better crop performance. Rather, a proper soil moisture status at critical stages of development must be the driving force for better yield. The quick response of the water table for NDIR and FDIR to the rainfall on 1 September is an indication that the soil was moist enough. Such response was not observed for NDNI or CDSI.

As in 2010, the ANOVA did not show any statistically significant difference in water table depth among treatments ($P>0.05$), despite the differences between averages being larger than in 2010. The average water table depth for the NDNI, NDIR, FDIR, and CDSI treatments in 2011 were 1.42, 1.41, 1.46, and 1.28 m, respectively. The difference between CDSI and NDNI (i.e. control) was around 0.15 m, arising from the drier season from July onwards, which led to the depletion of the water table by the plants, and from the extended sub-irrigated period. However, this difference was not enough to improve yields, as discussed on previous sessions.

As stated in the discussion about yield, lateral movement of water from the tiles could be a limiting factor for sub-irrigation. Figure 4.6 shows the difference in water table depth between the well close to the tile and the well at mid-spacing between tiles for 2010 and 2011 during the sub-irrigation period. In 2010, the horizontal hydraulic conductivity did not seem to hinder lateral movement of sub-irrigation as the water table at mid-spacing closely resembles the water table variation at the tile. This behaviour was likely due to the wet season, where wet soils facilitated water movement in the soil profile and, consequently, the water table rise by sub-irrigation. In that year, the maximum average difference between the wells at the tile and at mid spacing was 0.22 m. In 2011, the correlation between the water tables at the two wells was not observed. The water table at the well close to the tile rose more than that at the mid-space well; large variations close to the tiles caused small variations at mid-spacing. The maximum water table difference of 0.32 m was observed in 2011. This difference indicates that the soil horizontal hydraulic conductivity seems hinder the movement of water to the zone between tiles in dry years. Despite these differences, the analysis of variance did not show any statistically significant difference between the water table at the tile and at mid spacing in 2010 or 2011 ($P>0.05$).

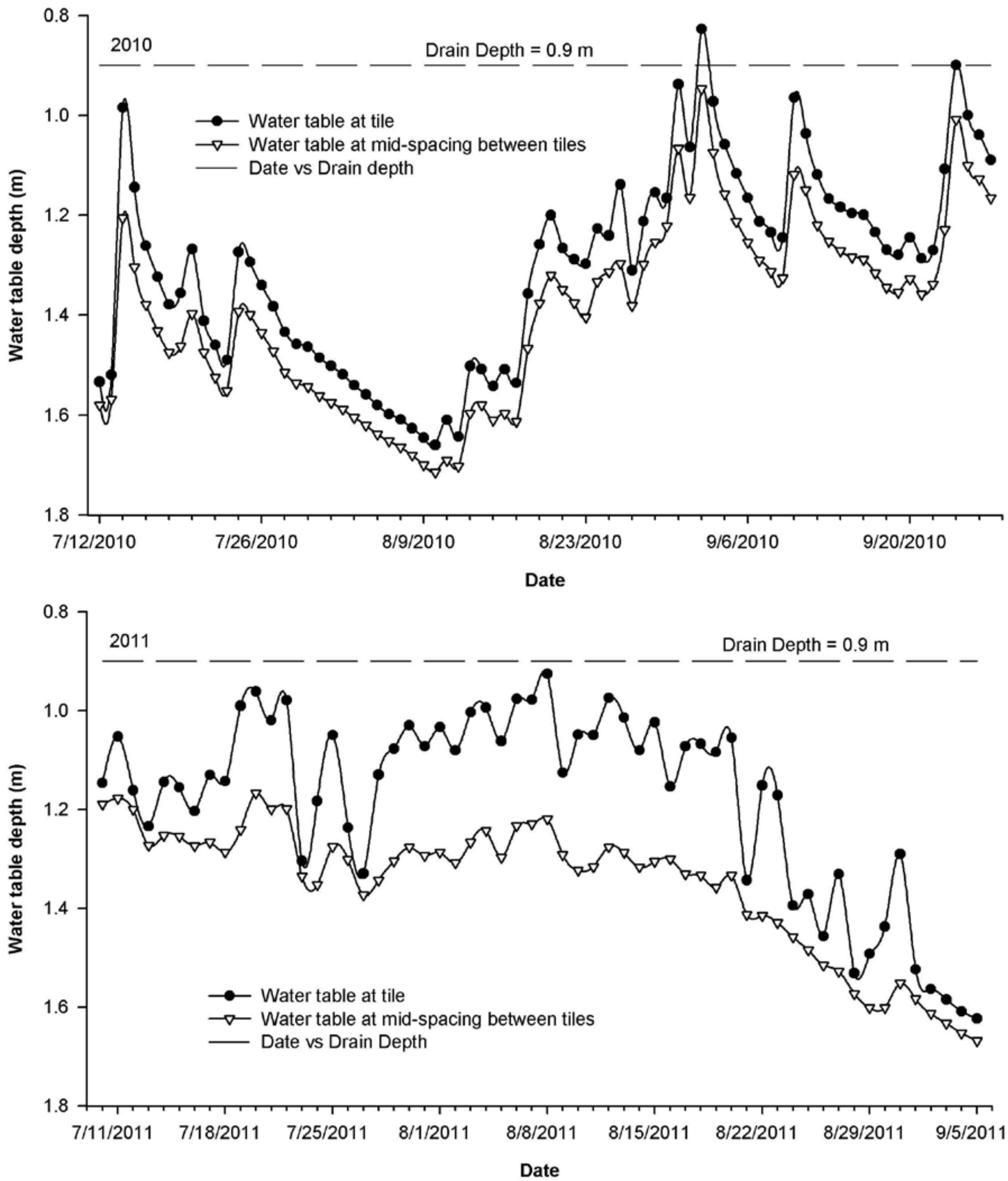

Figure 4.6. Water table variation at the tile and at mid-spacing between tiles during the sub-irrigated period (average of 3 replicates).

4.4.3 *Soil salinity*

The impact of soil salinity was also considered when assessing crop performance. Increased soil salinity causes higher osmotic potential, which can reduce ET by increasing plant water stress, thus leading to decreased corn yield (Hanks et al., 1976). However, the values of electrical conductivity (EC) obtained from the plots for both years were consistently lower than 1.3 dS m^{-1}(data not presented), which is below the threshold of 1.8 dS m^{-1} for yield losses in corn (Maas, 1990).

4.5 Summary and Conclusion

The impact of four irrigation/drainage treatments on corn yield was tested in this study: non-irrigated, non-drained (NDNI), overhead irrigated with no drainage (NDIR), overhead irrigated with free drainage (FDIR), and controlled drainage with sub-irrigation (CDSI). The results showed there were no statistically significant differences for the irrigation/drainage treatments for both years except for NDIR and CDSI in 2010. The NDIR treatment performed better than treatments with subsurface drainage in 2010 probably due to wet conditions. During the 2010 growing season, precipitation was 75% above average corresponding to an additional 257 mm. The FDIR treatment performed better in 2011, followed by NDIR. The overhead irrigation proved to be efficient in increasing corn yields due to the dry conditions prevailing during the second half of the growing season, with precipitation below average in July (15%) and August (12%). Subsurface drainage may have had a beneficial impact at the beginning of the season, increasing FDIR yields when compared to NDIR. The yield from the CDSI treatment could have been compromised due to the limited ability of the soil to transmit water upwards to the root zone under dry conditions.

5. DRAINMOD SIMULATION OF CORN YIELD UNDER DIFFERENT TILE DRAIN SPACING IN THE CANADIAN PRAIRIES

5.1 Abstract

The validation of agricultural system models using field research is an essential step to make a significant impact on agriculture. However, the use of modeling in an agricultural context under cold climates is challenging because of processes such as freezing, thawing, and snowmelt, which have significant effects on field hydrology. DRAINMOD, one of the most widely used models for design and performance evaluation of drainage systems, has been modified and tested for cold conditions. The objectives of this research were to validate DRAINMOD simulations of water table depth and drainage outflow under conditions prevailing in the Canadian Prairies and to use this model to evaluate the design criteria usually adopted in Manitoba. The data set from one year was used to calibrate the model and the water table depth and drainage outflow simulated using two additional years of data were used to validate. The validation was considered good, based on statistical assessment using the Nash–Sutcliffe modeling efficiency coefficient (EF), the normalized percent error (NPE), and the mean absolute error (MAE). Evaluation of drainage designs suggested for Manitoba, Canada, using a three-year dataset consisting of a wet, a mixed, and a dry year, indicated that the design criteria generally adopted in this province (i.e. 0.9-m depth and 15-m spacing) should not be widely adopted across different soil types. For the sandy loam soils used in this study, a maximum drain spacing of 40 m could be used without significant yield losses. Relative yields were found to be more sensitive to excess moisture conditions at the beginning of the growing season.

5.2 Introduction

Recent water management studies in Manitoba have shown the impact of irrigation and drainage systems on crop yields under weather conditions in the Canadian Prairies (Cordeiro and Sri Ranjan, 2012; Satchithanantham et al., 2012). These studies report valuable information about the performance of agricultural crops under different water management strategies such as overhead irrigation, sub-irrigation, free drainage, and controlled drainage. The importance of these studies is accentuated by the scarcity of research findings on water management in the Canadian Prairies' context (Farming for Tomorrow, 2011). Although the installation of subsurface drains has boomed in the past four years, the results have been mixed due to the non-optimal installation depth, incorrect slope, and inappropriate selection of the type of tile (Manitoba Co-Operator, 2013). This may be due to lack of area-specific drainage research information and high cost of commercial installation leading the farmers to do it themselves. Also, the large farm size makes it attractive to invest in drainage installation equipment without paying much attention to proper design aspects. The Soil Management Guide of Manitoba (MAFRI, 2013a) recommends general installation depths and drain spacings for the Province. Installation depths between 0.9 and 1.05 m are recommended to address wetness issues, and are adopted by most contractors and farmers. The drain spacing generally recommended for Manitoba is between 12 and 15 m, but it can be as large as 90 m for sandy loam soils. However, a generalized drain spacing of 15 m (i.e. 50 ft) seems to be adopted in most installations without attention being paid to the hydraulic properties and physiographic features of the field. Moreover, a trained professional, i.e. a drainage engineer, is rarely consulted in the design of these systems due to lack of appreciation of the complexity of the drainage design process.

Irrigation and drainage research in the Canadian Prairies is necessary for compiling agronomic and hydrologic datasets for computer modeling of agricultural systems specific to this area. The integration of agricultural system models and field research is an essential step to make a significant impact on agriculture. Ahuja et al. (2002) reported that system models are able to incorporate, in a single platform, individual processes of the agricultural environment such as water infiltration and redistribution, soil hydraulic properties, tile drainage, solute transport, plant-soil interactions (e.g. evapotranspiration), root growth, and soil nutrient dynamics. Among the benefits arising from this integration are: i) promotion of a systematic approach to field research, ii) better understanding and quantification of research results, iii) quick and accurate transfer of results to soil, weather, crop, and management conditions other than those used in the field research; iv) identification of fundamental knowledge gaps, and v) validation of models for other potential users (Ahuja et al., 2002).

The large number of specialized publications in the scientific literature reflects the importance of agricultural systems modeling. For example, the American Society of Agricultural and Biological Engineers, in a special collection of its Transactions, dedicated 22 research articles to hydrological and water quality modeling (Moriasi et al., 2012). These articles, written by model developers, discuss calibration and validation guidelines, which aim to: i) clearly define the model applicability, ii) document modeling studies, iii) improve assessment and comparison of different models, iv) define a consistent basis for assigning typical parameters and ranges for use in manual or automatic calibration and uncertainty analyses for a given model, and v) provide a knowledge platform to capture the recommendations from experienced model developers or users. Among the models presented in this collection are some of the most commonly used to simulate hydrological impacts of irrigation and drainage, such as DRAINMOD (Skaggs et. al., 2012), HYDRUS (Šimůnek et al., 2012), Root Zone Water Quality Model (RZWQM2) (Ma et al., 2012), and Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012).

Despite the number of models available, the application of hydrological modeling in an agricultural context under cold climates is challenging because of processes such as freezing, thawing, and snowmelt, which have significant effects on field hydrology (Dayyani et al., 2009). Thus, the use of models under these conditions usually requires modifications. The DRAINMOD has been modified and tested for cold conditions (Luo et al., 2000; Luo et al., 2001), and is one of the most widely used models for design and performance evaluation of drainage systems (Hassanpour et al., 2011). In fact, this model has been used in humid parts of Canada such as Quebec (Dayyani et al., 2010) and Ontario (Singh et al., 1994), but the authors are unaware of any modeling exercises using DRAINMOD in the Provinces (i.e. Manitoba, Saskatchewan, and Alberta) located in the Canadian Prairies.

The objectives of this research were to test the accuracy of DRAINMOD simulations of water table and drainage outflow under conditions prevailing in the Canadian Prairies, and to use this model to assess the design criteria usually adopted by contractors in Manitoba in terms of impact on corn yield. The DRAINMOD calibration and validation were graphically and statistically evaluated. Simulated relative yields using different subsurface drainage design criteria were compared to actual yields.

5.3 Material and Methods

5.3.1 Calibration and validation dataset

The agronomic and hydrologic datasets used in this study were obtained from the field research on water management in Manitoba, Canada, described by Cordeiro and Sri Ranjan (2012). The treatment with free-drainage and overhead irrigation of corn was used for this modeling exercise, which consisted of triplicate plots of 44 m X 50 m having 15-m drain spacing installed at 0.9-m depth. The drainage system had, by design, a drainage coefficient of 6 mm d^{-1} and an installation slope of 0.05%. The impermeable layer was located 6 m below the ground surface. Water table and drainage outflow data from the 2010-growing season was used for calibration and the data from 2011 and 2012 growing seasons were use for validation. The water table at midpoint between drains was used as the reference (Skaggs et al., 2005).

5.3.2 DRAINMOD project settings

In the DRAINMOD model, the hydrology project type was selected for this study. Simulations included the soil temperature option that accounts for the freeze and thaw processes. The crop yield option was also selected in order to investigate the effect of different subsurface drainage designs on relative corn yield. Potential evapotranspiration (PET) was calculated by DRAINMOD using the weather data from the field (Skaggs et. al., 2012). Conventional drainage was selected under the subsurface water management options.

5.3.3 DRAINMOD input files – Hydrology, Soil, Weather, and Crops

The DRAINMOD model needs, as a minimum, three major categories of input files to run simulations, i.e. hydrology, soil, and weather files. The model simulations can be run without specifying a crop file, where the crop parameters are entered in the input data section. In the present study, files were created for all the input file categories (i.e. hydrology, soil, weather, and crops). The general file (i.e. file with .GEN extension) in the hydrology category was created from existing example files in DRAINMOD, using the procedures described in the help section of the model. No runoff file was used in the simulations.

The soil file (i.e. file with .SIN extension) and the soil-water characteristic file (i.e. file with .MIS extension), within the soil category, were created using a procedure similar to that used by Singh et al. (2006). In this procedure, the soil utility program in DRAINMOD uses soil hydraulic parameters to define the relationships between water table depth versus volume drained, water table depth versus upward flux, and Green–Ampt parameters used to predict infiltration. The soil hydraulic parameters required are saturated water content θ_s ($cm^3\ cm^{-3}$), residual water content θ_r ($cm^3\ cm^{-3}$), curve parameter α (cm^{-1}), curve shape parameter n (dimensionless), matching point at saturation K_0 (cm day^{-1}), tortuosity/connectivity parameter L (dimensionless), and saturated hydraulic conductivity K_{sat} (cm day^{-1}). The initial values of the parameters were obtained from the Rosetta Model (Schaap et al., 2001) using textural class information (i.e. sand, silt, and clay percent content), soil bulk density (g cm^{-3}), and water content at 33 kPa ($cm^3\ cm^{-3}$). Bulk density and field capacity (assumed to be the water content at 33 kPa) were measured using a methodology adapted from Mkhabela and Bullock (2012) for three different random locations in the field at 0.15, 0.30, 0.60, 0.90, and 1.2 m depths. Soil samples for textural analysis were collected at the same depths and six different random locations. Averages of the soil parameters collected in the random locations were used as field values for each depth sampled (Table 5.1). This information was then used as input in the Rosetta Model.

Table 5.1. Soil parameters used as input in the Rosetta model for calculation of soil hydraulic parameters.

	Textural Analysis (%)				
Depth (m)	Sand	Silt	Clay	Bulk Density (g cm^{-3})	Field Capacity (cm^3 cm^{-3})
0.15	71	19	10	1.12	0.32
0.3	70	20	10	1.35	0.32
0.6	69	19	12	1.54	0.32
0.9	71	18	11	1.50	0.30
1.2	62	26	12	1.41	0.30

In the weather category, the hourly rainfall file (i.e. file with .RAI extension) and temperature file (i.e. file with .TEM extension) were created using the weather file utility in DRAINMOD. The required weather parameters (i.e. hourly precipitation, and maximum and minimum daily air temperatures) were obtained from the MAFRI Ag Weather Program (MAFRI, 2013b), which has a weather station 1.4 km east of the research site. The irrigation events, which took place over four hours of continuous application, were inserted as rainfall in the hourly rainfall data.

The crop file (i.e. file with .CIN extension) was created by editing an existing crop file within the DRAINMOD model. Even though the template crop window covered the entire year, in the present study, the growing season started on 7 May [day-of-year (DOY) 127 for desired planting date] and extended over 167 growing days. The last day of year to plant without yield loss was 7 May (MASC, 2013). A maximum root depth of 0.6 m and a lower limit of water content in the root zone of 0.12 $cm^3\ cm^{-3}$ were used.

5.3.4 DRAINMOD input parameters

The main input parameters required in the input data section of the model are presented in Table 5.2. The drainage coefficient used in DRAINMOD is defined as the hydraulic capacity of the system, which depends on parameters such as size, slope, and hydraulic roughness of the mainline (Skaggs et al., 2012). The maximum capacity of the mainline was calculated using the Manning's equation and imported into the model to be used as the drainage coefficient in the simulations. Most of the soil water relationships required by the DRAINMOD were calculated by it using the hydraulic parameters obtained from the Rosetta Model. The evapotranspiration (ET) monthly factors used in the weather section were 1.2 from October to February, 0.4 for March and April, 0.7 for May, 0.9 for June, 0.95 for July, and 1.0 for August and September. These factors are similar to those presented by Sands et al. (2003) for DRAINMOD simulations under cold climate conditions. The crops section was populated using the information contained in the crop input file, described above.

Table 5.2. Main input parameters specified for DRAINMOD simulations. Units were kept consistent with DRAINMOD input variables.

Parameter	Value	Unit
Drainage System		
Drain depth	96	cm
Drain spacing	1,500	cm
Effective radius of drain	0.51	cm
Depth to impermeable layer	600	cm
Drainage coefficient	1	cm d^{-1}
Maximum surface storage	2.5	cm
Kirkham’s depth for flow to drains	0.5	cm
Soil†		
Lateral saturated hydraulic conductivity (all five layers)	5	cm h^{-1}
Thermal conductivity function coefficient a	0.5	W m^{-1} °C
Thermal conductivity function coefficient b	1.5	W m^{-1} °C
Air temperature below which precipitation is snow‡	0	°C
Air temperature above which snow begins to melt‡	2	°C
Snowmelt coefficient	5	mm d^{-1} °C
Critical ice content above which infiltration stops	0.25	cm^3 cm^{-3}

† Most of the soil information required in the soil section of the model was calculated by DRAINMOD using the soil input files and is not shown in this table.

‡ Based on values presented by Luo et al. (2010) for Minnesota.

5.3.5 DRAINMOD calibration

In order to simplify the calibration process, the soil parameters calculated by Rosetta model for the five soil depths sampled were combined into two layers for modeling. The first soil layer went from soil surface to 0.4-m depth and represented the soil stratum most affected by farm operations. The second soil layer went from 0.4- to 2.5-m depth and represented the more stable soil stratum. The parameters θ_r, θ_s, n, K_0, and L were kept the same for both layers (Table 5.3). They were derived from the Rosetta output and were comparable to the class-average values for sandy loam USDA textural class (Schaap, 1999). The primary parameters used for calibration were α, n, and K_{sat}. These values were calibrated and validated using water table and drainage outflow data. The calibrated value of K_{sat} is within the range of the values observed in the field measurements (Whetter and Saurette, 2008). Calibration was done using the 2010 growing season dataset, while the 2011 and 2012 growing season data were used for validation.

The accuracy of DRAINMOD simulations during the calibration and validation process was assessed by statistically comparing observed and simulated drainage outflow volumes and water table depths (Youssef et al., 2006). For drainage volumes, the statistical performance measures used were the normalized percent error (NPE) and the Nash–Sutcliffe modeling efficiency coefficient (EF); for water table depth, the statistical performance measures used were the mean absolute error (MAE) and EF (Van Liew and Garbrecht, 2003; Youssef et al., 2006). Drainage outflow and water table simulations were classified as acceptable, good, excellent based on the NPE, MAE, and EF values presented by Skaggs et al. (2012).

Table 5.3. Soil hydraulic parameters after model calibration.

Parameter	Value	Unit
Saturated water content θs	0.39	$cm^3\ cm^{-3}$
Residual water content θr	0.039	$cm^3\ cm^{-3}$
Curve shape parameter n†	1.75	–
Matching point at saturation K_0	2.92778	$cm\ day^{-1}$
Tortuosity/connectivity parameter L	-0.83187	–
Curve parameter α†		
Layer 1	0.014	cm^{-1}
Layer 2	0.012	cm^{-1}
Saturated hydraulic conductivity Ksat †		
Layer 1	150	$cm\ day^{-1}$
Layer 2	60	$cm\ day^{-1}$

† Calibrated parameter.

5.3.6 Assessment of drainage design impact on relative corn yield

In order to assess the impact of different drainage designs on corn yield, the calibrated model was used to simulate the relative corn yield for different drain spacings. The depth and spacing generally adopted in Manitoba (i.e. 0.9 m deep and 15 m wide; MAFRI, 2013a) was used as the initial design. Drainage depth in the simulated scenarios was kept constant at 0.9 m because this depth has been widely adopted in recent installations. The increased cost of installing drains at deeper depths (King and Willardson, 2007) and the reduced excavation required for connections are likely among the reasons contributing to the adoption of this drainage base depth. On the other hand, simulations of depths shallower than 0.9 m were not conducted because drains are not installed shallower than 0.9 m due to possible interference with farm operations such as deep soil ripping. The simulated drain spacings were 20, 30, 40, 60, and 90 meters. The maximum spacing was based on a recommendation for sandy loam soils having moderately slow to rapid permeability (Beauchamp, 1955). The DRAINMOD simulations were run using weather data from 2010 to 2012. The first year represents a wet year; in which growing season was around 60% wetter than the long-term average (Cordeiro and Sri Ranjan, 2012). The second year represents a mixed year, which started wet and became dry after June (MASC, 2012), while the last year was a dry year from the start of the growing season (MAFRI, 2012). The relative yield calculated by DRAINMOD was used to assess the impact of drainage design on corn yield. The impact of excess moisture stress was the focus during the analysis.

5.4 Results and Discussion

5.4.1 DRAINMOD calibration and validation

The 2010 growing season was used for the calibration of the DRAINMOD model. The drainage outflow dataset spanned from 30 April to 31 August. However, for water table, the dataset only spanned from 28 May to 31 August due to delays in equipment acquisition, which led to a delay in when the monitoring began. The graphical comparison of observed versus predicted values of water table and drainage outflow in 2010 is shown in figure 5.1. For the water table, DRAINMOD was able to closely reproduce the water table depth over the growing season, but the values were generally underestimated. The observed and predicted values of water table simulations were very similar soon after the beginning of the monitoring period, but the observed water table depth increased more rapidly compared to the DRAINMOD simulation. The average observed water table depth for the period was 135 cm, while the simulated average depth was 121 cm. Despite this difference, simulations seemed to be acceptable based on the trend of the variation in water table depth. The statistical assessment of the simulation also deemed the results acceptable. The values of the model efficiency (EF) and the mean absolute error (MAE) were 0.54 and 14.5 cm, respectively. According to Skaggs et al. (2012), daily water table simulations are acceptable for EF > 0.4, good for EF > 0.6, and excellent for EF > 0.75; while simulations are acceptable for MAE < 20 cm, good for MAE < 15 cm, and excellent for MAE < 10 cm.

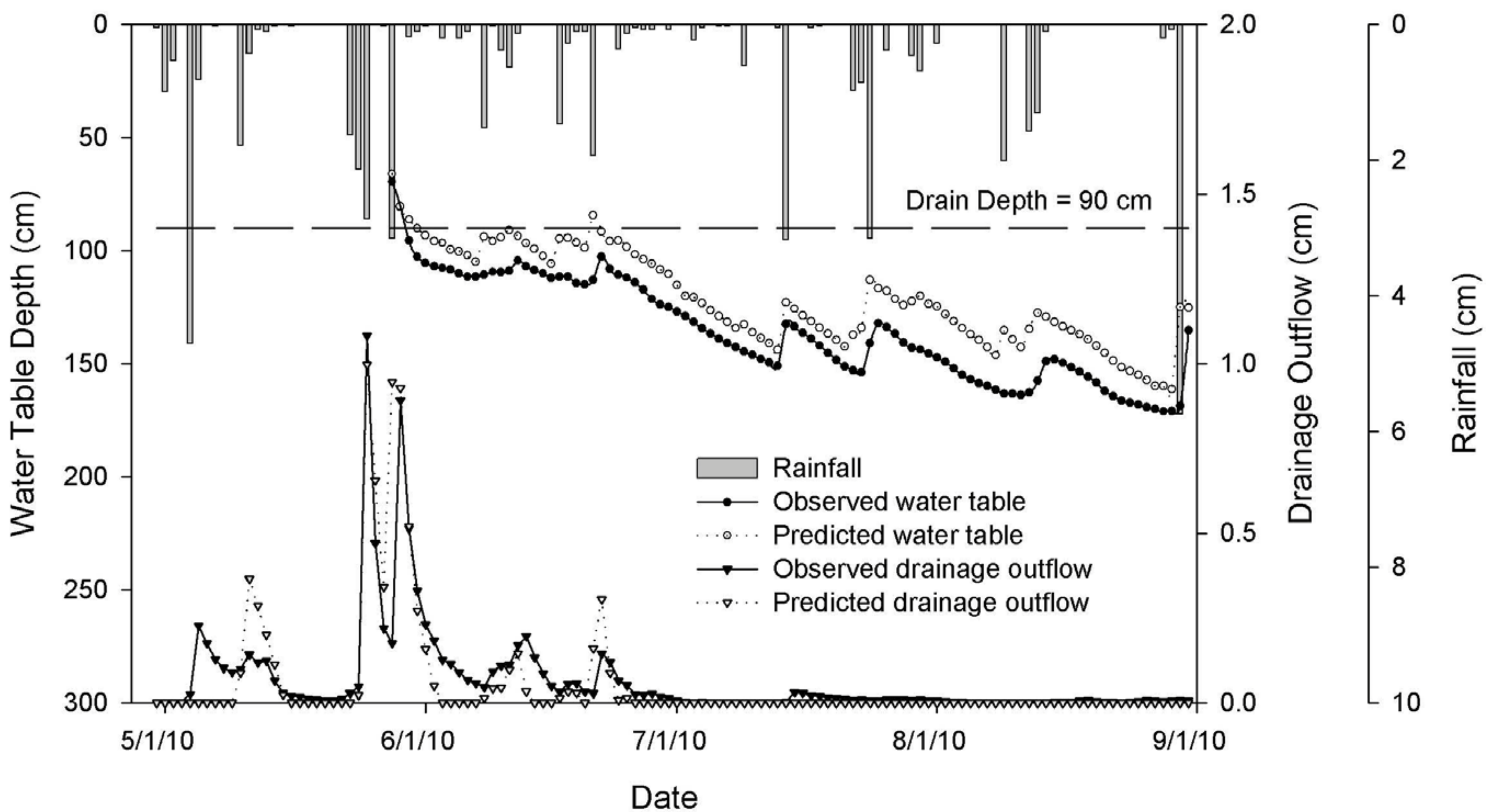

Figure 5.1. Comparison of observed and predicted values of water table and drainage outflow in 2010.

The underestimation of the water table depth by DRAINMOD in 2010 may be due to unaccounted for transient effects in the soil properties caused by the disturbances resulting from the installation of the drainage system, which happened in the fall of 2009. The soft soil in the trench above the drains likely had a larger hydraulic conductivity than that of the surrounding soil, allowing water to drain more quickly at the beginning of the monitoring, when the water table was above the drainage base depth (i.e. 0.9 m). This difference then persisted over the entire growing season. Trying to compensate for this difference during calibration resulted in unrealistic flows because there is a relationship between drainage outflow and water table depth. For example, artificially increasing the water table depth by modifying the parameter α during calibration would automatically decrease the drainage outflow.

The simulation of drainage outflow was better than that of water table depth for 2010. The overall description of the drainage hydrograph closely resembled that observed in the field (fig. 5.1). More noticeable differences occurred in early May and between two large rainfalls in late May. The DRAINMOD predicted a delayed 4.0-cm drainage peak on 11 May, while the drains were running as early as 3 May. The model also predicted flows larger than those observed in late May and late June. Despite these differences, simulations were deemed good for drainage outflow, with EF = 0.65 and the normalized percent error (NPE) = 13.6%, respectively. The EF thresholds for daily drainage volume are the same specified above for daily water table depth, while simulations are acceptable if NPE < 25%, good if NPE < 15%, and excellent if NPE < 5%. (Skaggs et al., 2012).

Luo et al. (2010) used DRAINMOD to simulate cold climate conditions and observed over- and under-estimation of flow simulations during the spring snowmelt period. They acknowledged that the model predicted some snowmelt during periods when the air temperature was above 0°C, but below-zero soil temperature prevented infiltration and subsurface drainage from occurring in the model simulations. This model behaviour illustrates the complex relationship between soil, temperature, and drainage outflow, which makes the springtime model simulations more difficult. Mellander et al. (2007), quoting different sources, explain that snow strongly influences below-ground temperatures during the winter due to its insulating properties, and the extent and duration of snow cover strongly influence the timing and rapidity of soil warming in spring. While DRAINMOD does take into consideration the initial snow depth at the beginning of the simulations, it is very difficult to account for random phenomena such as snowdrift or the effect of shelterbelts on snow accumulation and wind action. These processes may influence the depth of the snow pack and, thus, directly influence soil temperature. This is particularly important when the snow depth is defined much earlier than the snowmelt period in the spring. In the present study, a snow depth of 0.1 m was defined on 1 January 2010, and despite the weather data that accounted for snowfall events since then, this depth might have been influenced by snowdrift. With regards to the higher simulated flows during the growing season, it seemed to be due to the shallow water table predictions, as discussed above.

The datasets from the 2011 and 2012 growing seasons were used to validate the DRAINMOD simulations. Inspection of the observed and predicted values of water table for 2011 (fig. 5.2) showed better agreement than that observed in 2010. The average observed water table depth was 145 cm, while the average simulated depth was 142 cm. In 2011, it was wet up to late June, and then it was dry from July until the end of

September (MASC, 2012). In the early part of the season, the simulated water table depth was again underestimated, but the agreement improved from July onwards. In 2011, the predicted and measured flows started about the same time and were found to be very close. Differences in the peak flows were observed on 22 May and 23 June. The DRAINMOD limited the flow during these events, based on the drainage coefficient defined during calibration. Apart from these differences, the water table depth simulation was very good. Both statistical measures deemed water table depth simulation to be excellent, with EF = 0.92 and MAE = 8.2 cm. The drainage outflow simulation was also considered excellent based on the EF = 0.76, while it was considered good based on the NPE = 11.5%.

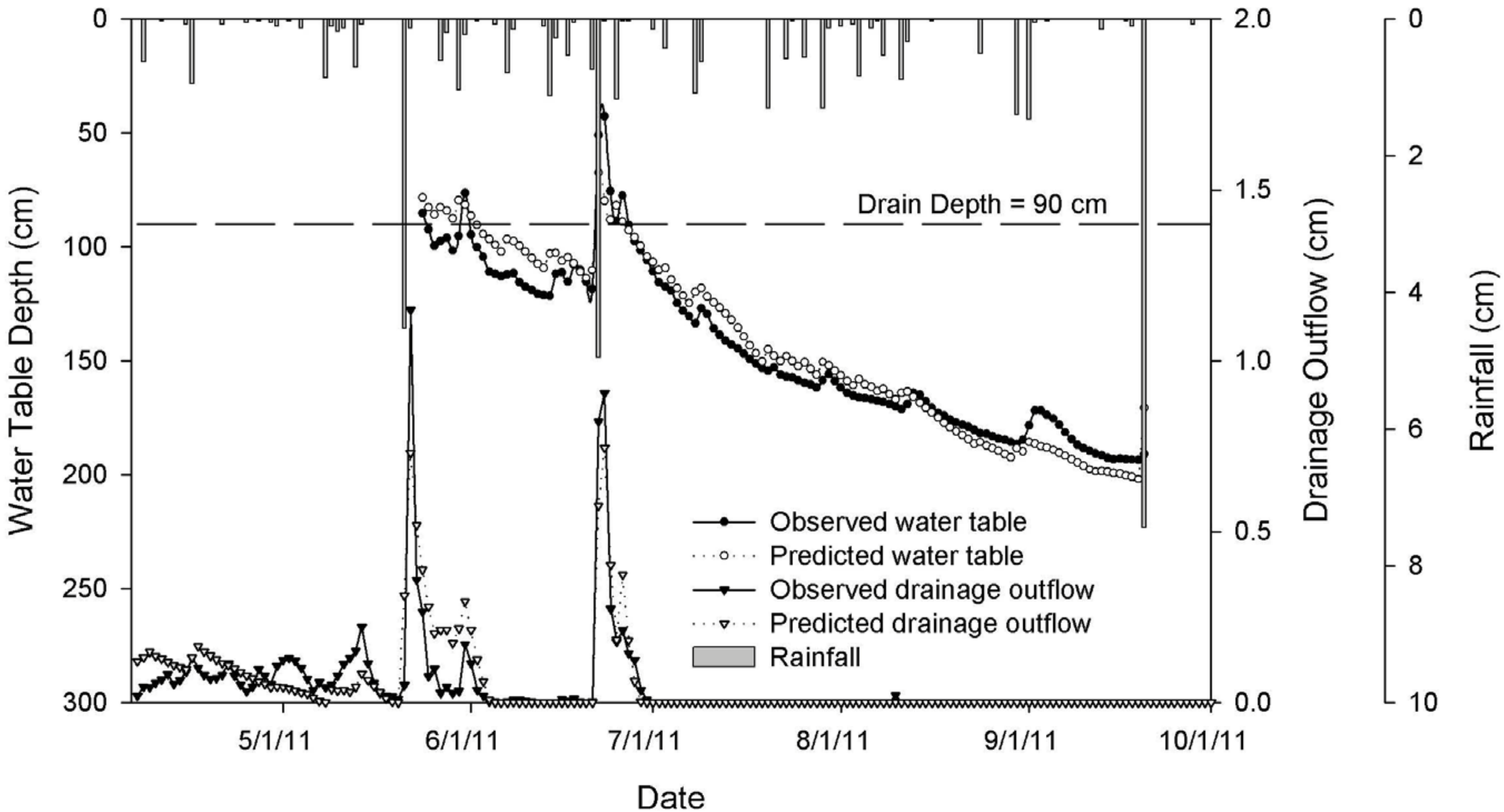

Figure 5.2. Comparison of observed and predicted values of water table and drainage outflow in 2011.

In contrast to 2010 and 2011, 2012 was a drier year since spring (MAFRI, 2012). Drought conditions were also observed in other parts of Canada and the United States (Reddoch and Reddoch, 2012; Al-Kaisi et al., 2013). As a result, there was no drainage flow that year, as shown in fig. 5.3. Factors that contributed to this were i) the water table being around 200 cm during the fall of 2011 (fig. 5.2), ii) the likely low soil moisture due to the dry season after June 2011, iii) the small amount of snow received in the winter of 2012 (Maclean's, 2012), and iv) the reduced precipitation during the spring and summer of 2012. Figure 5.3 shows that the water table depth was 150 cm at the end of April, which contrasts with much shallower depths during the later months of the 2010 and 2011 growing seasons (figs.5.1 and 5.2). The average observed water table depth for the period was 171 cm, while the simulated average depth was 176 cm. The DRAINMOD was able to satisfactorily predict water table depth and variation over the course of the growing season. Since EF was 0.81 and MAE was 7.1 cm, simulations were considered excellent.

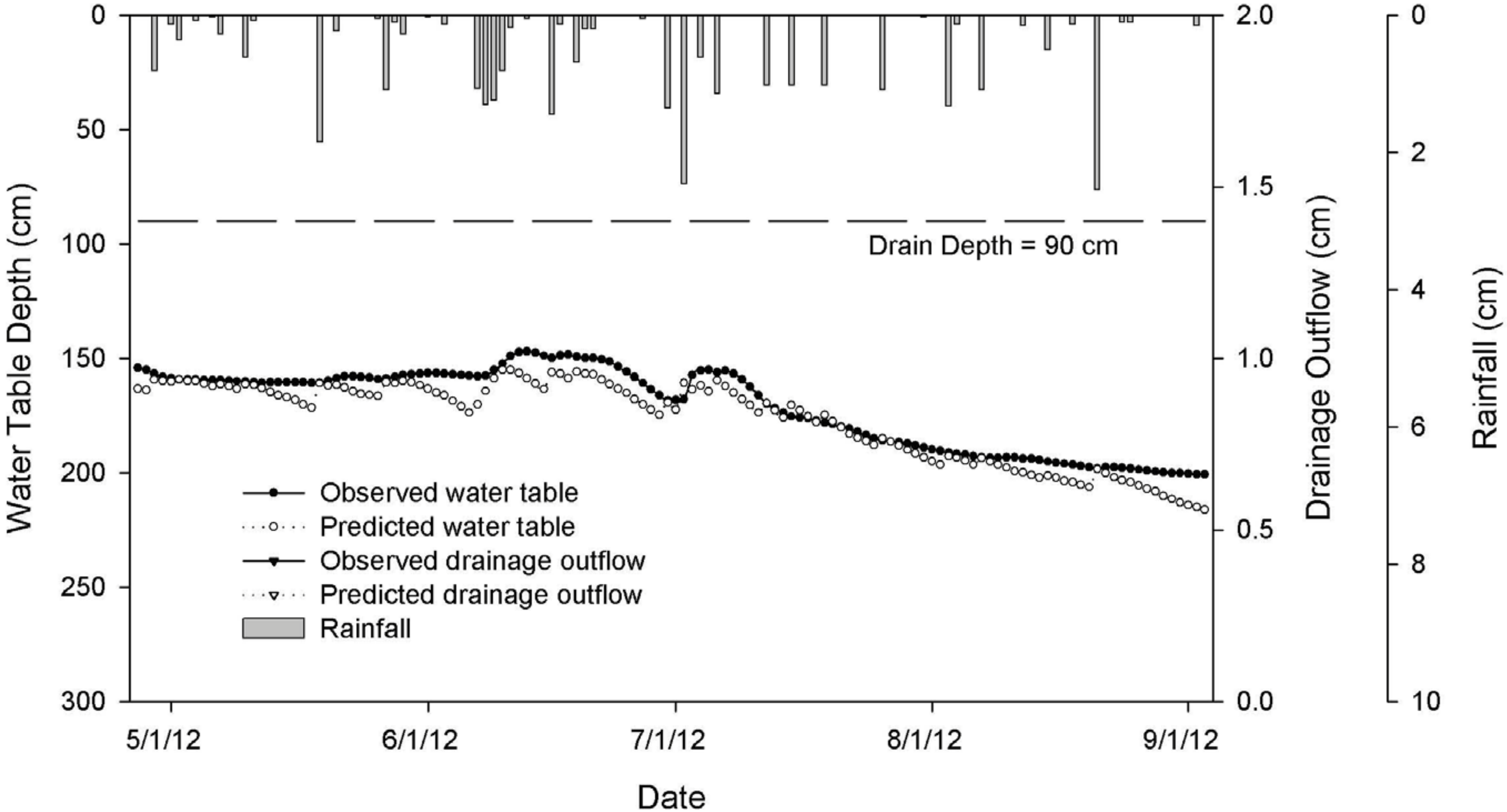

Figure 5.3. Comparison of observed and predicted values of water table and drainage outflow in 2012.

5.4.2 *Impact of drainage designs on relative corn yield*

Given the good results obtained from the calibration and validation of DRAINMOD, the calibrated model was used to simulate alternative drainage design scenarios that would not impact corn yields negatively. The initial design used during the model calibration (i.e. 0.96 m depth and 15 m spacing) indicated that moisture stress did not cause any yield reduction. In fact, corn yields in 2010 were consistently higher than Manitoba's ten-year average and Manitoba's 2010 yield for the corn variety planted (Cordeiro and Sri Ranjan, 2012). Modifying the drainage depth to 0.9 m and increasing the drainage spacing to 20 and 30 meters did not have an impact on yields for any year (fig. 5.4). However, increasing the drain spacing to 40 m had a small effect, where relative yields for 2010 and 2011 were decreased by 0.8% and 0.3%, respectively. These results suggest 40 m as a threshold for drain spacing, beyond which yields will start to decrease. It also indicates that the drain depth and spacing currently practiced in Manitoba may cause over-draining, at least for sandy soils. Doty et al. (1984) state that when sandy soils are drained too rapidly or too deeply, drought stress will develop unless it rains again within 4 to 7 days. Thus, rapid draining will cause the water table to be lowered quickly, possibly creating a water deficit later in the growing season.

It is important to note that 2010 was a wet year throughout and 2011started wet and became dry as the season progressed; however, the relative yields were quite similar. These results imply that corn is more sensitive to the negative impacts of excess moisture at its early stages. Kanwar et al. (1988), reviewing the early literature about the effect of excess moisture on corn at early stages, state that maximum crop damage is observed when excess moisture occurred at the early stages of growth. According to Kanwar et al.

(1988), the duration and timing of wet conditions in relation to the stage of crop development have considerable effect on yield. For example, high water tables during the seedling stage can be fatal, whereas a well developed corn crop is likely to suffer relatively little damage from similar conditions.

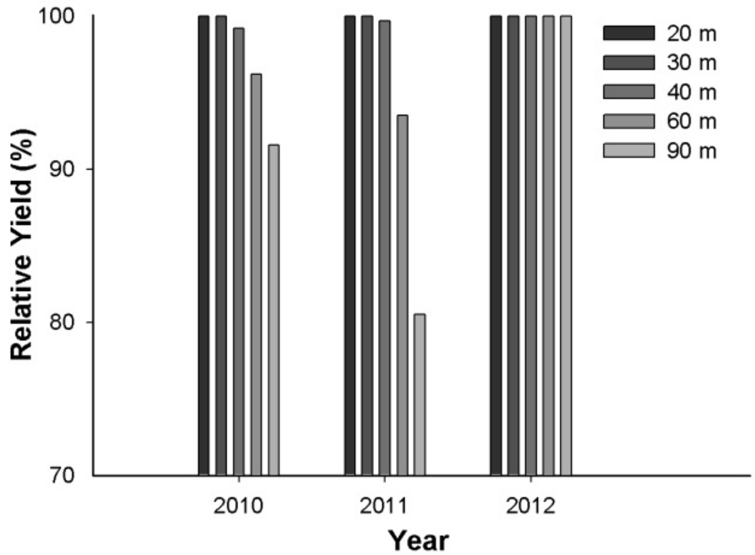

Figure 5.4. Relative yields from 2010 to 2012 growing seasons calculated by DRAINMOD for drain spacing varying from 20 to 90 m, while the drainage base depth was kept constant at 0.9 m.

Further increases in drain spacing to 60 m would cause a yield reduction of 3.8% in 2010 and 6.5% in 2011. The larger yield reduction in 2011 indicated that, despite that being a mixed year, the wet stress during the spring had a more severe consequence than that in 2010. This aspect was confirmed by the delay in the planting date in 2011 (16 May) when compared to 2010 (28 April; Cordeiro and Sri Ranjan, 2012). When the drain spacing was increased to 90 m, the relative yields were 91.6% in 2010 and 80.5% in 2011. The relative yields observed in the non-drained treatment when compared to the drained treatment during the field experiment in 2010 and 2011 were 83% and 82%, respectively (Cordeiro and Sri Ranjan, 2012). Although the overhead irrigation had an effect on the performance of the drained treatment, it was observed that drainage had a beneficial impact at the beginning of the season. The similarity between the simulated relative yields at 90-m drain spacing and that observed for the non-drained treatment (especially in 2011) suggest that the 90-m spacing does not have a beneficial effect on the agronomic performance of corn.

5.5 Conclusion

The assessment of DRAINMOD simulations using statistical methods confirmed the usefulness of this model to simulate water table depth variation and drainage outflow during the growing season under conditions prevailing in the Canadian Prairies. Divergences between predicted and observed values of water table were likely caused by soil disturbances during the installation of the subsurface drains, indicating that collection of datasets for model calibration shortly after drain installation should be avoided. Simulations in the second year after installation seem to indicate that a two-year time needs to elapse before data is collected for modeling. Testing of different drainage designs using the calibrated model indicated that the generally recommended design criteria for Manitoba (i.e. 0.9-m deep and 15-m wide), which is widely adopted by contractors in the Province, is not appropriate for all soil conditions. For the soil simulated, a maximum drain spacing of 40 m could be used without considerable negative impacts on yield. On the contrary, it could cause excessive drainage of the soil, which may result in crop water stress during periods of high water demand. The drain spacing of 90 m based on soil textural class was not found to be appropriate as the relative yields were comparable to the non-drained soils. Simulations of relative yield indicated that duration and timing of the wet conditions in relation to the stage of crop development have considerable effect on yield, and that excess moisture at early stages has the most detrimental effect on yields.

6. NITRATE, PHOSPHORUS, AND SALT EXPORT THROUGH SUBSURFACE DRAINAGE FROM CORN FIELDS IN THE CANADIAN PRAIRIES

6.1 Abstract

High fertilizer inputs and uncontrolled subsurface drainage can result in the export of nutrients from the farmland leading to negative environmental impacts. Controlled drainage can be an effective best management practice to minimize the export of nutrients. However, information about controlled drainage in the Canadian Prairies is scarce. The objective of this study was to compare free drainage with overhead irrigation (FDIR) to controlled drainage with sub-irrigation (CDSI) in terms of nitrogen, phosphorus, and salt export from corn fields in the Canadian Prairies. The low concentrations of nitrate (≤ 0.2 mg L-1) and orthophosphate (< 0.1 mg L 1), and the low electrical conductivity (0.55 dS m-1) of the irrigation water were assumed not to influence the input to or export of nutrients and salts. In 2010, the export of NO3-N (138 kg ha-1), PO4-P (0.6 kg ha-1) and salts (2.34 Mg ha-1) from the FDIR treatment during the growing season were significantly larger ($p <0.05$) than exports from CDSI, which were 0.07 kg ha-1, 0.08 kg ha-1, and 0.41 Mg ha-1, respectively. This comparison did not include the drainage outflow arising from spring snowmelt due to delays in the installation of monitoring equipment. However, in 2011, which included the drainage outflow due to spring snowmelt events, the exports of NO3-N (36 kg ha-1), PO4-P (0.27 kg ha-1), and salts (1.1 Mg ha-1) from FDIR were significantly larger ($p < 0.05$) than the exports from CDSI which were 10 kg ha-1, 0.08 kg ha-1, and 0.39 Mg ha-1, respectively. Therefore, controlled drainage with subirrigation (CDSI) showed significant reductions in

export of NO3-N (71%), PO4-P (69%), and salts (64%) compared to the free drainage with overhead irrigation (FDIR). This study shows the advantage of controlled drainage over free drainage in reducing the nutrients and salt exports.

6.2 Introduction

Increasing grain yields in recent decades has been attributed to intensive agricultural production systems dependent on fertilizer input for primary nutrient needs and supplemental irrigation (Tilman et al., 2002). The application of nitrogen and phosphorus fertilizers has steadily increased since the 1960s, a trend that will likely continue due to the large demand for grains projected for 2050 (Tilman et al., 2002). This demand will be driven by an increase in per capita real income leading to a dietary shift towards a higher proportion of meat produced by grain-fed livestock. Recent global estimates for 2012-2013 forecasted a cereal production of 2.3 billion tons, while the estimated utilization is larger than production, reaching 2.33 billion tons (FAO, 2013). The total fertilizer nutrient (i.e. nitrogen, phosphorus, and potassium) consumption in 2011 was estimated to be 175.7 million tonnes and is expected to reach 190.4 million tonnes by 2015 (FAO, 2011). This increasing trend in fertilizer use has been observed since 2009 (FAO, 2011), with a forecasted annual average increase in global fertilizer demand by 2.1% annually until 2017 (Heffer and Prud'homme, 2012). The source of nutrients applied as fertilizers, however, varies geographically (Potter et al., 2010). Mineral fertilizers are largely used in the Northern hemisphere, including the central United States, Canada, much of Europe and China, and parts of Southeast Asia. Manure is more utilized in South America and Africa, as well as parts of the eastern United States, Eastern Europe, central and southeast Asia, and northeastern Australia.

Fertilizer input to agricultural systems is the largest alteration of the global nitrogen (N) and phosphorus (P) cycles, as these two nutrients are commonly applied beyond agricultural needs (Bouwman et al., 2011). Excessive fertilizer application on agricultural lands often results in pollution of water sources via run off and leaching (Thomas et al., 2007), where the latter is enhanced by artificial subsurface drainage. The widespread negative environmental effects of nutrients from agricultural landscapes across North America and Europe are reported in the literature, which include hypoxia and eutrophication of water bodies (Borah et al., 2006; Cherry et al., 2008).

Uncontrolled drainage has been identified as an agricultural practice that can potentially enhance nutrient mobility due to rapid water removal from farmland (Adeuya et al., 2005). Research has shown that, compared to natural conditions, drainage improvements for agricultural purposes can increase nutrient losses (Skaggs et al., 1994; Sands et al., 2008; Skaggs et al., 2012; Helmers et al., 2012). Additionally, increasing the intensity of drainage has been shown to increase field-scale nutrient losses (Kladivko et al., 1989). Nitrate, which is highly soluble, is closely associated with water movement and easily exported through drainage outflow (Adeuya et al., 2005). Phosphorus is lost from the agricultural landscapes primarily through sediments transported during surface runoff events (Eastman et al., 2010); however, it can have an increased downward movement due to the accumulation and decreased sorption in surface horizons of soils that have been fertilized over a long period of time (Beauchemin et al., 1998). Export of phosphorus in drainage outflow has also been associated with the movement of sediments into subsurface drains (Bottcher et al., 1981).

In order to prevent nutrient export through drainage outflow, better water management strategies for subsurface drainage have been developed. The ability to control the subsurface drainage outflow can help decrease the nutrient export. Controlled drainage (CD) or drainage water management (DWM) can be implemented to reduce drainage volumes and nutrient losses (Skaggs et al., 2010). CD involves the use of a weir or an overflow device to raise the water level at the drainage outlet, which helps to maintain the water table in the soil profile at a user-defined height. It may also include sub-irrigation, in which water is pumped back into the drainage outlet to hold the water table high and supply irrigation water during dry periods directly into the root zone.

Although research has reported extensively on the impact of water management strategies on nutrient export in the United States and humid regions of Canada (Grigg et al. 2003; Skaggs et al., 2010; Tan et al., 2007; Drury et al., 2009), comprehensive studies on subsurface drainage are few and recent in the Canadian Prairies (Cordeiro and Sri Ranjan, 2012; Satchithanantham et al., 2012). Thus, data on the export of nutrients from farmland through subsurface drainage in this region are scarce in the literature. In the Canadian Prairies, nutrient export from agriculture has been reported as the leading cause of eutrophication of lakes (Booty et al., 2011; Page, 2011; Schindler et al., 2012), and a number of best management practices for reducing nutrient export from agricultural land have been tested under the Canadian Prairie conditions (Li et al., 2011). However, these management practices were tested at small watershed-scale and did not include subsurface drainage. Investigation of nutrient exports through the subsurface at field-scale has yet to be carried out.

The objective of this study was to compare free drainage with overhead irrigation (FDIR) to controlled drainage with sub-irrigation (CDSI) in terms of nitrogen, phosphorus, and salt export from cornfields in the Canadian Prairies. Volume flow rates, total exports, and flow-weighted-mean concentrations were used to compare the performance of the treatments.

6.3 Material and Methods

6.3.1 Experiment

The study area was located in Winkler, Manitoba. Cordeiro and Sri Ranjan (2012) report a complete description of the soils, agronomic practices, drainage systems, and monitoring methodology in the field where this study was carried out. They also provide the corn varieties used and the respective planting dates. The soil in the study area is imperfectly drained and has a loamy texture. The textural percentages are 70%, 19%, and 11% for the sand, silt, and clay fractions, respectively. Prior to establishing the research plots of the present research study for assessment of water management strategies, the field was always planted a single crop each year and received uniform agronomic and management practices. The most common crops planted in the recent years were potatoes, corn, canola, and wheat. Drainage volume and its nutrient concentrations were monitored for two treatments in the 2010 and 2011 growing seasons. The first treatment consisted of free drainage with overhead irrigation (FDIR), while the second consisted of controlled drainage with sub-irrigation (CDSI). Corn yields were minimally impacted due to using controlled drainage, with no statistically significant difference between FDIR and CDSI during the two years of experiment (Cordeiro and Sri Ranjan, 2012). Each treatment was replicated in three separate plots in each year, where each replicate of each treatment had its own dedicated drain outlet with a flow-measuring weir that permitted drainage outflow measurement and water sampling. The FDIR treatment consisted of plots of 44 m by 50 m having a drain spacing of 15 m. The CDSI treatment consisted of plots of 40 m by 50 m having a drain spacing of 8 m. The drain tile was installed at 0.9 m depth and 0.05% slope. A drainage coefficient of 6 mm d^{-1} and a depth to the impermeable layer of 6 m were used in the design of the drainage system. The target water table depth in the CDSI treatment was 0.75 m, which was managed by a drainage control structure (Agri Drain Corp., Adair, Iowa) for each replicate. The stoplogs in the control structures of the CDSI treatment were removed around 15 November and the drains were allowed to run dry. The stoplogs were placed back in the control structures around 1 May, after the excess moisture due to snowmelt infiltration was allowed to drain.

Irrigation in the FDIR treatment was applied using a traveling gun, while sub-irrigation in the CDSI treatment was done by pumping water back into the subsurface drains (Cordeiro and Sri Ranjan, 2012). In 2010, which was a wet year with abundant rainfall over the entire growing season, 6 mm and 20 mm of overhead irrigation were applied on 9 July and 9 August, respectively. In 2011, which started wet but became dry after July, overhead irrigation was done on 20 July (13 mm), 29 July (13 mm), 11 August (9 mm), 24 August (5 mm), and 30 August (14 mm), totalling 54 mm applied. For the CDSI treatment, sub-irrigation was applied to keep the water table at the target depth of 0.75 m below the soil surface. A total of 147 and 290 mm were applied through sub-irrigation to the CDSI treatment during the growing seasons in 2010 and 2011, respectively. The water used for irrigation came from the snowmelt runoff, which was pumped into a reservoir during spring and stored for irrigation during the summer. Given the source of the irrigation water, its quality was deemed appropriate for the experiment. The low concentrations of nitrate (≤ 0.2 mg L^{-1}) and orthophosphate (< 0.1 mg L^{-1}), as well as the low electrical conductivity (0.55 dS m^{-1}) of the irrigation water were assumed not to influence the input to or export of nutrients and salts to the plots.

Drainage outflow was sampled from each plot for analysis of nutrients. Samples were collected in 120-ml plastic bottles, kept refrigerated, and taken for analysis. The samples were analyzed for Nitrate-Nitrogen (NO_3-N), orthophosphate (PO_4-P), and electrical conductivity (EC). In 2010, water samples were analyzed for NO_3-N and PO_4-P using a QuickChem 8500 Ion Analyser (Lachat Instruments, Milwaukee, WI, USA). Determination of EC was done using a FieldScout Direct Soil EC Meter (Spectrum Technologies Inc., Aurora, IL, USA). In 2011, the water samples were sent to Agvise Laboratories (Northwood, ND) for analyses using standard methods (Tiessen et al., 2010). The EC measurements were compensated for temperature variations using the reference temperature of 25°C. Fertilizer application by the farmer was the only source of mineral nutrient input to the soil. The application was uniform for all the plots in both years. In 2010, a total of 150 kg N ha^{-1} was applied as urea (46-0-0) and ammonium polyphosphate (10-34-0), while 60 kg P ha^{-1} was applied as ammonium polyphosphate (10-34-0). In 2011, the amounts of N and P fertilizer applied decreased to 122 kg N ha^{-1} and 34 kg P ha^{-1}, respectively. The reduction in fertilizer application in 2011 was due to a reduction in yield goals by the farmer as a result of late planting.

6.3.2 *Calculation of loads and flow-weighted mean concentrations*

The daily nitrate and phosphorus loads in the drainage outflow from FDIR and CDSI treatments for each drainage event was calculated by multiplying the nitrate and orthophosphate concentrations in the drainage outflow (mg L^{-1}) by the daily flow volume. Electrical conductivity was used as a measure of salinity. The salt concentration in the drainage outflow was calculated from the EC using the conversion factor of by 670 mg L^{-1} dS^{-1} m, which is an average factor used to convert EC from conductivity in dS m^{-1} to salt concentration in mg L^{-1} (Whipker and Cavins, 2000). The selection of this conversion factor was a conservative choice because the temperature was compensated for 25°C; however, values can range from 640 to 700 mg L^{-1} dS^{-1} m depending on the type of fertilizer used (Whipker and Cavins, 2000). The daily salt load was then calculated by multiplying the salt concentration in the drainage outflow by the daily drainage volume. Since not all the drainage events could be sampled for water quality test (e.g. during weekends), a methodology similar to that described by Algoazany et al. (2007) was adopted for calculating the missing values. In this case, the first half of the unsampled period was multiplied by the nutrient concentration of the preceding available water quality sample, while the second half of the period was multiplied by the nutrient concentration of subsequent available water quality sample. The flow-weighted-mean concentration of NO_3-N, and PO_4-P was calculated by dividing the sum of the daily loads by the sum of the daily drainage flow volume. The exported loads and flow-weighted-mean concentrations were statistically compared using the t-test in JMP 8.0 (SAS Institute Inc., Cary, N.C.). The three replicates of each measurement were used in the statistical analysis. In 2010, monitoring of the FDIR treatment started on 30 April and ended on 14 October, but monitoring of the CDSI treatment was delayed due to difficulties in equipment acquisition, which led to a late start on 31 May. In order to make a fair comparison between nutrient loads and nutrient flow weighted mean concentration from both treatments in 2010, only the period from 31 May and 14 October was used in the analysis. However, the monitoring period in 2011 extended from 7 April to 9 November for both treatments.

6.4 Results and Discussion

6.4.1 Drainage outflow

The drainage outflow from the FDIR and CDSI treatments in 2010 and 2011 are shown in figure 6.1. The flow in the CDSI treatment from snowmelt in the early part of 2010 is not shown in figure 6.1a because of delay in monitoring due to difficulties in timely equipment acquisition. After the snowmelt event, there was very limited drainage outflow from the CDSI treatment since the system was set to keep a target water table depth of 0.75 m from the ground surface. During the monitored period in 2010, the average total drainage from the CDSI treatment was only 4.0 mm. The CDSI drainage outflow occurring in August and September are attributed to two separate large rainfalls events. In contrast, the FDIR treatment drained 156 mm over the same period, which was statistically higher ($p = 0.01$) than the CDSI drainage outflow. Drainage events in the FDIR treatment took place until late June, with only minimum drainage during the period of high evapotranspiration (ET) in July and August making larger soil storage possible. Large flows due to rainfall events occurred again towards the end of the growing season, when ET began to decrease. At this point, the controlled drainage system was very effective in decreasing the drainage outflow, despite the large rainfall events at the end of the 2010 season. In 2011, when the flow due to snowmelt could be monitored, the drainage outflow for CDSI was larger than that of FDIR (fig. 6.1b) due to the higher drainage intensity of CDSI (i.e. 8-m drain spacing), which was allowed to freely drain the snowmelt water. However, the flow in CDSI ceased at the beginning of May due to control (i.e. addition of stoplogs to the control structures) at the outlet, while the FDIR treatment continued to freely drain. Controlled drainage systems have an effect on the drainage coefficient by affecting the way the system behaves when flow is uncontrolled or restricted. The drainage intensity of CDSI increases when the system is freely flowing and decreases upon restriction of the outlet at the control structure. The effectiveness of the CDSI treatment was more evident during large rainfall events (i.e. > 40 mm) on 21 May and 21 June, 2011. On 21 May, the CDSI decreased the drainage volume by more than 25%, while on 21 June this reduction was close to 50%. There were no more drainage events from July until the end of the growing season due to the dry conditions prevailing during this period. Therefore, even a large rainfall observed on 20 September, 2011, did not lead to drainage outflow in either FDIR or CDSI treatments. The total seasonal drainage outflow in 2011, averaged over the three replicates, was 87 mm for FDIR and 53 mm for CDSI. These values represent a 39% reduction in average drainage outflow due to controlled drainage, which is similar to the average reduction of 33% found by other studies in and around Iowa (Iowa Department of Agriculture and Land Stewardship, 2013). However, the difference between drainage outflows from FDIR to CDSI was not statistically significant ($p = 0.07$) due to the wide variability between the replicates. The standard error of the FDIR was 11.53 mm, while for CDSI it was 18.67 mm.

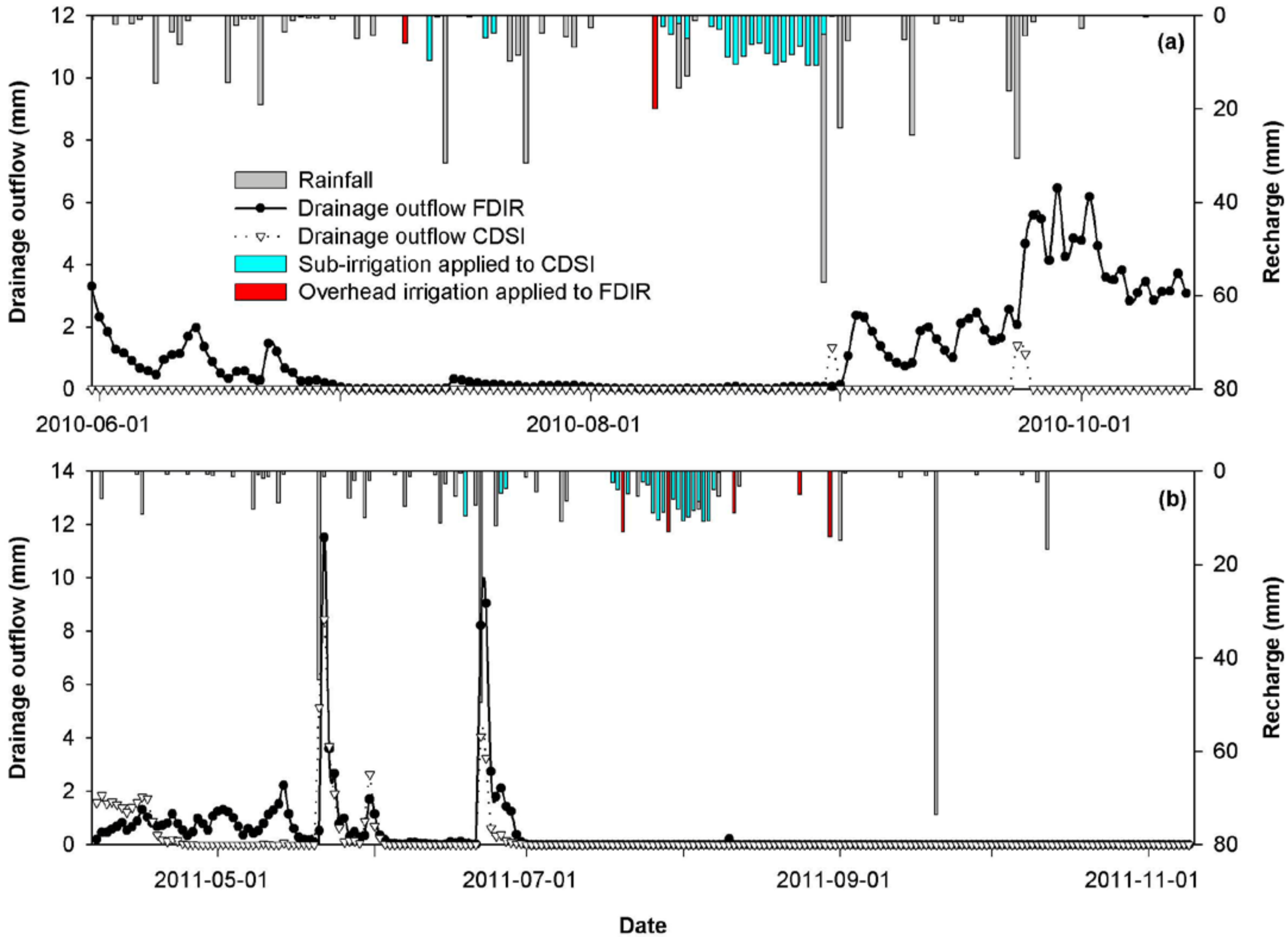

Figure 6.1. Drainage outflow and rainfall for the free drainage with overhead irrigation (FDIR) and controlled drainage with sub-irrigation (CDSI) treatments in 2010 (a) and 2011 (b).

6.4.2 Nutrient and salt exported loads and flow-weighted means

Nitrate

The total nitrate exported over the growing season and the flow-weighted-mean concentrations of NO_3-N for 2010 and 2011 are presented in figure 6.2. The average export in 2010 from FDIR (138 kg N ha^{-1}) was significantly higher ($p = 0.01$) than that from CDSI (0.07 kg N ha^{-1}) (fig. 6.2a). The decreased export from CDSI, the bar for which is hardly visible in figure 6.2a, was a result of the lower drainage outflow rate and dilution effects of subirrigation. The reduction of drainage volumes and nitrate export are interrelated (Lalonde et al., 1996), and previous studies showed that drainage exports are proportional to drainage volume (Gilliam et al., 1979). The flow-weighted mean concentration from FDIR (98.9 mg L^{-1}) was significantly higher ($p = 0.01$) than that from CDSI (1.7 mg L^{-1}) (fig. 6.2b). Mejial and Madramootoo (1998), working in eastern Canada, also found flow-weighted nitrate-N concentrations of 1.7 mg L^{-1} in controlled drainage treatments. They argue that the reduction of nitrate concentrations in controlled drainage can be attributed to the combined effect of dilution by sub-irrigation and denitrification. Both these process could be responsible for the reduced flow-weighted nitrate concentrations observed in the present study. In 2011, the monitored period encompassed the spring snowmelt and the exports and flow-weighted mean concentrations became more comparable. The average export in 2011 from FDIR (36 kg N ha^{-1}) was significantly higher ($p = 0.03$) than that from CDSI (10 kg N ha^{-1}) (fig. 6.2a). The flow-weighted mean concentration from FDIR (41.2 mg L^{-1}) was significantly higher ($p = 0.04$) than that from CDSI (21.3 mg L^{-1}) (fig. 6.2b).

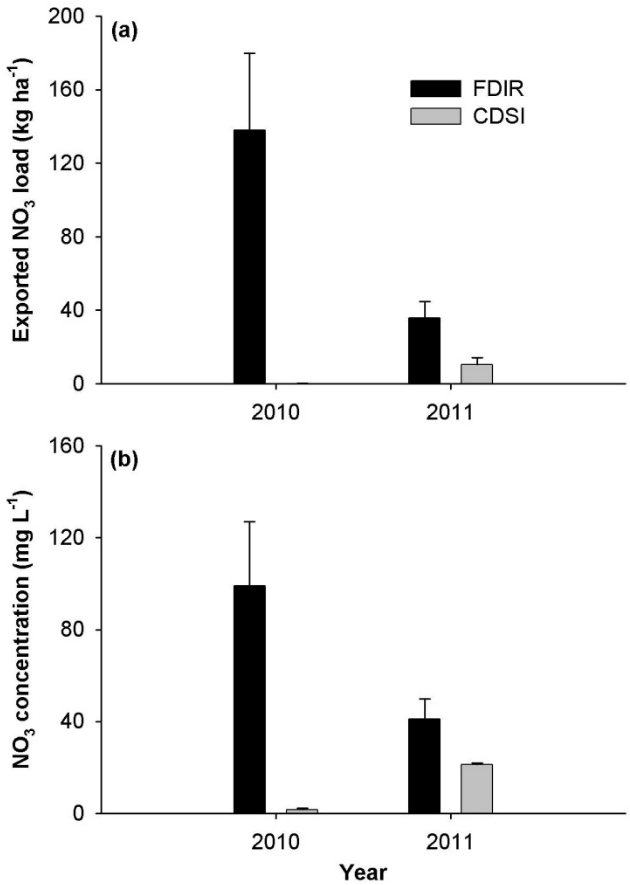

Figure 6.2. Comparison of NO_3-N export from the free drainage with overhead irrigation (FDIR) and controlled drainage with sub-irrigation (CDSI) treatments in 2010 and 2011. (a) Exported NO_3-N loads and (b) Flow-weighted-mean NO3-N concentrations. Error bars are shown for means with statistically significant difference ($p < 0.05$).

Besides the decreased CDSI drainage outflow volume in 2010, the difference between the two treatments was further enhanced by the extremely high nitrate export from the FDIR treatment. The nitrate export observed for FDIR in this study in 2010 exceeded the values reported in the literature for agricultural systems with free drainage, while the export observed in 2011 fell within the reported ranges. For example, Jaynes et al. (2001) found a maximum export of 61 kg N ha^{-1} in a corn field with a drainage system installed at 1.45-m depth and receiving high fertilizer rates (i.e. 202 kg N ha^{-1}). For medium and low fertilizer rates (i.e. 135 and 67 kg N ha^{-1}, respectively), which are more comparable to those used in this study, the maximum nitrogen export were 48 and 37 kg N ha^{-1}, respectively. Also, Burchell II et al. (2005) found maximum nitrate export loads of 37 kg ha^{-1} in plots receiving swine wastewater application and having drains at 1.5-m depth. For plots having drains installed at 0.75-m depth, which is more comparable to the drainage depth used in the present study, the export decreased to 27 kg ha^{-1}. Comparison of the 2010 and 2011 values of nitrogen export in the present study seem to indicate that the 2010 N export was an abnormal behaviour due to some erratic process, although high nitrate losses through subsurface drainage up to 64 kg ha^{-1} had been observed in Midwest US when large volume of water moved through the soil (Dinnes et al., 2002). One reason could be the high amounts of nitrate that was accumulated in the soil profile flushing through the newly installed drainage system that was allowed to freely drain in the FDIR treatment. This possibility is supported by the flow-weighted mean and exported loads, which decreased from 2010 to 2011, and fell within the ranges reported in the literature.

Since the nitrate export in 2010 was out of range and was likely caused by the abnormal conditions in that year, only the export in 2011 was used in the analysis of export reduction. This conservative approach was preferred to avoid misinterpretation of the results (i.e. overestimation of reductions of nitrate export by controlled drainage) and prevent extrapolation of reductions by CDSI to weather conditions not typical of the Canadian Prairies. In 2011, the CDSI treatment achieved 39% reduction in drainage volume, which resulted in 71% reduction in nitrate export. These reductions in drainage volume and N loss are comparable to the values presented by Skaggs et al. (2010) for a wide range of soils and climatic conditions. As stated in the previous section, flow reductions between 30% and 40% have been reported in the literature. Additionally, Drury et al. (2009), comparing controlled drainage with subirrigation to unrestricted drainage in Ontario, found that controlled drainage reduced N losses by 66%, which is similar to the reduction found in the present study. According to Skaggs et al. (2010), results published in the literature show that controlled drainage can reduce drainage volumes up to 85% when compared to free drainage, while N losses in drainage waters can be reduced from 17% to over 80%, depending on soil properties, crops, drainage intensities, control strategies, and location.

Phosphorus

There were large differences between the two treatments in terms of phosphorus exports in 2010. The average export in 2010 from FDIR (0.6 kg P ha^{-1}) was significantly higher ($p = 0.01$) than that from CDSI (0.08 kg P ha^{-1}) (fig. 6.3a). However, the difference in flow-weighted mean concentrations from FDIR (0.4 mg L^{-1}) and CDSI (0.3 mg L^{-1}) was not statistically significant ($p = 0.21$) in 2010 (fig. 6.3b). In 2011, the average export from FDIR (0.27 kg P ha^{-1}) was significantly higher ($p < 0.01$) than that from CDSI (0.08 kg P ha^{-1}) (fig. 6.3a). The difference in P export between FDIR and CDSI represents close to 69% reduction attributed to controlled drainage. The flow-weighted mean concentration of phosphorus for FDIR (0.32 mg L^{-1}) was also statistically significantly higher ($p = 0.03$) than that for CDSI (0.19 mg L^{-1}) in 2011 (fig. 6.3b).

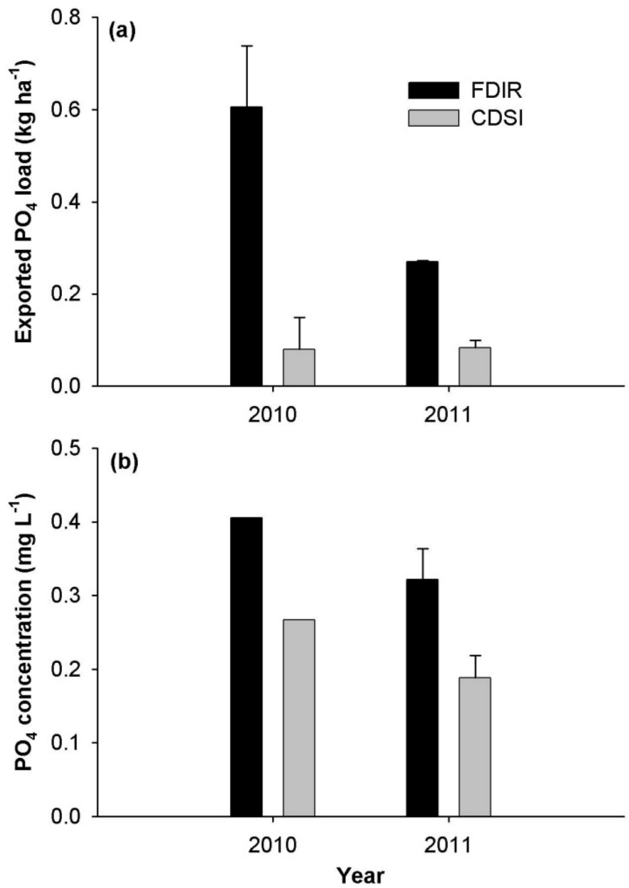

Figure 6.3. Comparison of PO_4 export from the free drainage with overhead irrigation (FDIR) and controlled drainage with sub-irrigation (CDSI) treatments in 2010 and 2011. (a) Exported PO_4 loads and (b) Flow-weighted-mean PO4 concentrations. Error bars are shown for means with statistically significant difference ($p < 0.05$).

Given the relative immobility of P in soils, P losses from agricultural fields via subsurface runoff have rarely been considered important; however, environmentally significant export of P in agricultural drainage may occur under certain conditions such as high organic matter soils or soils with high soil P concentrations from long-term over-application of fertilizer and/or excessive use of manure (Sims et al., 1998). The P export for the FDIR treatment in the present study was within the range of values reported in the literature for farmlands with free drainage. For humid regions of Canada, Goulet et al. (2006) found phosphorus losses through subsurface drainage in corn plots varying from 0.75 to 1.13 kg P ha^{-1}. Also, Sharpley et al. (2001), reviewing the literature on phosphorus losses from agricultural lands through subsurface drainage, found that artificially drained farmland cropped with corn had total P losses from 0.42 to 0.62 kg P ha^{-1}. The values found in the present study were in agreement with values seen in the literature; however, direct comparison between exports found in this study and those in the literature is difficult because phosphorus leaching through subsurface drainage depends on complex mechanisms. Factors influencing P release from soils include the dominant forms of P in soil, texture of the soil, movement of soil particles, degree of interaction between soil and water, organic matter content, vegetative soil cover, and sorption capacities (Sharpley et al., 2001). Among these, soil texture was found to impact the overall P export from farmland and interact with subsurface drainage. For example, Eastman et al. (2010) found that for fine-texture soils, subsurface drainage minimizes surface runoff and total phosphorus losses (i.e. both surface and subsurface losses combined). Conversely, the proportion of phosphorus in tile drainage tends to be higher in coarse textured soil with high P levels (Kinley et al., 2007). Also, controlled drainage can, under certain circumstances, increase the phosphorus release from agricultural lands. For instance, Valero et al. (2007) working on very fine sandy loams in Eastern Canada, found increased P loads in tile drainage from controlled drainage/sub-irrigation plots compared to free drainage plots. The authors suggest that the increased P loads from CDSI was due to an increase in P solubility due to shallow water table. However, this was not observed in the present study because the exports from CDSI were smaller than those from the FDIR treatment.

Salts

In 2010, the salt export from FDIR (2.34 Mg ha^{-1}) was larger ($p = 0.02$) than that from CDSI (0.41 Mg ha^{-1}) (fig. 6.4a). This difference corresponds to 82% reduction in salt export from CDSI compared to FDIR. The electrical conductivity of the FDIR drainage outflow (2.05 dS m^{-1}) was higher ($p = 0.01$) than that of the CDSI (0.60 dS m^{-1}) (fig. 6.4b). In 2011, the salt export from FDIR (1.10 Mg salts ha^{-1}) was also higher ($p = 0.01$) than that from CDSI (0.39 Mg salts ha^{-1}) (fig. 6.4a). This difference corresponds to a 64% reduction in salt export due to controlled drainage. The electrical conductivity of the FDIR drainage outflow (1.85 dS m^{-1}) was also higher ($p < 0.01$) than that of CDSI (0.50 dS m^{-1}) (fig. 6.4b). Figure 6.4b also shows that the electrical conductivity of both treatments remained fairly stable from 2010 to 2011, with the EC in CDSI being much lower than that of FDIR. This lower EC seems to confirm the dilution effect discussed previously. Another feature of figure 6.4a is the 53% reduction in salt export from FDIR between 2010 and 2011.

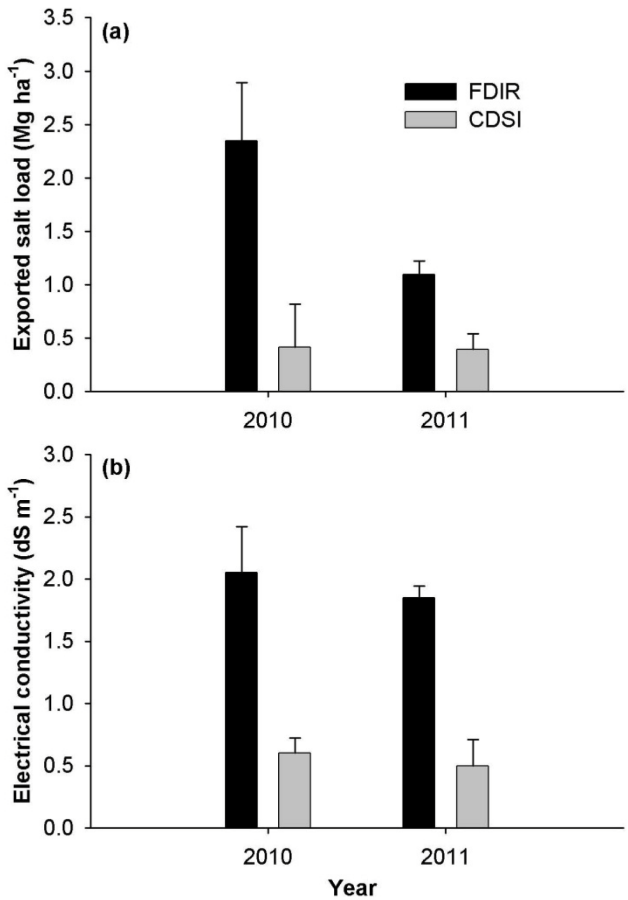

Figure 6.4. Comparison of total salt export from the free drainage with overhead irrigation (FDIR) and controlled drainage with sub-irrigation (CDSI) treatments in 2010 and 2011. (a) Exported total salt loads and (b) Electrical Conductivity. Error bars are shown for means with statistically significant difference ($p < 0.05$).

The salt exported from the FDIR treatment was lower than the range of salt export amounts from farmland having subsurface drainage reported in the literature. For example, Carter et al. (1971), found a salt export of 7.26 Mg ha^{-1} through subsurface drainage from an 82,000-ha irrigation tract, planted with a variety of crops including corn. Over two irrigation seasons in Australia, Christen and Skehan (2001) found an average salt export of 2.9 Mg ha^{-1} from vineyard plots with drains installed at 1.8-m depth. However, salt export was decreased by 49% in the vineyard study when plots were operated as controlled drainage. In other plots of the vineyard with shallow drains installed at 0.7-m depth and 3.65-m apart, the salt export was decreased by 95% over the two irrigation seasons. The smaller salt export observed in the present study is likely due to the non-saline soil and low salinity of the groundwater. For comparison, Christen and Skehan (2001) observed drainage outflows with an average EC of 11 dS m^{-1}, while the highest average in the present study was 2.05 dS m^{-1}.

6.5 Conclusion

Free drainage with overhead irrigation (FDIR) was compared with controlled drainage with sub-irrigation (CDSI) in this study. In 2010, the export of NO_3-N (138 kg ha^{-1}), PO_4-P (0.6 kg ha^{-1}) and salts (2.34 Mg ha^{-1}) from the FDIR treatment during the growing season were significantly larger ($p < 0.05$) than exports from CDSI, which were 0.07 kg ha^{-1}, 0.08 kg ha^{-1}, and 0.41 Mg ha^{-1}, respectively. This comparison in 2010 did not include the drainage outflow arising from spring snowmelt due to delays in the installation of monitoring equipment. It should be noted that the major flow in tile drains occurs during the spring snowmelt period. However, in 2011, which included the drainage outflow due to spring snowmelt events, the exports of NO_3-N (36 kg ha^{-1}), PO_4-P (0.27 kg ha^{-1}), and salts (1.1 Mg ha^{-1}) from FDIR were significantly larger ($p < 0.05$) than the exports from CDSI which were 10 kg ha^{-1}, 0.08 kg ha^{-1}, and 0.39 Mg ha^{-1}, respectively.

The results show that the controlled drainage was very effective in decreasing drainage outflow and, consequently, the export of NO_3-N, PO_4-P, and salts from cornfields under Canadian Prairies semi-arid conditions. The drainage outflow from CDSI in 2011 was 39% lower than that from FDIR. In the same year, the CDSI treatment showed a 71% reduction in exported loads of nitrate when compared to FDIR treatment. In 2011, the CDSI treatment also showed a 69% reduction in exported loads of phosphorus when compared to FDIR treatment. In the same year, the CDSI showed a salt export reduction of 64% compared to FDIR. This study clearly shows the advantage of controlled drainage over free drainage in reducing the nutrients and salt exports from agricultural lands under corn.

7. PRACTICAL APPLICATIONS

The research presented in the preceding chapters is useful for the design and operation of irrigation and drainage systems under the climatic and physiographic conditions found in the Canadian Prairies. Although the principles of irrigation and drainage engineering have been well developed and tested in other regions, their application and the consequent agronomic and environmental impacts have not been evaluated under Canadian Prairies conditions.

The first practical application of this study is to show how the groundwater, a usually neglected source of water to crop evapotranspiration demands, can be utilized by corn to meet its water needs. This work showed that the diurnal water distribution within the corn root zone is a dynamic process, in which the soil moisture in the top layers of the soil profile is replenished by contributions from the ground water. The description of this redistribution and its relationship to root development, water table depth, and soil moisture status is important for farmers and irrigators because it describes an important component of the soil water balance. Therefore it should be accounted for during irrigation scheduling in order to improve water management at the farm level and decrease the cost of pumping.

Another application of this work is to show the effects of different water management systems in terms of yield and environmental benefits. This study provides scientific evidence to compare the agronomic and environmental performance of different combinations of irrigation and drainage, supporting the decision-making process of famers according to their primary goal, which is to maximize yields while protecting the environment. This research quantified differences in relative yields and nutrient export using different water management strategies, allowing farmers to calculate their return on investment for different irrigation and drainage strategies. Moreover, this work provides background for when to expect beneficial impacts from irrigation and drainage during the different stages of crop development and different weather conditions (i.e. wet, mixed, and dry conditions over the course of the growing season).

This study also allowed the application of modeling to evaluate the agronomic performance of different drainage designs, the change in soil moisture status, and the groundwater contribution to plant water demands. Modeling allows the simulation of different scenarios without having to physically test in the field. Among the possible scenarios to be simulated are the impacts of different drainage designs such as drainage spacing and depth on yield, water table variation, and drainage outflow. Also, the effect of irrigation amounts on yields and the impact of weather conditions on soil moisture status and its consequence on yields could also be simulated. This work has shown that a general guideline for subsurface drainage currently practiced in southern Manitoba need to be applied with caution under the risk of over-draining the land and adversely affecting corn yields. The design of a drainage system must take into account the soil and weather conditions specific to the area. The model helps to assess the design parameters based on soil and weather data for a particular location.

Finally, this research generated important knowledge to farmers and engineers about the efficiency of controlled drainage as a best management practice (BMP) to decrease nutrient export from the farmland. By indicating the reductions in nutrient export when compared to free drainage, this study allows for ranking controlled-drainage among other potential BMP options to minimize the nutrient export and, thus, environmental impacts.

8. CONCLUSIONS

1. The water distribution within the corn root zone is a dynamic process where the soil moisture status changes diurnally. This chance is driven by crop evaporative demand, which creates a hydraulic gradient in the soil through the root water uptake. The soil moisture in the root zone is supplied by shallow groundwater, which contributes to the replenishment of the moisture taken up by roots through the upward water flux from the water table;

2. Groundwater is an important component of the water balance and meets a large portion of the corn plant water demand during periods of high evapotranspiration. However, this contribution may vary from year to year, depending on both weather and physiographic features such as antecedent soil moisture status, water table depth, root development, and soil texture. While the groundwater contribution to crop water demand has been documented in the literature for other arid regions of North America and Europe, its dynamics had never been described in semi-arid regions of the Canadian Prairies. This region has a particular hydrology, receiving 30% of its annual precipitation as snowfall, having shallow water tables during the early growing season, and large rainfall events during the later summer months. These conditions separate the Canadian Prairies from other semi-arid regions and highlight the importance of the diurnal water dynamics and the water table contribution described in this study;

3. The Hydrus-1D model can accurately predict changes in soil moisture and upward water flux into the root zone over short periods of time. These predictions can be simulated using readily available soil and weather data coupled with information

about the water table depth in the field. These simulations can be used by farmers to forecast changes in the soil available water, to predict groundwater contribution to the root zone, and to schedule irrigation accordingly;

4. Overhead irrigation proved to be the primary factor increasing corn yields. The beneficial effect of subsurface drainage is more pronounced at the beginning of the season, especially during wet springs. The effect of sub-irrigation on corn yield could have been compromised due to the limited ability of the soil to transmit water upwards to the root zone under dry conditions. Research results on water management of corn reported in the literature usually compare only uncontrolled drainage to controlled drainage with/without sub-irrigation. The present study adopted a new approach by testing the effect of overhead irrigation coupled with different subsurface drainage strategies. By doing this, it was able to compare the relative effects of irrigation and drainage on yields at different phenological stages of corn.

5. The results show that the controlled drainage was very effective in decreasing drainage outflow and, consequently, the export of NO_3-N, PO_4-P, and salts from cornfields under semi-arid conditions in the Canadian Prairies. The drainage outflow from controlled drainage was 39% lower than that from free drainage. The controlled drainage treatment showed a 71% reduction in exported loads of nitrate when compared to the free drainage treatment. The controlled drainage treatment also showed a 69% reduction in exported loads of phosphorus when compared to the free drainage treatment. The controlled drainage treatment showed a salt export reduction of 64% compared to the free drainage treatment. This study clearly

shows the advantage of controlled drainage over free drainage in reducing the nutrients and salt exports from agricultural lands under corn;

6. The DRAINMOD model can accurately predict variations in water table depth and drainage outflow under the soil and weather conditions found in Canadian Prairies. Simulations seem to indicate that a two-year time window between drain installation and monitoring is appropriate for data collected for modeling;

7. Testing of different drainage designs using DRAINMOD indicated that the generally recommended design criteria for Manitoba (i.e. 0.9-m deep and 15-m wide), which is widely adopted by contractors in this Province, is not appropriate for all the soil conditions. The maximum drain spacing without considerable negative impacts on yield should thus be based on a more detailed assessment of the hydraulic properties of different soil types. The maximum drain spacing based on soil textural class also seemed not to be appropriate since the relative yields were as low as those observed for non-drained soils. Simulations of relative yield indicated that duration and timing of the wet conditions in relation to the stage of crop development have considerable effect on yield, and that excess moisture at early stages are most detrimental to yields. These results represent a new effort to incorporate modeling for assessing the agricultural practices in the Canadian Prairies for corn production.

9. FUTURE WORK

1. To monitor the soil moisture status within the corn plant root zone using TDR mini-probes over a longer period of time to investigate the persistence of the redistribution pattern observed in this study and to investigate how precipitation and drainage affect it. Since the soil-plant-water interaction is very dynamic and depends on several variables such as root depth, plant developmental stage, evapotranspiration rates, weather, water table depth, and soil moisture status, investigations over the course of the entire growing season may indicate different redistribution patterns during different stages of corn development;

2. To calculate the contribution of the water table to the corn root zone during the entire growing season. The observations reported in this study focussed on the period of high plant water demand. However, the contribution of the water table is likely less apparent during the early stages of crop development. A full assessment of the water table contribution over the entire growing season will provide a good estimate of the total contribution of groundwater to the soil water balance;

3. To evaluate a different management strategy for the controlled-drainage/sub-irrigation treatment. In the present study, the depth of the water table was allowed to drop and was then raised. Maintaining a shallow water table from the beginning of the growing season, just sufficient to complete field operations, may help take advantage of the spring snowmelt and reduce the amount of water applied as sub-irrigation;

4. To test sub-irrigation in a field with a shallower depth to the impermeable layer. The higher depth to the impermeable layer made it difficult to raise the water table by subirrigation at this experimental site. A shallower impervious layer may improve the distribution of subirrigation water and affect yields more dramatically.
5. To evaluate a shallower installation depth for the sub-irrigation laterals in order to offset the distance between the water sources the effective root depth. This strategy may improve water use efficiency by minimizing water loss below the root zone;
6. To run DRAINMOD to simulate the nitrogen dynamics in the cornfield. As stated throughout this manuscript, managing nitrogen dynamics is an important challenge facing agriculture. Using DRAINMOD to simulate best management scenarios will help devise efficient strategies to minimize nitrogen losses from the farmland while keeping or improving current productivity levels.

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APPENDICES

List of Appendices

Appendix 1: Standard error of average volumetric soil water content for different times of the day at the same distance from the plant and depth in 2009.

	0.12 m			0.24 m			0.36 m		
Depth (m)	Morning	Afternoon	Evening	Morning	Afternoon	Evening	Morning	Afternoon	Evening
0.1	0.02	<0.01	0.01	0.01	0.02	0.01	0.03	0.03	0.03
0.2	0.01	<0.01	0.01	0.01	0.01	<0.01	0.02	0.01	0.01
0.4	0.01	0.01	0.01	0.01	<0.01	<0.01	0.01	<0.01	0.01
0.6	0.01	<0.01	0.01	0.01	0.02	0.02	<0.01	<0.01	<0.01
0.8	0.01	<0.01	0.01	0.02	0.01	0.01	0.01	0.01	<0.01

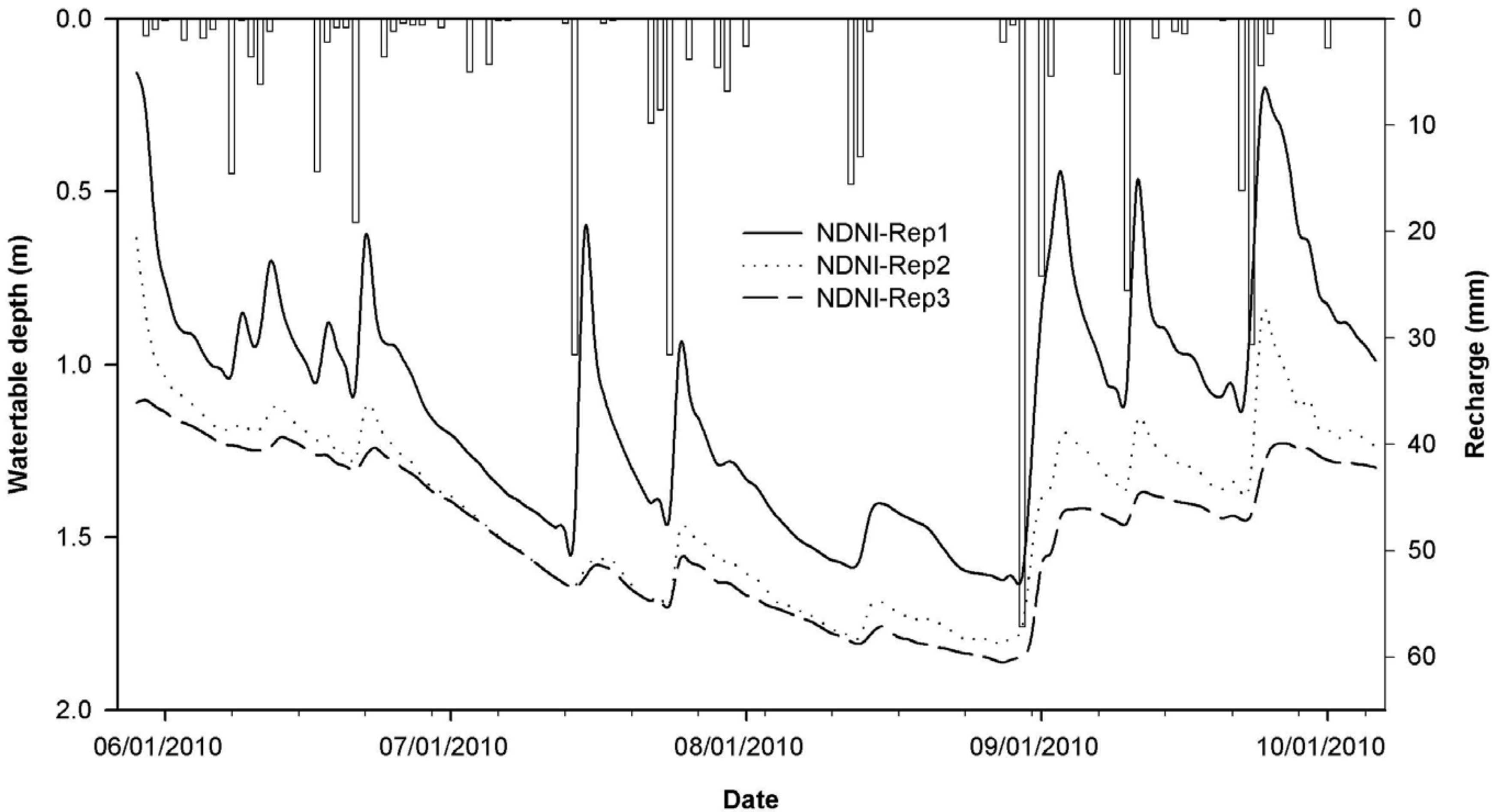
† Values are averages of the three replicates; times are considered after the irrigation event.

Appendix 2: Standard error of average volumetric soil water content for different times of the day at the same distance from the plant and depth in 2010.

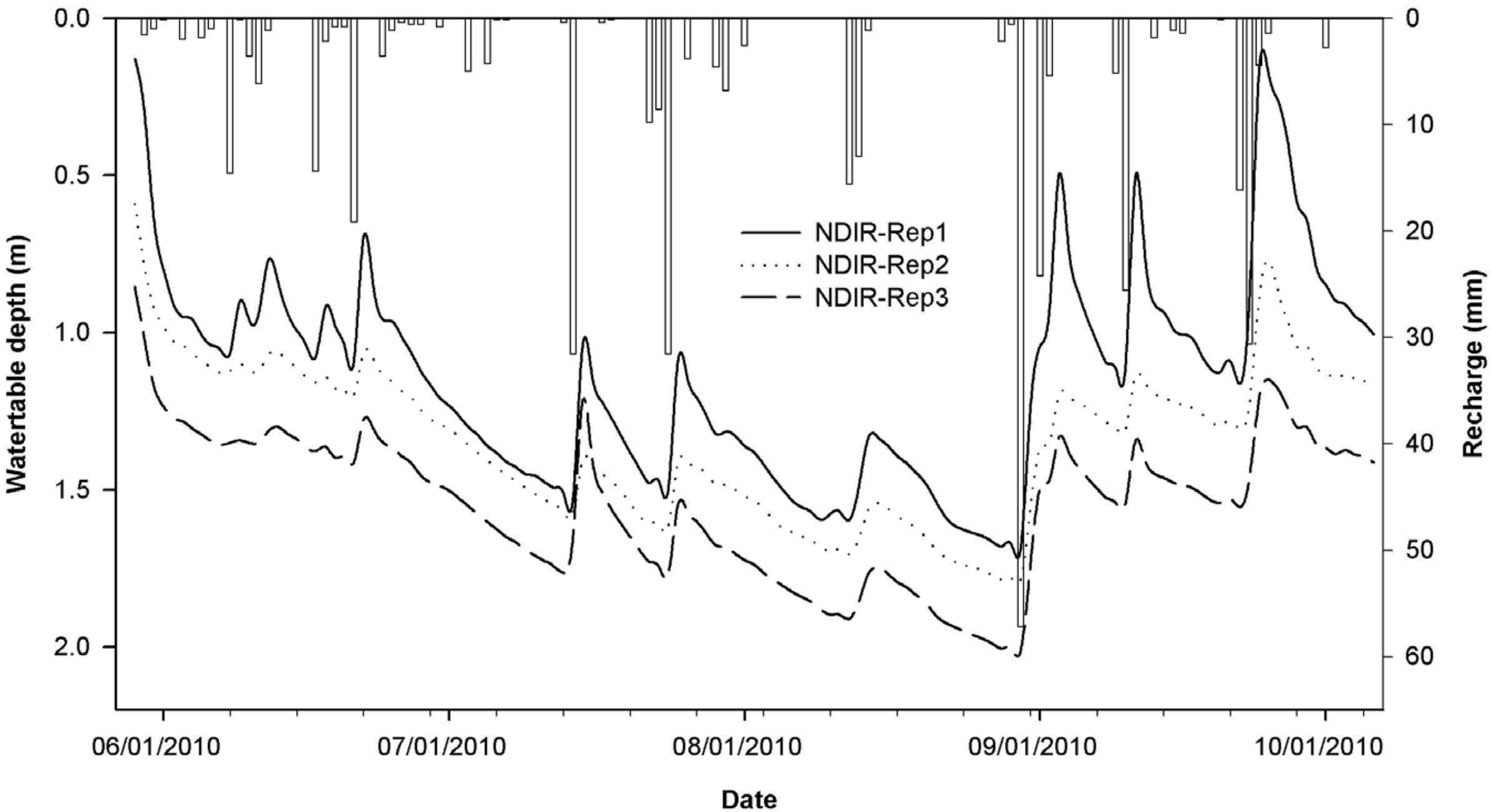
	0.12 m			0.24 m			0.36 m		
Depth (m)	Morning	Afternoon	Evening	Morning	Afternoon	Evening	Morning	Afternoon	Evening
0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.6	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.8	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

† Values are averages of the three replicates; times are considered after the irrigation event.

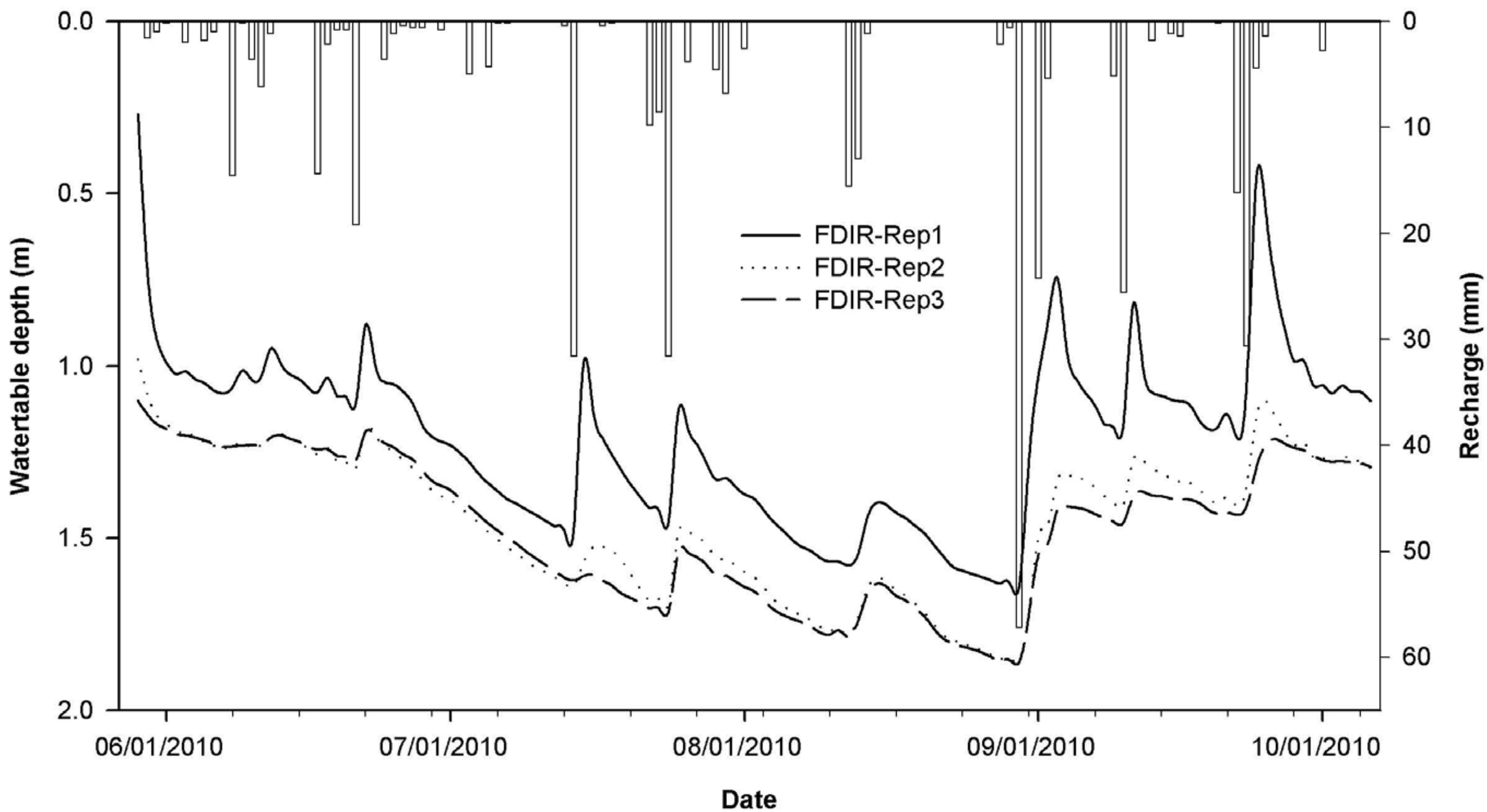
Appendix 3: Variation in water table depth during the 2010 growing season for all replicates of the treatment with no drainage and no irrigation (NDNI).



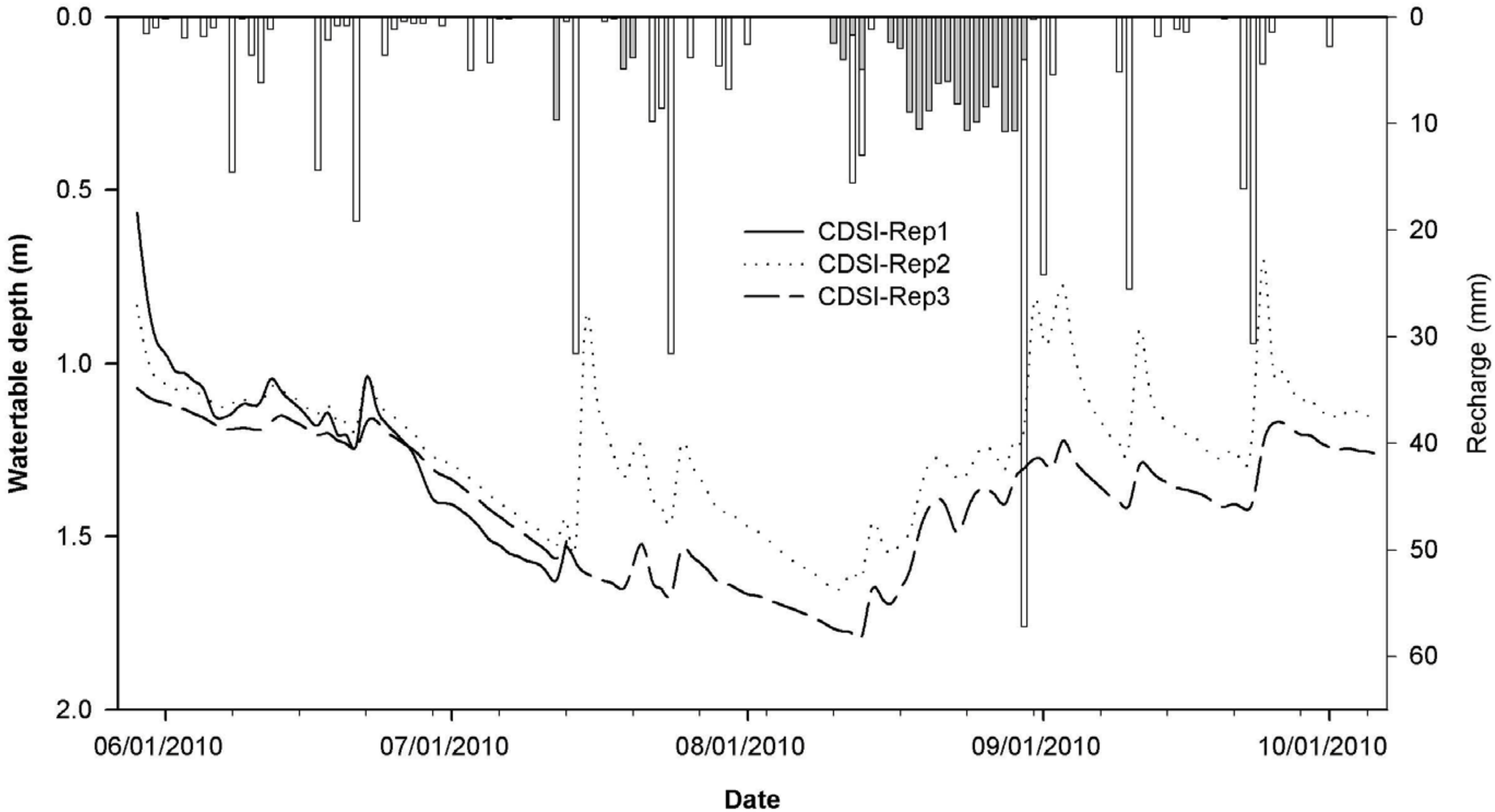
Appendix 4: Variation in water table depth during the 2010 growing season for all replicates of the treatment with no drainage and overhead irrigation (NDIR).



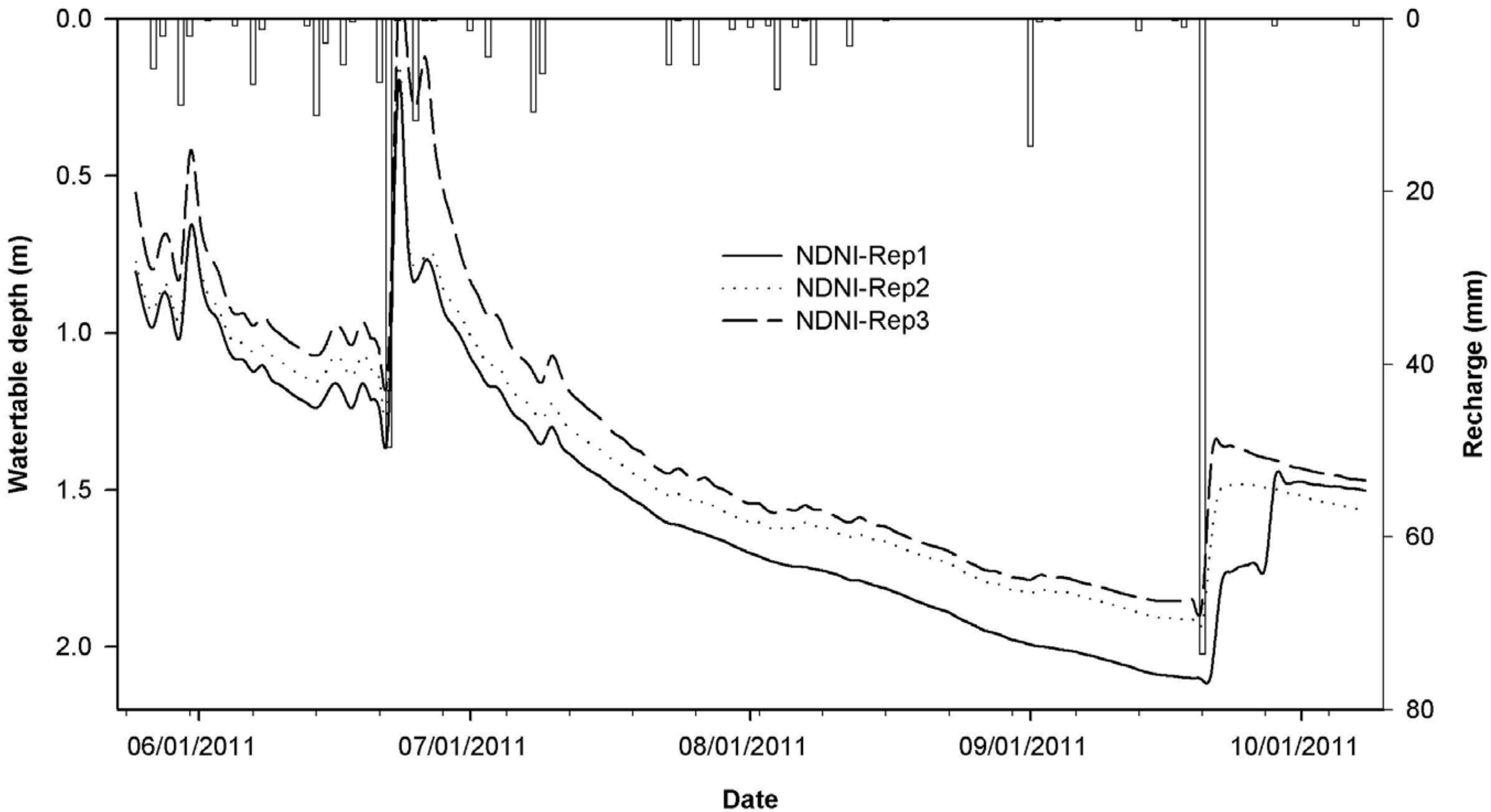
Appendix 5: Variation in water table depth during the 2010 growing season for all replicates of the treatment with free drainage and overhead irrigation (FDIR).



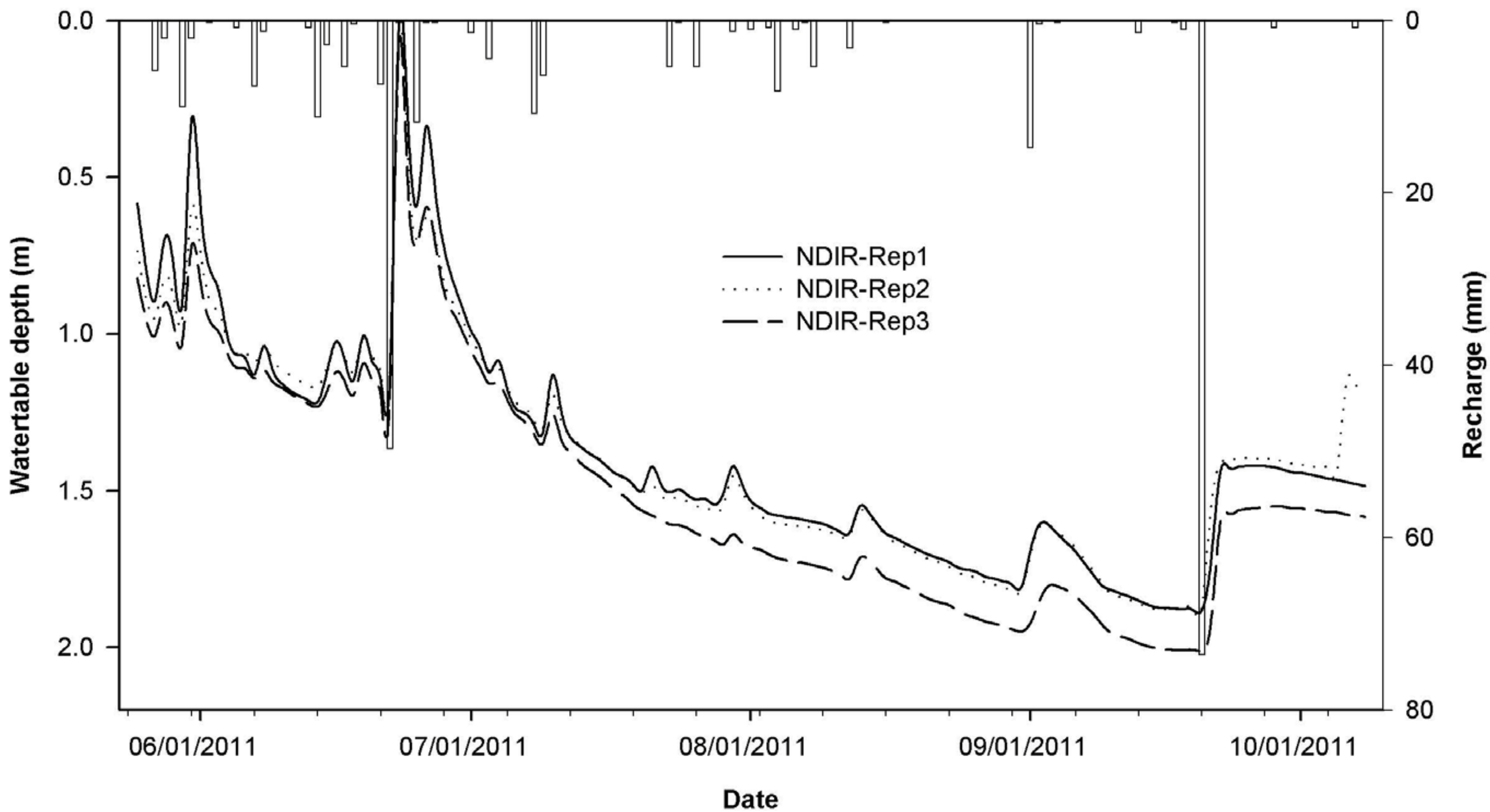
Appendix 6: Variation in water table depth during the 2010 growing season for all replicates of the treatment with controlled drainage and sub-irrigation (CDSI).



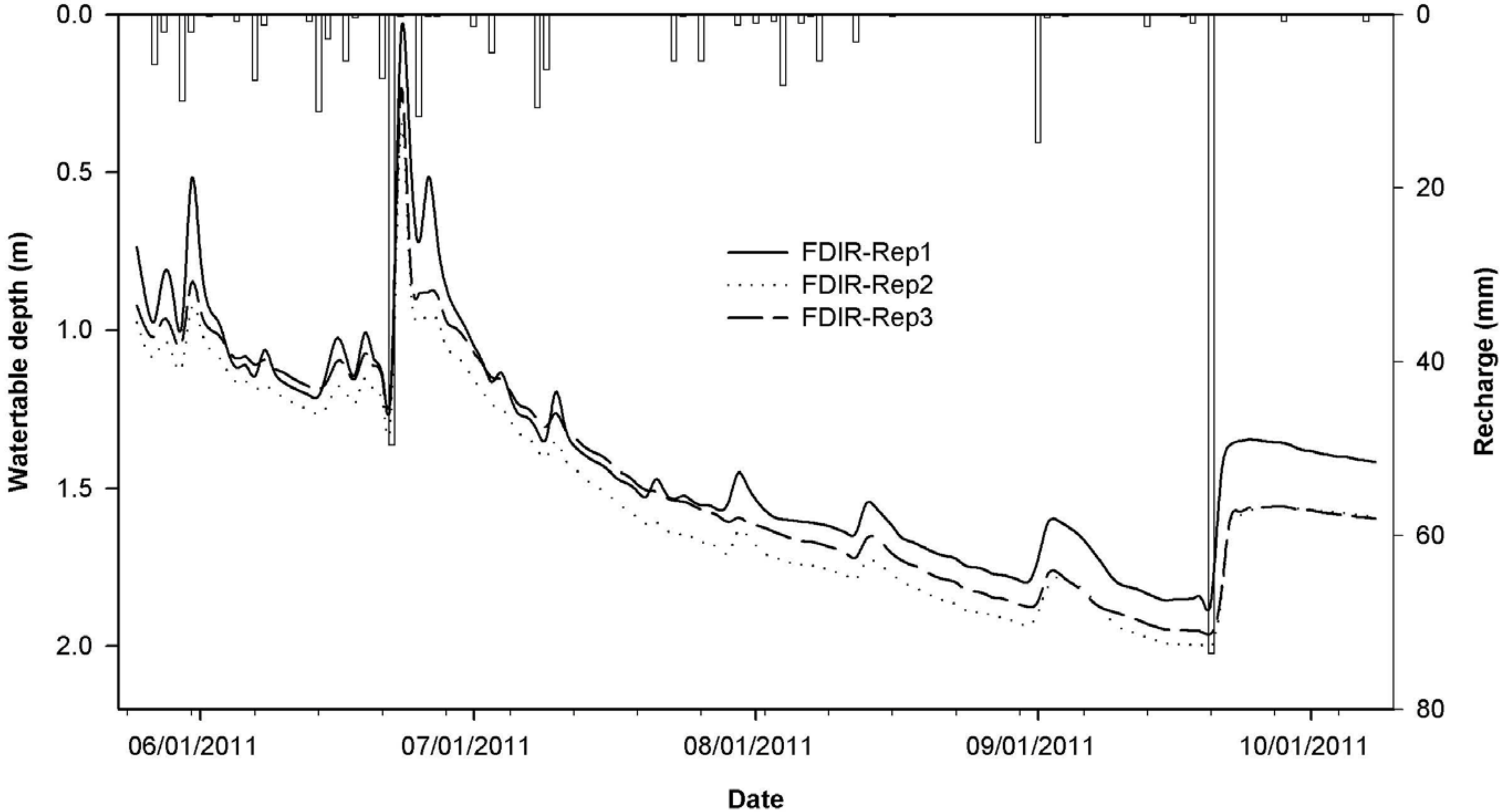
Appendix 7: Variation in water table depth during the 2011 growing season for all replicates of the treatment with no drainage and no irrigation (NDNI).



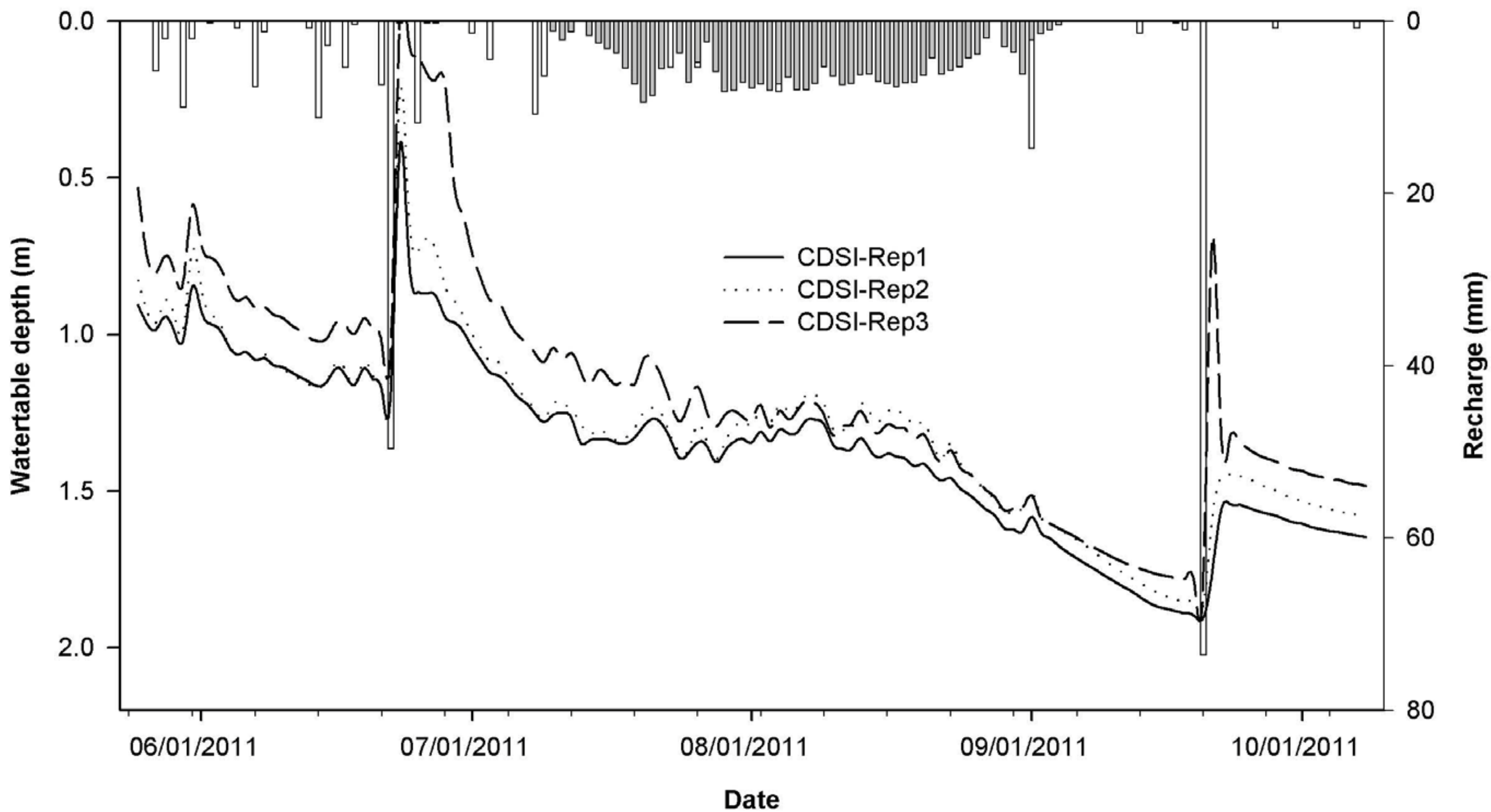
Appendix 8: Variation in water table depth during the 2011 growing season for all replicates of the treatment with no drainage and overhead irrigation (NDIR).



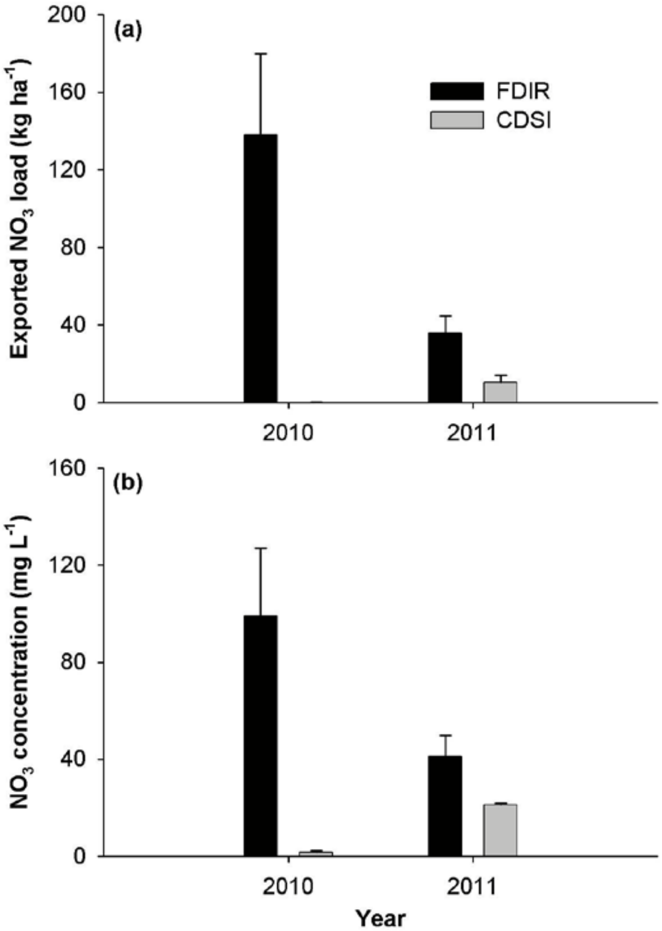
Appendix 9: Variation in water table depth during the 2011 growing season for all replicates of the treatment with free drainage and overhead irrigation (FDIR).



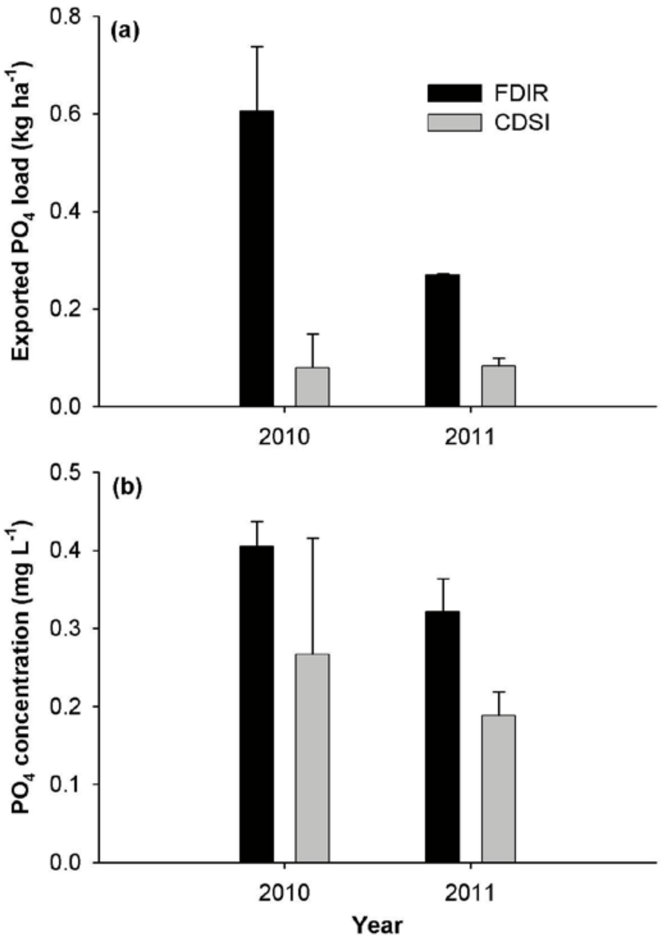
Appendix 10: Variation in water table depth during the 2011 growing season for all replicates of the treatment with controlled drainage and sub-irrigation (CDSI).



Appendix 11: Comparison of NO_3export from the free drainage with overhead irrigation (FDIR) and controlled drainage with sub-irrigation (CDSI) treatments in 2010 and 2011. (a) Exported NO_3 loads (b) Flow-weighted-mean NO_3 concentrations. Standard error shown for all means.



Appendix 12: Comparison of PO_4export from the free drainage with overhead irrigation (FDIR) and controlled drainage with sub-irrigation (CDSI) treatments in 2010 and 2011. (a) Exported PO_4 loads (b) Flow-weighted-mean PO_4 concentrations. Standard error shown for all means.



Appendix 13: Comparison of total salt export from the free drainage with overhead irrigation (FDIR) and controlled drainage with sub-irrigation (CDSI) treatments in 2010 and 2011. (a) Exported total salt loads (b) Electrical conductivity. Standard error shown for all means.