Impact of Overhead Irrigation on Nitrogen Dynamics and Marketable Yield of Potato

by

Haider Abbas

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Department of Biosystems Engineering
University of Manitoba
Winnipeg, Canada

ABSTRACT

In Southern Manitoba, potato producers are experiencing wetter and drier conditions within the soil profile during the growing season leading to poor quality and inconsistent yields. Russet Burbank Potato cultivar was grown in Southern Manitoba on fine sandy loam soil in a two year (2013-2014) study using two water management treatments: (i) overhead irrigation and (ii) no-irrigation. The main objectives of the study were (i) to assess the impact of overhead irrigation on water table depth and potato yield (ii) to estimate the shallow groundwater contribution to potato water requirement through upward flux (iii) to track the nitrogen dynamics within the potato root-zone under overhead irrigation and no-irrigation scenarios (iv) to examine the effects of no-irrigation and overhead irrigation system at critical growth stages on marketable yield and quality of potatoes. In 2013, water was applied using a linear move irrigation system and in 2014 a rain gun irrigation system was used for the irrigated treatment. Volumetric soil water content, precipitation, irrigation depth, water table depth, nitrate concentration and electrical conductivity in potato root-zone, groundwater electrical conductivity, weather variables, total potato yield, marketable yield, and quality parameters were measured. The total yield was not significantly different between the two treatments in both years. The marketable yield of the irrigated treatment (36.89 MT/ha) was 20% higher ($p = 0.017$) compared to the non-irrigated treatment (30.74 MT/ha) in 2013. However, no significant difference was found between the irrigated (39.0 MT/ha) and non-irrigated (43.7 MT/ha) treatments in 2014. Potato yields from both treatments were significantly correlated with the average groundwater depth. Water balance analysis within the root-zone during rainy and rain-free periods showed that nitrate rich groundwater may have contributed to some of the crop water demand. The lack of rainfall and high temperature during tuber initiation and tuber bulking stages resulted in the accumulation of high concentration of nitrates within the root-zone by the late release of nitrates from the polymer-coated urea and the upward migration of groundwater containing 55 ppm and 70 ppm of nitrates in the 2013 and 2014 growing seasons, respectively. Overhead irrigation was found to be economically advantageous to produce better quality potatoes with higher marketable yields.

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1. GENERAL INTRODUCTION

1.1 Overview

Potato (*Solanum tuberosum* L.) is considered as a cash crop in North America and the increase in its production has made it an important component of the agricultural industry and the provincial economy of Manitoba. Commercial potato production had been initiated in Manitoba in 1908 with a potato-seeded area of 8,400 ha that has been growing steadily with the expansion of potato processing and irrigation in Manitoba. The estimated potato seeded area in 2013 was recorded as 28,328 ha in Manitoba. The province of Manitoba, being the second largest potato producer after Prince Edward Island in Canada, produces about one-fifth of Canada's total potato production. Favourable soil type and climatic conditions of Southern Manitoba makes it one of the most productive places in Canada for growing potatoes. Potato producers in Southern Manitoba are experiencing wetter and drier conditions within the soil profile during the growing season leading to poor quality and inconsistent yields. Potato crop needs precise irrigation and nutrients management to achieve the goals of higher yield and best quality. Potato has a shallow root system and is very sensitive to moisture and nutrients extremes (excess and/or deficit). Excessive or insufficient supply of water and fertilizers (especially nitrogenous fertilizers) could lead to reduced yield and poor quality of tubers. Simultaneous management of both irrigation and nutrients is necessary because imbalance in one factor may affect the benefit from the other.

Rainfall is the largest source of water that supplies moisture to the crops. In order to bridge the gap between the crop water demand and the moisture received through rainfall, supplemental irrigation is applied. The selection of an appropriate irrigation system that may supply the required amount of water with an even distribution is of great importance to achieve target yield and quality. Self-propelled mobile irrigation systems e.g. sprinkler or spray irrigation with center pivot or linear move, and rain gun are becoming the first choice of the potato growers in Southern Manitoba to supply moisture to tuber roots. These systems are convenient, apply uniform amount of water, and have relatively higher water use efficiency compared to the other forms of sprinkler irrigation systems.

Excessive water supply is not only harmful to potato plants but also is a great threat to the environment, and aquatic species. Excessive water supply, for a longer period of time, may lead to saturated soil condition, which results in poor root zone aeration. After satisfying the crop water demand, evapotranspiration, and storage capacity of soil, excessive water either leach down to groundwater through percolation. Chemicals present in the fertilizers and pesticides applied to the potato crop may leach below and contaminate the groundwater. Deficit soil moisture condition is also a great threat to potato yield and quality. Southern Manitoba has shallow groundwater table. Plants have the ability to pull the water from the ground under moisture deficit conditions through capillary rise. If the amount of water received through upward flux from the groundwater is sufficient to meet the crop water demand, it may decrease the need for supplemental irrigation. However, if the groundwater quality is not fit for irrigation, it may significantly affect the marketable potato yield and fry color quality.

1.2 Scope

Self-propelled mobile irrigation systems e.g. sprinkler/spray irrigation with center pivot or linear move, and rain gun systems are generally used for irrigating the potato crop in Southern Manitoba. However, the effectiveness of shallow groundwater to meet the crop water demand without the need for supplemental irrigation has not been studied. In addition, nitrate dynamics within the potato root zone has not been investigated with and without irrigation. Perhaps the most significant challenge is to meet the quality requirements of the processing industry in Manitoba. This thesis is comprised of a collection of three manuscript-styled chapters and each of them contributes towards the main objectives. Chapters 2, 3 and 4 contain the individual manuscripts and were written in a format that is acceptable for submission to peer-reviewed journals. Each of those chapters is related to one of the specific objectives listed under objectives.

1.3 General Objectives

The main objective of the study was to evaluate the effect of two different agricultural water management practices on potato yield and quality under conditions prevailing in Southern Manitoba. The two different agricultural water management practices are: (1) overhead irrigation (IR), and (2) no-irrigation (NI).

The main objectives of the study were:

- To assess the impact of supplemental irrigation via overhead irrigation system on water table depth and potato yield in Manitoba by comparing the two different water management scenarios;
- To estimate the shallow groundwater contribution to potato water requirement through upward flux;
- To track the nitrogen dynamics within the potato root zone under overhead irrigation and no-irrigation scenarios in Southern Manitoba conditions;

- To examine the effects of no-irrigation and irrigation applied through linear move irrigation system at tuber initiation and tuber bulking stages on marketable yield and quality of Russet Burbank potatoes.

2. Groundwater Contribution to Irrigated Potato Production in the Canadian Prairies

ABSTRACT: Potato is a moisture sensitive crop with soil water deficit/excess causing yield reduction. In Southern Manitoba, potato producers are experiencing wetter and drier conditions within the soil profile during the growing season leading to poor quality and inconsistent yields. The objective of this study was to compare the effect of overhead irrigation, with no-irrigation as a control, on potato yield in a fine sandy loam soil in Southern Manitoba. To assess the water balance in potato production water table depth, volumetric soil water content, precipitation, irrigation depth, and potato yield data were collected during the 2013 and 2014 growing seasons. Although, the overhead-irrigated plots had a marginally higher yield, the difference was not statistically significant compared to the control in both years. Potato yields from both treatments were significantly negatively correlated with the average groundwater depth. A water balance analysis was conducted within the rootzone during rainy and rain-free periods which showed that groundwater contribution may have met some of the crop water demand. The deeper the groundwater table the lower the upward flux to the rootzone from the water table which had a significant influence on potato yield. High yield even under dry conditions shows the importance of upward migration of water from the shallow groundwater table. Since upward flux is a major contributor to potato water uptake, the quality of groundwater should be monitored to ensure the quality of potatoes.

2.1 INTRODUCTION

Potato (*Solanum tuberosum* L.) enjoys the status as one of the four staple foods in the world. The demand for potatoes is increasing at a greater rate as compared to many other food crops (Fabeiro et al., 2001). The average annual diet of a global citizen includes about 33 kg of potato. The total world production of potato is reported as 3.24×10^8 MT. China is the world's largest potato producer with an annual production of 7.48×10^7 MT. Canada contributes 4.42×10^6 MT to the world's total potato production, of which Manitoba contributes 9.86×10^5 MT from an area of 33,000 ha (Agriculture and Agri-Food Canada, 2007). Canada is the largest exporter and the second largest producer of processed potatoes in the world (USDA, 2004). Furthermore, the potato industry in Canada contributes about $6.4 billion in both direct and indirect income as well as generates 33,000 jobs for the individuals living in Canada (Potato Innovation Network, 2007). The cool and humid climatic conditions of Manitoba make it very favorable for growth and development of potato, which is emerging as one of the major cash crops. Manitoba is the second largest potato producing province after Prince Edward Island in Canada. The contribution of Prince Edward Island in Canada's total potato production is about 27% while Manitoba's contribution is about 19% (Statistics Canada, 2009). Manitoba's potato production has increased from 286,000 tonnes (t) to 986,000 t (19% of Canada's production) in the past quarter century with an increase in potato seeded area from 20,000 ha to 33,000 ha (Statistics Canada, 2007).

Major factors affecting potato yield include climatic conditions, crop rotation, tillage management, production practices including seed piece spacing (Rex, 1991), irrigation management (Ahmadi et al., 2010; Unlu et al., 2006; Ojala et al., 1990), and nutrient management (Ierna et al., 2011; Alva et al., 2012; Stark et al., 1993). Of all these factors, irrigation management is one of the important factors that decide the total tuber yield. Harris (1978) reported that every 10 mm increment in the water supply can increase the yield by 1 t/ha. World's average water demand for potato crop varies from 450 to 800 L/kg of tuber dry matter depending on the environmental conditions (Wright and Stark, 1990). When compared to legumes and grain crops, potatoes have a shallow root zone with 85% of root length within the upper 0.3 m soil layer (Opena and Porter, 1999). In soils having low water holding capacity, the potato crop needs more water during periods of high evapotranspiration (ET) (Ojala et al., 1990). Several irrigation trials in different parts of the world have discovered that potato is a moisture sensitive crop (Ierna et al., 2011; Ierna and Mauromicale, 2006; Onder et al., 2005; Yuan et al., 2003; Fabeiro et al., 2001; Opena and Porter, 1999; Porter et al., 1999; Shock et al., 1998; Foti et al., 1995; Marutani and Cruz, 1989; Hang and Miller, 1986; Shalhevet et al., 1983). Both the deficit and the excess of soil moisture within the potato root zone cause reduction in potato yield (Western Potato Council, 2003). The sparse and shallow root system (0.5-0.6 m), and the fast stomatal closure at a relatively high soil moisture make it less tolerant to water deficit (Harris, 1992). With increasing soil moisture stress, photosynthesis and transpiration rates decrease very rapidly in potatoes compared to other crops (Hang and Miller, 1986). There is a threat of potato plant stunting, if the stress condition is sustained for a long time (Ojala et al., 1990). Harris (1978) reported that soil water content of less than 50% of maximum available water within the potato root zone during the tuber initiation corresponded to a drastic reduction in the yield. In order to meet the ET losses and to maintain optimal soil moisture tension (25 kpa), the average daily water requirement for growing potatoes falls between 3-5 mm (Marutani and Cruz, 1989).

Water requirement of potato crop increases gradually from emergence until the developing canopies begin to overlap. After two weeks of row closure by the overlapping canopies, the daily water requirement of potato plants remains nearly constant until the vines start to mature. After vine maturation, the water requirement declines rapidly. The total growing season of potato may be divided into five stages i.e. (1) sprout development, (2) vegetative growth, (3) tuber initiation, (4) tuber bulking, and (5) maturation stage. The effect of water extremes (excess or deficit) on tuber yield is different at different growth stages (Opena and Porter, 1999). An adequate supply of soil moisture is crucial at all stages but soil moisture stress during the tuber initiation and bulking stages limits the yield (Jefferies and Mackerron, 1993). Water stress at tuber initiation and early bulking stages suspends the potato growth for some time after which it resumes. It leads to a reduction in marketable potato yield by increasing tuber malformations. Mid-bulking is the most critical stage of potato growth. Water stress at this stage causes a reduction in tuber size and total yield (Ojala et al., 1990).

Depending on environmental conditions, soil type and cultivar, the water requirement of potato crop falls between 350 and 500 mm throughout the growing season in different parts of the world (Sood and Singh, 2003). This requirement is partially fulfilled by precipitation and the deficit is applied through artificial means i.e. supplemental irrigation. There are no specific guidelines available for supplemental irrigation depth because of the wide diversity of rainfall pattern, temperature, and soil conditions under which potatoes are grown (Silver et al., 2011). Potato receives an average of 90 mm as supplemental irrigation in Manitoba (Western Potato Council, 2003). Silver et al. (2011) reported that the variability of crop yield caused by inconsistent rainfall might be decreased by supplemental irrigation. Supplemental irrigation caused an increase in tuber yield of two potato cultivars in New Brunswick but the response varied with sites and climatic conditions (Belanger et al., 2000).

Potato is a popular cash crop in Southern Manitoba due to the higher economic benefit and returns as compared to other crops grown in Manitoba. The potato producers in Southern Manitoba have been facing poor product quality and inconsistent yield due to the great variability of field moisture regime (MASC, 2010). Excessive precipitation and/or supplemental irrigation can contribute to a rise in the water table elevation and eventually lead to adverse effect on root zone aeration. Therefore, the presence of water table at the recommended depth below the ground surface is important.

Self-propelled mobile irrigation systems e.g. sprinkler/spray irrigation with center pivot or linear move, and rain gun systems are generally used for irrigating the potato crop in Southern Manitoba. Major advantages of these systems include convenience, application uniformity, and relatively higher water use efficiency than other forms of sprinkler irrigation systems. The high level of automation and low consumption of electric power, manpower and water, increase the economic significance of overhead irrigation systems (Tacker et al., 2004). The irrigation efficiency of linear move irrigation system is reported to be up to 90 % (Hanson, 2005) while center pivot has lower irrigation application efficiency (80%). Many researchers have reported considerable yield increase using self-propelled linear move irrigation system in several parts of the world (Dukes and Perry, 2006; Amir and Alchanatis, 1992; Evans at al., 1995). Many factors influence the sprinkler irrigation uniformity. These factors include wind speed and direction, sprinkler nozzle characteristics such as size and pressure, sprinkler spacing (Seginer and Konstrinsky, 1975; Brito & Willardson, 1982; Vories and Von Bernuth, 1986; Seginer et al., 1992; Heermann and Hein, 1968) riser height (Volker and Hart, 1968), field topography (Evans et al., 1995), and jet straightening vane inside the main nozzle, discharge angle, number and configuration of the sprinklers (Tarjuelo et al., 1999a, 1999b).

In areas where the groundwater table is shallow, there is a potential for upward water flux to meet part of the crop water demand. Contribution of shallow groundwater to the plant roots (subsurface irrigation) may reduce the required volume of water applied through overhead irrigation. However, groundwater quality should be adequate to achieve the high yield goals. Depth of groundwater from the ground surface, growth stage, and daily ET are the main factors controlling the amount of shallow groundwater contribution to the plant roots (Ayars et al., 2006). Ayars and Schoneman (1986) reported the contribution of upward flux of water from groundwater located at 1.7 m depth below the ground surface to meet the needs of increased ET. They further attributed the increase in water table depth from 1.7 m to 2.1 m to the contribution of water from groundwater to the plant roots. During periods of high ET, Wallender et al. (1979) reported 60% contribution of groundwater to meet the cotton crop water demand. Pratharpar and Qureshi (1998) found that shallow water table could replenish ET and decrease surface irrigation requirements by up to 80% without compromising crop yield. Soppe and Ayars (2003) found groundwater contribution up to 40% of daily safflower crop water needs met by upward flux from the water table located at 1.5 m depth. Kahlown et al. (1998) found a significant groundwater contribution from water table depths less than 1.0 m compared to water table depths exceeding 2 or 3 m. Shallow groundwater contribution to the plant roots plays an important role in the water balance within the plant root zone.

Uniformity of application of irrigation water is necessary for uniform growth and development of any crop. American Society of Agricultural Engineers (2003) Standards has explained the procedures for uniformity testing. Many researchers have reported the reduction in yield under water deficit/excess conditions (Onder et al., 2005; Yuan et al., 2003). Therefore, irrigation management is an essential for higher tuber yield and better water use efficiency. The main objective of this study was to determine the impact of supplemental irrigation via an overhead irrigation system on water table depth and potato yield in Manitoba.

2.2 MATERIALS AND METHODS

2.2.1 Study Site

A two year study (2013-2014) was conducted in Southern Manitoba, south of Winkler (49^o 10`N Lat., -$97^o$ 56`W Long., 272-m elevation) in the rural municipality of Stanley to compare the effect of two water management treatments i.e. Irrigated (IR) and Non-Irrigated (NI), on tuber yield and water uptake. In the first year of study (2013) experimental location was at the Canada Manitoba Crop Diversification Center (CMCDC) farm while the second year of the study was conducted at the Hespler Farm site one km away (2014). The soil characteristics are similar at both sites.

2.2.2 Climatic Conditions

The climate of study area is typically humid continental; resulting in dry cold winters and hot, frequently dry summers (Natural Resources Canada, 1957). The growing season in this area usually starts in May and lasts up to the end of August. Harvesting is done by mid-September. The average summer temperature typically ranges from 12 to 22 °C, while average temperature range for winters is -15 to -25 °C. The study area gets the most heat units for crop production in Manitoba. Winkler receives an annual average precipitation of 533 mm. However, the growing season receives 342 mm precipitation in the form of rainfall (Environment Canada, 2013).

2.2.3 Soil Type

Winkler having the most fertile soil in Manitoba serves as a regional hub for agriculture, with potato, corn, and beans as the major crops. The study area has coarse-textured sandy loam soil (70% sand, 19% silt, 11% clay). This soil type is considered suitable for irrigation and is among the best soils for agricultural production. The average field capacity (FC) and permanent wilting point (PWP) of this soil are 28% and 11.6%, respectively on a volumetric basis (Whetter and Saurette, 2008).

2.2.4 Experimental Design

In 2013, the field area of 1.2 ha (2.97 ac) was divided into six equal plots of approximately 0.2 ha (0.49 ac) with dimensions of 44.6 m X 40.3 m. In 2014, an area of approximately 1.29 ha (3.19 ac) was divided into six equal plots with dimensions of 50 m X 44 m. The field plots were replicated three times with Randomized Complete Block Design (RCBD). All the plots were planted with potatoes. In 2013, water was applied using a linear move irrigation system and in 2014 a rain gun irrigation system was used for the irrigated (IR) treatments which also received rainfall. The selection of the irrigation system was dependent on what was available at the site. The irrigation water was pumped from a reservoir established and maintained by a group of local farmers who captured and stored the spring snowmelt runoff. The three Non-Irrigated plots only received rainfall in both years. Soil moisture contents and soil water tension were measured in each plot at 0.2, 0.4, 0.6, 0.8 and 1.0 m depths from the ground surface, throughout the growing season using C-probe and Watermark sensors, respectively. Observation wells were installed in the center of each plot to continuously measure the depth to the groundwater table.

2.2.5 Instrumentation and Data Collection

Water level sensors (WLS) (Solinst Levelogger Junior 3001, Solinst Canada, Ltd., Georgetown, Ontario, Canada) were used to monitor the groundwater level in each plot throughout the season. These sensors were set to take a reading at half an hour intervals. These sensors were hung inside the piezometers installed at the center of each plot. The piezometers were made from 2.5 m long steel pipes with an inner diameter of 41 mm. In order to avoid any hindrance to farming operations, such as hilling and spraying, all the piezometers were installed along the crop rows. The piezometers were manually installed using a soil auger. Manual readings of ground water level were also taken using a water level sensing tape as a check. A barometric pressure sensor (Solinst Barologger Gold) was used for subsequent barometric correction of the water level sensor data.

Volumetric soil moisture contents and soil temperature were monitored using capacitance/frequency domain probes (C-probe) (Model EC-5, Decagon Devices, Inc., Pullman, Wash.) continuously throughout the growing season. These probes were installed at five different depths (0.2, 0.4, 0.6, 0.8, and 1.0 m) in the center of each plot. The C-probe provided real time soil moisture and soil temperature data through the Weather Innovations Network (WIN) website. Logging interval was 15 minutes. Soil water tension (kPa) was tracked at five consecutive depths (0.2, 0.4, 0.6, 0.8, and 1.0 m) by Watermark sensors installed at the center of each plot.

Precipitation, temperature, wind speed, relative humidity and solar radiation data were collected continuously on site on a daily basis through the Manitoba Ag Weather Network station located on site (Spectrum Technologies, Inc. Weather Station, 2000 Series). The reference evapotranspiration (ET_o) was computed using the Penman-Montieth method. In 2013, the irrigation water was applied using a linear move (LM) irrigation system (O3000 Orbitor, Nelson Irrigation Corporation, Walla Walla, WA). The linear move irrigation system was tested according to ASAE standards for uniformity of application prior to the critical growth stage i.e. mid to late June. In 2014, the irrigation water was applied using a travelling gun irrigation system.

The stage of plant growth and rooting depth were the main factors considered in determining the depth of irrigation (mm). Allowable depletion for the irrigated plots was based on 25% available water. This was corresponded to a soil matrix tension of 25 kPa. Irrigation application was triggered when the tensiometer reading exceeded 25 kPa at any of the 0.2, 0.4, 0.6 m soil depth in the irrigated plots. Volume of irrigation was based on % volumetric depletion integrated over the depth of the root zone (600 mm). Field capacity (FC) was determined using C-probes by saturating the soil soon after installation. Irrigation nozzles were manually turned on/off to ensure no irrigation outside of the selected plot boundaries. Irrigation application rates were measured by in-field rain gauges. The irrigation rate was adjusted to replenish the daily ET of the potato crop.

Seedbed was prepared by mowing the corn stubble and tilling in early May. Fertilizer (N, P, K and S) rates for the study area were based on soil test results. Immediately after broadcasting fertilizers, all the plots were cultivated to incorporate fertilizer with a chisel plough. All the plots were fertilized equally, and based on “very high” target yield to ensure that nutrients are not limiting. The cultivar used in this study was Russet Burbank, a commonly grown cultivar in Manitoba. Hilling/ridging was done by power hiller to stabilize the stems of potatoes against wind effects. Berming was done along the plot boundaries following hilling operations to minimize overland flow of surface water between plots and from outside the study area. Seed spacing between the rows was kept at 0.91 m (36 in.) whereas within row seed spacing was maintained at 0.36 m (14 in.). Planting was done mechanically on May 17th in 2013 and on May 13th in 2014. Fungicides were applied on a weekly basis. However, herbicides and insecticides were applied when needed. All the other agronomic practices were carried out in accordance with the Manitoba Potato Production Guidelines.

At maturity, potatoes were flailed and harvested on three 20 m length strips per plot. Potatoes were harvested using a single row potato digger and collected in burlap bags, separated by treatments, and weighed in the field. Harvesting was done on September 26th in 2013 and September 25th in 2014. Statistical analysis was done using JMP software (ver. 8, SAS Institute, Inc., Cary, N.C.).

2.3 RESULTS AND DISCUSSION

2.3.1 Weather Conditions at the Site

The 2013 growing season (May to September) received 12% higher rainfall (389 mm) compared to the 30-year average (342 mm). During this period the average T_{max} was 23.6 ^{o}C and T_{min} was 10.2 ^{o}C. However, the 2014 growing season was comparatively drier with a total precipitation of 262 mm (26 % less than the 30-year average) and an average T_{max} of 23 ^{o}C, and T_{min} of 9.5 ^{o}C. On average, the potato crop in Manitoba needs 90 mm of supplemental irrigation (Western Potato Council, 2003). Using eleven irrigation events, a relatively higher (130 mm) than normal supplemental irrigation was applied during the 2013 growing season. In 2014, overhead irrigation was carried out five times, with a total application of 95 mm.

In the beginning of the growing season (sprout development and vegetative growth stages), supplemental irrigation was not required in both years because rainfall was sufficient to meet the crop water demand. In 2013, total precipitation for the month of May was reported as 144 mm. The supplemental irrigation was done, when needed, from 29 June to 20 August (53 days) in 2013, which coincided with the tuber initiation and tuber bulking stages. During this period, total rainfall depth was reported as 120.6 mm. The total amount of supplemental irrigation was considerably higher than the average annual moisture deficit of 90 mm during this year. Since the tuber bulking stage experienced a number of days with > 25 ^{o}C, higher than normal supplemental irrigation was needed. During the months of May, June and September the potato crop was sustained by the moisture received through rainfall.

In the 2014 growing season, a 30-day dry period from 23 July (tuber initiation stage) to 21 August (tuber bulking stage) with only 14.6 mm rainfall resulted in the need for supplemental irrigation. The tensiometer readings fell below 25 kPa during several days because rainfall was not adequate to meet the crop water demand. During this period, supplemental irrigation was applied to the irrigated (IR) treatment, through the five irrigation events to replenish the losses from evapotranspiration (ET). Although 2014 was a comparatively drier year, lower mean temperature (T_{max}) during the critical growth stages of tuber initiation (11.4 ^{o}C) and tuber bulking (10.9 ^{o}C), lowered the ET demand. A total of 97.7 mm rainfall received during critical growth stages and contribution of shallow groundwater to the plant roots reduced the need for irrigation. The irrigated period spanned over the tuber initiation and tuber bulking stages in both years. Since the potatoes do not need as much water during the maturation stage (Rowe, 1993), no supplemental irrigation was applied during this stage.

2.3.2 Potato Yield

Yield data were analyzed using ANOVA, and means were compared using Student's t-test at the 0.05 significance level. The total growing season lasted about 135 days in both years. Average potato yield in the non-irrigated (NI) plots were lower compared to the irrigated (IR) plots in both years, although the differences were statistically not significant (Table 2.1). Better availability of water within the potato root zone resulted in a comparatively higher yield. In 2014, yields were higher than in 2013 across both treatments. Several factors including change in the study location, weather conditions, and initial groundwater levels may be attributed to the higher yield in the 2014 growing season.

Table 2.1 Potato yields for overhead irrigated and non-irrigated treatments. Analysis are based on Student's t-test at 0.05 significance level (SE = standard error).

Treatment	2013 Yield		2014 Yield	
	MT/ha	SE	MT/ha	SE
Overhead Irrigated	51.2 a	1.09	62.9 a	1.77
Non-irrigated	50.0 a	1.62	61.7 a	4.26

2.3.3 Depth to the Groundwater Table

Table 2.2 shows the seasonal average water table depth from the ground surface for both years. The analysis of variance showed a significant difference in the depth to water table between the treatments.

Table 2.2 Seasonal average water table depth from the ground surface for overhead irrigated and non-irrigated treatments. Analysis are based on Student's t-test at 0.05 significance level.

Treatment	Seasonal Average Ground Water Depth (m)	
	2013	2014
Overhead Irrigated	1.69 a	1.10 a
Non-irrigated	1.77 b	1.03 b

Potato yield from both treatments was significantly negatively correlated with the average groundwater depth during each of the three important potato growth stages i.e. tuber initiation, tuber bulking, and maturation stage in both years (Fig. 2.1). Although the groundwater depth was significantly negatively correlated with the potato yield during all the three stages, the tuber initiation stage was influenced the greatest. This shows that the tuber initiation stage is the most critical stage, among all the potato growth stages, with respect to the moisture availability and moisture deficit at this stage has the greater impact on the total yield. The deeper the groundwater table, the lower the supply of water to the root-zone by upward flux. In the 2013 growing season (CMCDC farms), the groundwater level was lower as compared to the 2014 growing season (Hespler farms). Therefore, in 2014, yields were higher than in 2013 across both treatments. However, the water table was never within the effective root zone depth of potato tubers (0.6 m). Therefore, the vadose zone remained sufficiently aerated providing conditions conducive for plant growth.

Water table depth from the ground surface was responsive to the recharge events. However, the pattern of groundwater dynamics was different between the two years due to the differences in soil moisture status, which impacted the unsaturated hydraulic conductivity within the soil profile.

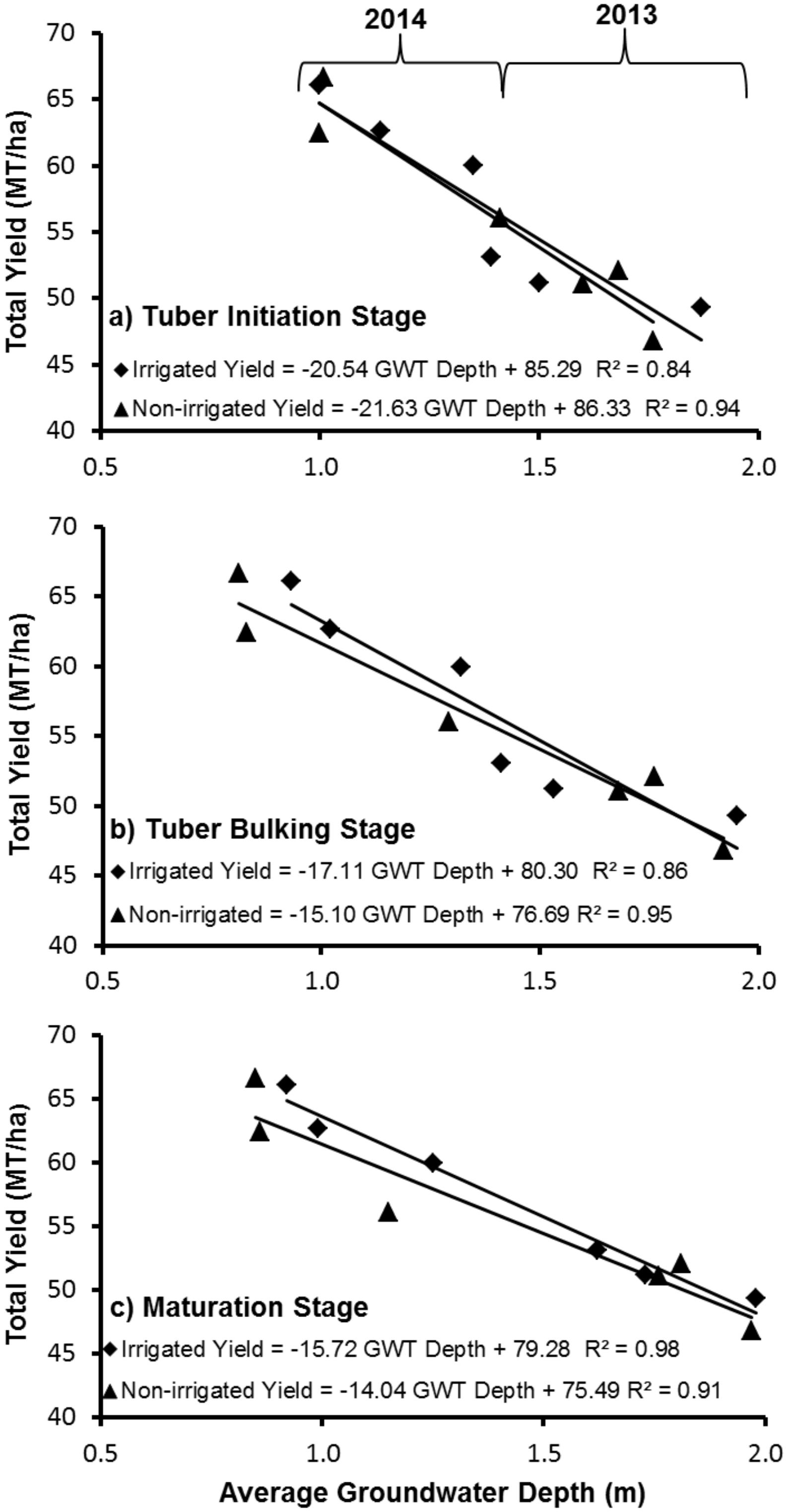

Figure 2.1 Relationship between stage specific average water table depth and potato yield for 2013 (CMCDC Farm) and 2014 (Hespler Farm) growing seasons.

2.3.4 Water Table Response in 2013

Figure 2.2 shows the variations in water table depth from the ground surface as an average for the three replicates in relation to the recharge events (precipitation and overhead irrigation) in 2013. Despite large rainfall events in 2013, the water table remained below the depth of the tile (0.9 m) due to higher plant water uptake as a result of the higher seasonal average temperature (26 °C). Ground water level in both treatments remained the same prior to the first irrigation event. After the application of supplemental irrigation, ground water level rose in the irrigated treatment due to the contribution of the recharged water to groundwater. However, in the non-irrigated treatment, water table depth from the ground surface declined at this stage. Water table depth in the non-irrigated treatment remained below the water table depth in the irrigated treatment from the tuber initiation to maturation stage as a result of upward flux of groundwater to meet the plant water requirement.

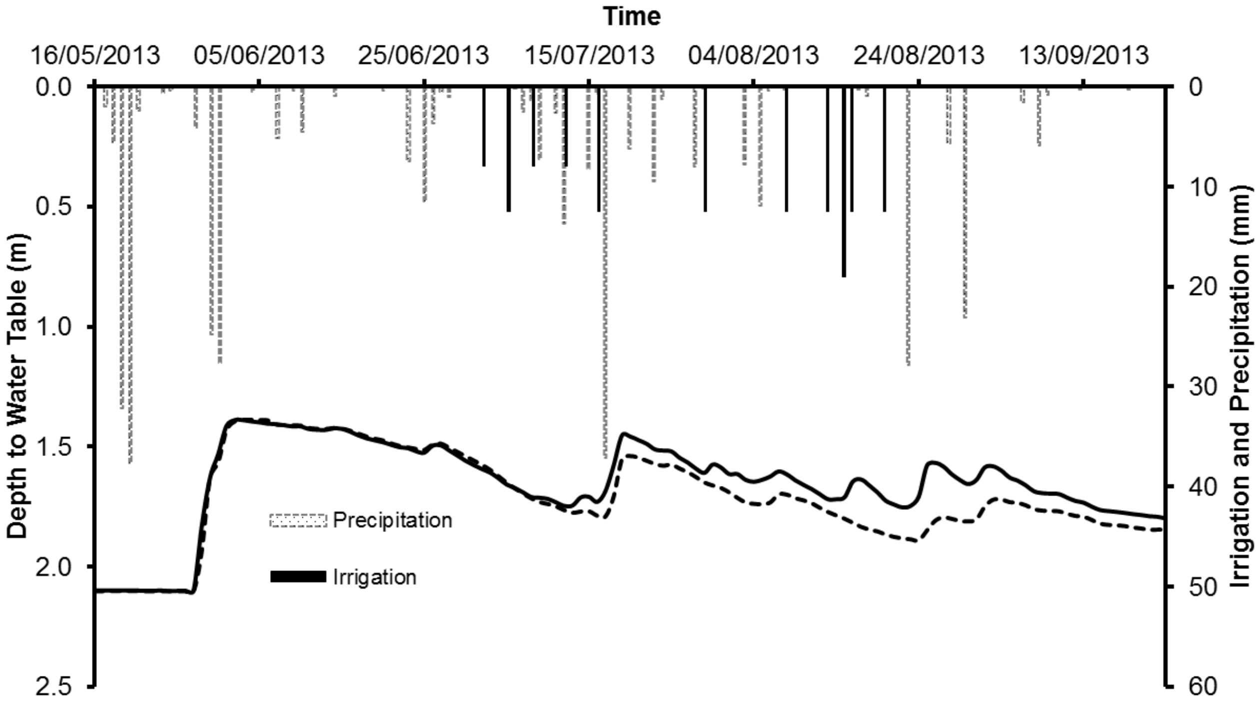

Figure 2.2 Water table depth, precipitation, and irrigation amounts in 2013.

Total precipitation during the 2013-growing season was reported to be 389 mm. An adequate water supply through the rainfall events increased the hydraulic conductivity between the soil profile and the saturated zone (water table). The rainfall contributed sufficient moisture within the potato root zone leading to a lower uptake from the groundwater table. However, during the rain-free periods, the plant roots pulled up the water from the groundwater table to replenish the soil moisture within the root zone. This upward migration of groundwater towards the plant roots resulted in the drop in groundwater level in the non-irrigated treatment more than the irrigated treatment, commensurate with plant water needs. In order to verify this hypothesis, three rain-free and three rainy periods at different growth stages were selected from the non-irrigated treatment to analyze the contribution of groundwater due to the ET and the resultant crop water demand (CWD). The ET was calculated specifically for the potato crop at the study location.

Figure 2.3 shows the cumulative contribution of groundwater to the root zone in the Non-irrigated (NI) treatment during the three rain-free and rainy periods along with the corresponding cumulative crop ET. The initial value of each period was taken as zero to calculate the cumulative values for the subsequent days within each period. Groundwater level was found to be responsive to the crop ET. Generally, the water table depth from the ground surface increased with an increase in crop ET confirming the contribution from the shallow groundwater table. The lowering of the ground water table may be attributed to the upward migration of water during the dry periods. The depth of water released to meet the crop water demand was obtained by multiplying the drop in water table height by drainable porosity (25%) to develop the graphs presented in Figures 2.3 and 2.5. The average daily volumetric water content within the effective root zone depth (0.6 m) during dry period 1, 2, and 3 were recorded as 0.29, 0.26, and 0.27 $m^3 m^{-3}$, respectively. The constant water content within the soil profile in the absence of rainfall confirms the replenishment of crop ET by the upward migration of water from the water table. During the rainy periods, the depth of rainfall was recorded as16.8, 4.1, and 20.1 mm, respectively. The groundwater table did not contribute to the potato root zone during the rainy periods 1 and 3 because adequate depth of water from rainfall replenished the crop water demand negating the upward migration of groundwater. This was confirmed by no change in water table depth during these periods. However, during the rainy period 2, only 4.1 mm rainfall depth resulted in the upward migration of groundwater to meet the crop water demand with consequent lowering of the water table.

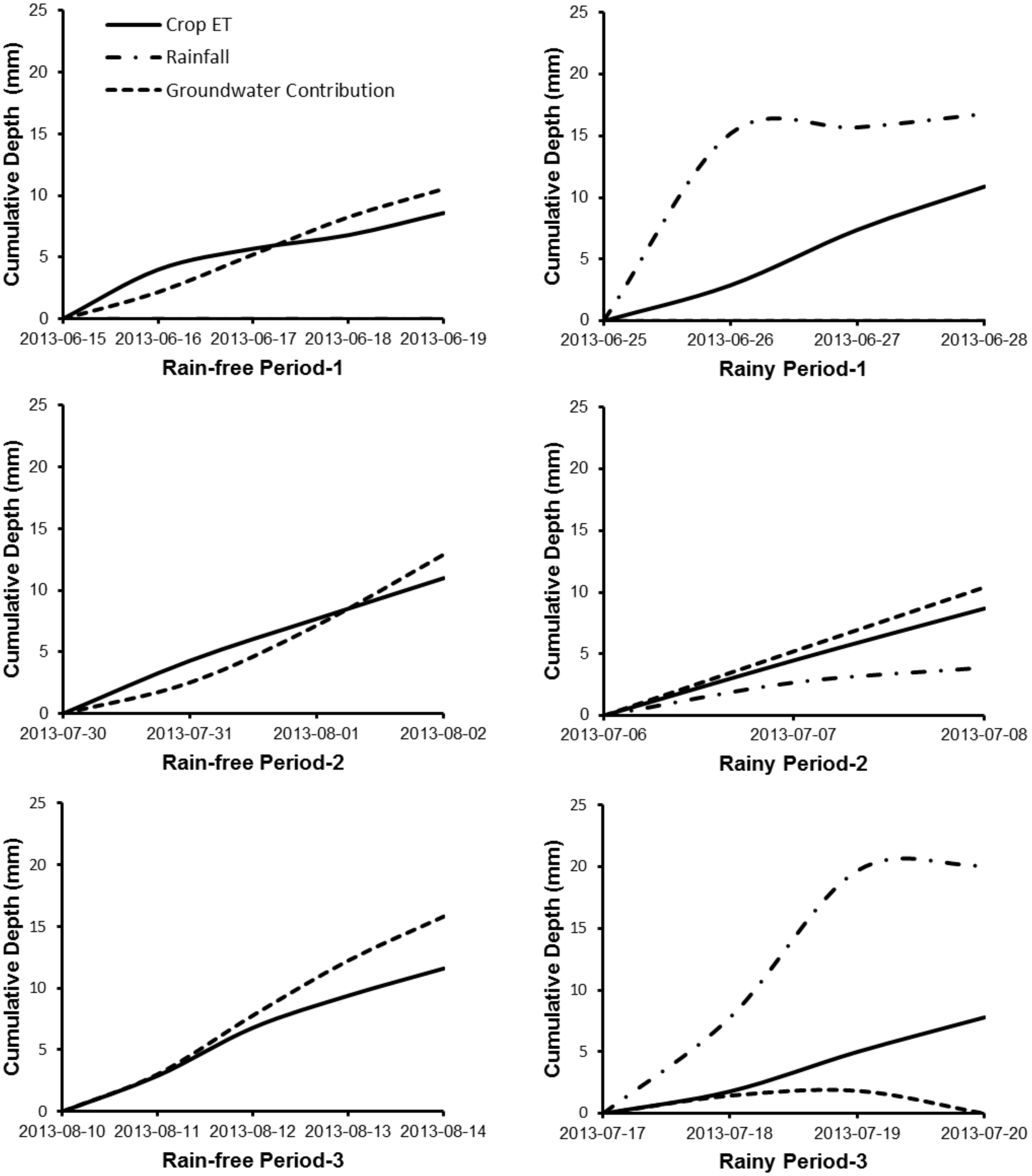

Figure 2.3 Cummulative groundwater contribution to the non-irrigated treatment during rain-free and rainy periods (2013).

2.3.5 Water Table Response in 2014

Figure 2.4 shows the variation in water table depth from the ground surface as an average for the three replicates in relation to the recharge events (precipitation and overhead irrigation) in 2014. During this growing season, although the water table often rose to the level of tile drains no significant tile flow was recorded. Regardless of the supplemental irrigation, groundwater level in the non-irrigated plots remained very close to the groundwater level in the irrigated plots until the middle of tuber bulking stage. During this period the irrigated plots received a total of 95.2 mm supplemental irrigation with five irrigation events to meet the crop ET.

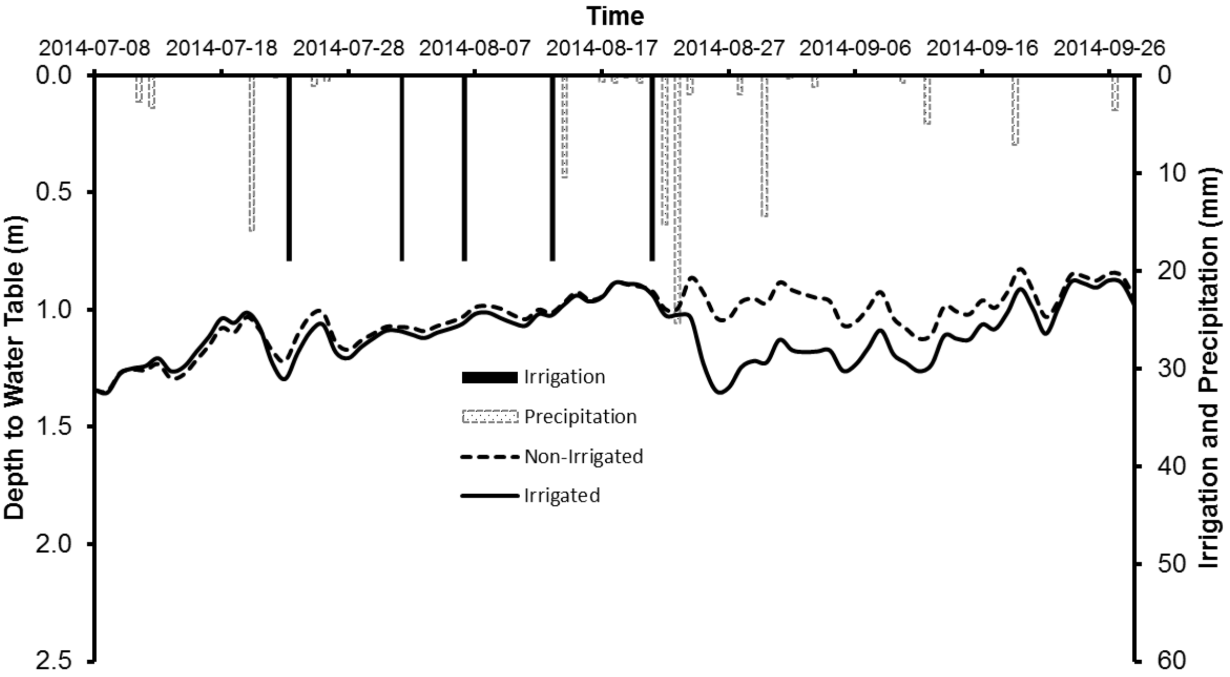

Figure 2.4 Water table depth, precipitation, and irrigation amounts (2014).

The water applied through irrigation remained within the root zone and was used up by the plant. The groundwater table depth remained the same indicating no contribution to the upward migration during this period. A 30-day dry period from August 25 to September 25 (mid bulking to maturation stage) with only 30.9 mm rainfall resulted in upward movement of groundwater in the irrigated plots leading to a lowering of the watertable. However, in the non-irrigated plots the watertable remained significantly higher than the irrigated plots indicating no contribution to upward movement. A decline in groundwater level in the irrigated plots starting from the mid of tuber bulking stage, confirms the contribution from the groundwater. Crop water demand is relatively higher at tuber bulking stage (Rowe, 1993). The dry conditions and a higher hydraulic conductivity in the irrigated plots at this stage supported the upward migration of groundwater. On the contraty, the dry conditions in the non-irrigated plots may have resulted in a lower hydraulic conductivity leading to a reduction in the upward water flux from the watertable. The contribution of groundwater to the plant roots started to decrease as the growth stage proceeded towards maturation in late September 2014. In order to verify this hypothesis, three rain-free and rainy periods were selected from the irrigated treatment at different growth stages to analyze the cumulative contribution of groundwater due to the change in crop ET.

Figure 5 shows the cumulative contribution of groundwater to the root zone in the irrigated treatment during the three rain-free and rainy periods along with the cumulative crop ET. Groundwater level was found to be responsive to crop ET. Generally, the water table depth from the ground surface increased with an increase in crop ET confirming the contribution of shallow groundwater towards the plant roots. Lowering of the ground water table may be attributed to the upward migration of water during the dry periods. The average daily volumetric water content within the effective root zone depth (0.6 m) during dry period 1, 2, and 3 were recorded as 0.19, 0.22, and 0.21 $m^3 m^{-3}$, respectively.

During the rainy periods, the depth of rainfall was recorded as 6, 1.5, and 14.8 mm during rainy period 1, 2 and 3, respectively. Groundwater did not contribute to the potato root zone during the rainy periods 1 and 3 because an adequate depth of rainfall met the crop ET. However, only 1.5 mm rainfall depth during the rainy period 2 led to the upward migration of groundwater to meet the crop ET.

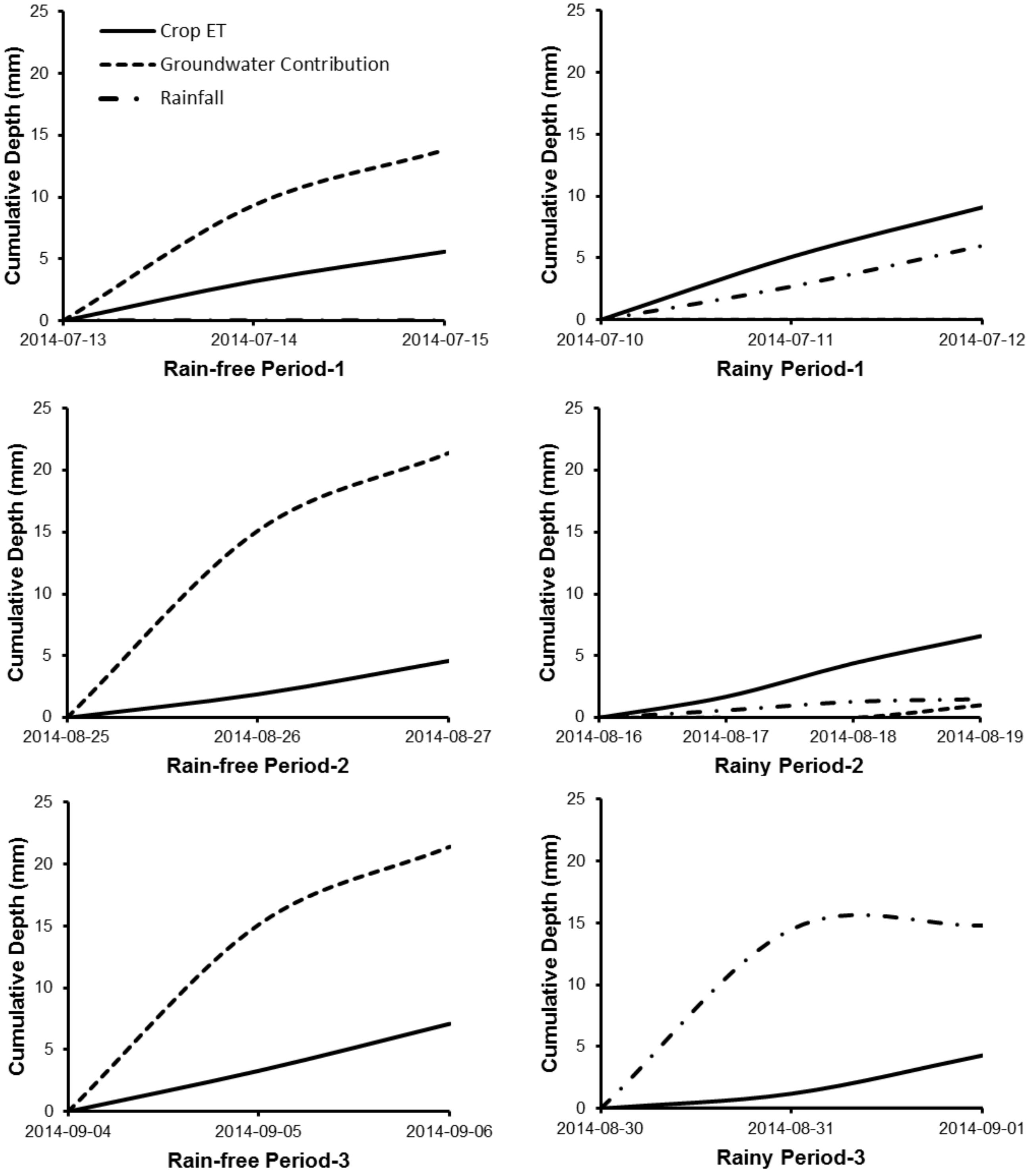

Figure 2.5 Cumulative groundwater contribution to the irrigated (IR) treatment during rain-free and rainy periods (2014).

2.3.6 Growth Stage Specific Groundwater Levels

A statistically significant difference between irrigated and non-irrigated treatments was found in the groundwater levels at the tuber initiation stage (p = 0.0006) and tuber bulking stage (p = 0.0001) in the growing season of 2013 (Fig. 2.6). However, the difference was not significant at the maturation stage (p = 0.308). In 2014, the difference between groundwater levels in both of the treatments was not significant at tuber initiation stage (p = 0.320). However, a statistically significant difference was found in the groundwater levels at tuber bulking (p = 0.0001) and maturation stages (p = 0.020).

As crop water demand is different at different growth stages, groundwater contribution to crop water use varied depending on the potato growth stage and rainfall event. Crop water demand decreases towards the maturation stage. The 2013 growing season was wetter with above average rainfall. Wetter conditions in the beginning (sprout development and vegetative growth stages) and later period of the growing season (maturation stage) led to lesser need for contribution from the groundwater table in both treatments during these growth stages. Soil moisture within the potato root zone was adequately being replenished by frequent rainfall events. The tuber initiation stage received 114.5 mm rainfall precluding the need for contribution from the water table. However, the tuber bulking stage was relatively drier with only 67.1 mm rainfall and 23 rain-free days. During this stage, daily ET in the irrigated treatment was being replenished by the application of overhead irrigation. However, plants in the non-irrigated treatment were fulfilling the crop water demand by upward flux from the shallow groundwater table. Similar results were reported by Ayars et al. (2009) and Kahlown et al. (2005) in response to shallow groundwater depths.

The 2014 growing season was comparatively drier with below average rainfall. During this season, 65% of the total seasonal rainfall occurred in the initial growth stages i.e. sprout development, vegetative growth, and tuber initiation. High rainfall events, during this period, led to a lower need for contribution from the groundwater table in both treatments. The difference between groundwater levels in both treatments was not significant at tuber initiation stage. During the tuber initiation stage only 38.1 mm irrigation water was applied in the irrigated treatment in two irrigation events. The supplemental irrigation during tuber bulking and maturation stages precluded the need for contribution from the water table in the irrigated treatment. The total irrigation application of 95.2 mm as supplemental irrigation improved the hydraulic conductivity between the root zone and the water table. The drier conditions in the non-irrigated treatment developed a capillary barrier below the root zone preventing contribution from the water table. Therefore, the difference between groundwater levels was significantly higher in the irrigated treatments during tuber bulking and maturation stages.

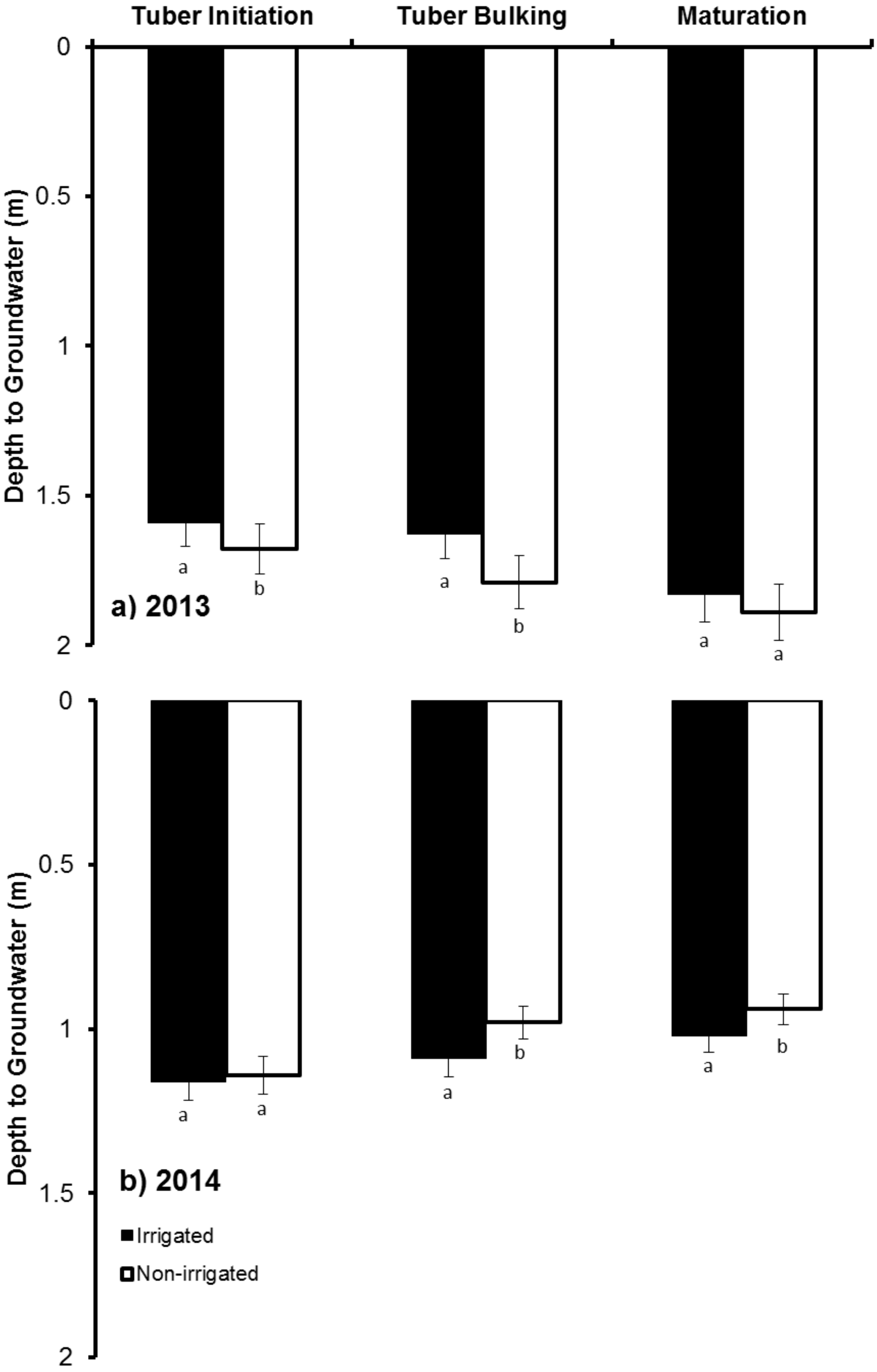

Figure 2.6 Growth stage specific average water table depth.

2.3.7 Soil Water Distribution within the Effective Root Zone

C-probes were used to continuously measure the water content at 0.2 m intervals within the top 1 m of the soil profile throughout the growing season. The daily average volumetric soil water content (SWC) within the effective root zone of potato (0 - 0.6 m) for the 2013 and 2014 growing seasons are shown in Figures 2.7 and 2.8, respectively. During the recharge event, the soil water content quickly increased in the top layer (0.2 m). However, the water infiltrated into the deeper soil layers after each recharge event. Daily ET gradually depleted the top layer water content in the following days making this soil layer drier. Therefore, the deeper layers remained wetter than the surface layer. As a result, the hydraulic conductivity of the soil increased within the root zone and the soil profile below the root zone. Improved hydraulic conductivity led to conditions conducive for upward movement of groundwater towards the plant roots. Higher water content at 0.4 and 0.6 m depths as compared to the top layer (0.2 m) in both treatments indicates the supply of moisture from the groundwater. In the absence of recharge events, the upward movement of water may have replenished the soil moisture depletion due to ET leading to a decline in the water table.

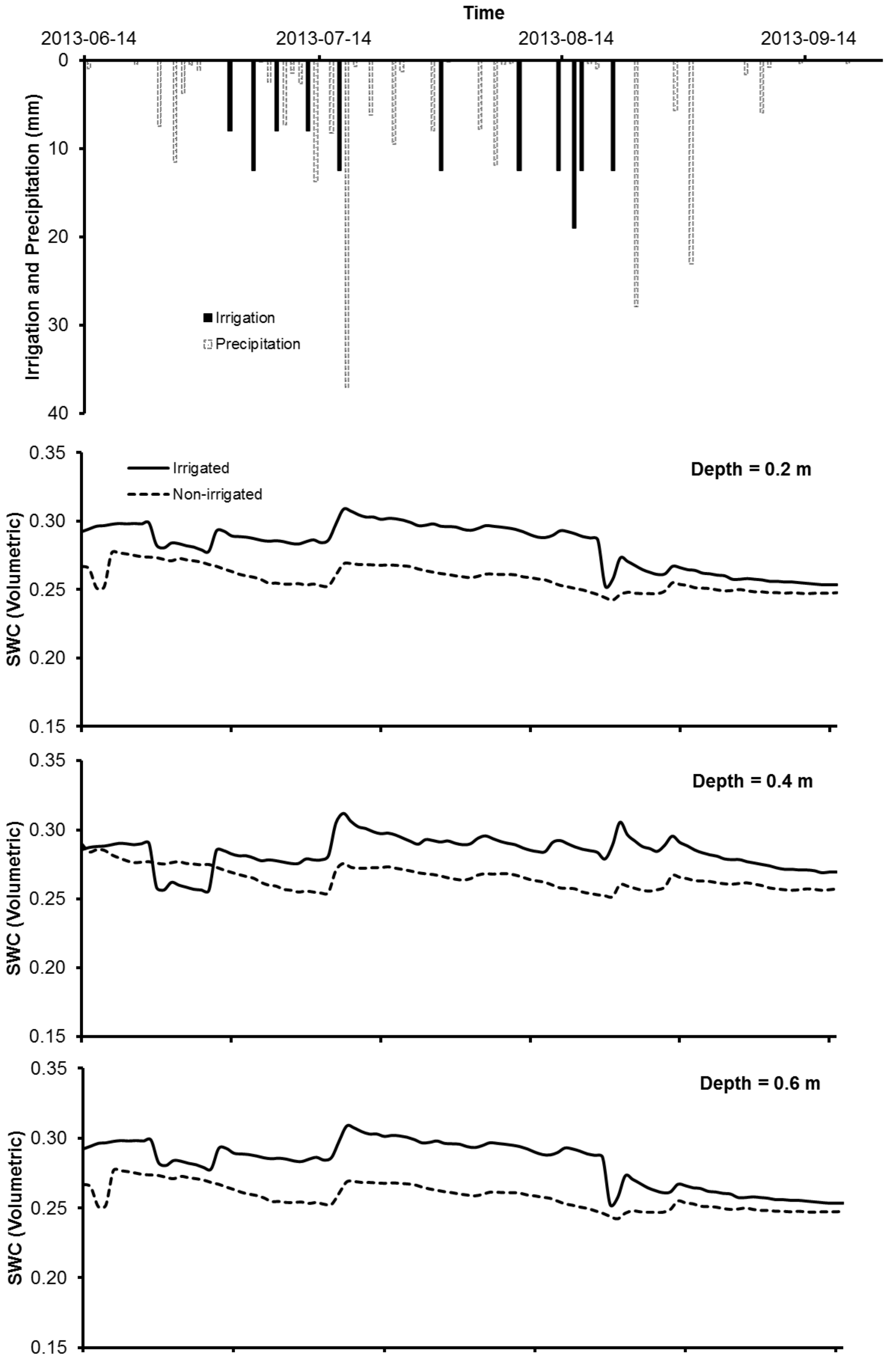

Figure 2.7 Volumetric soil water content (SWC) and recharge in the 2013 growing season.

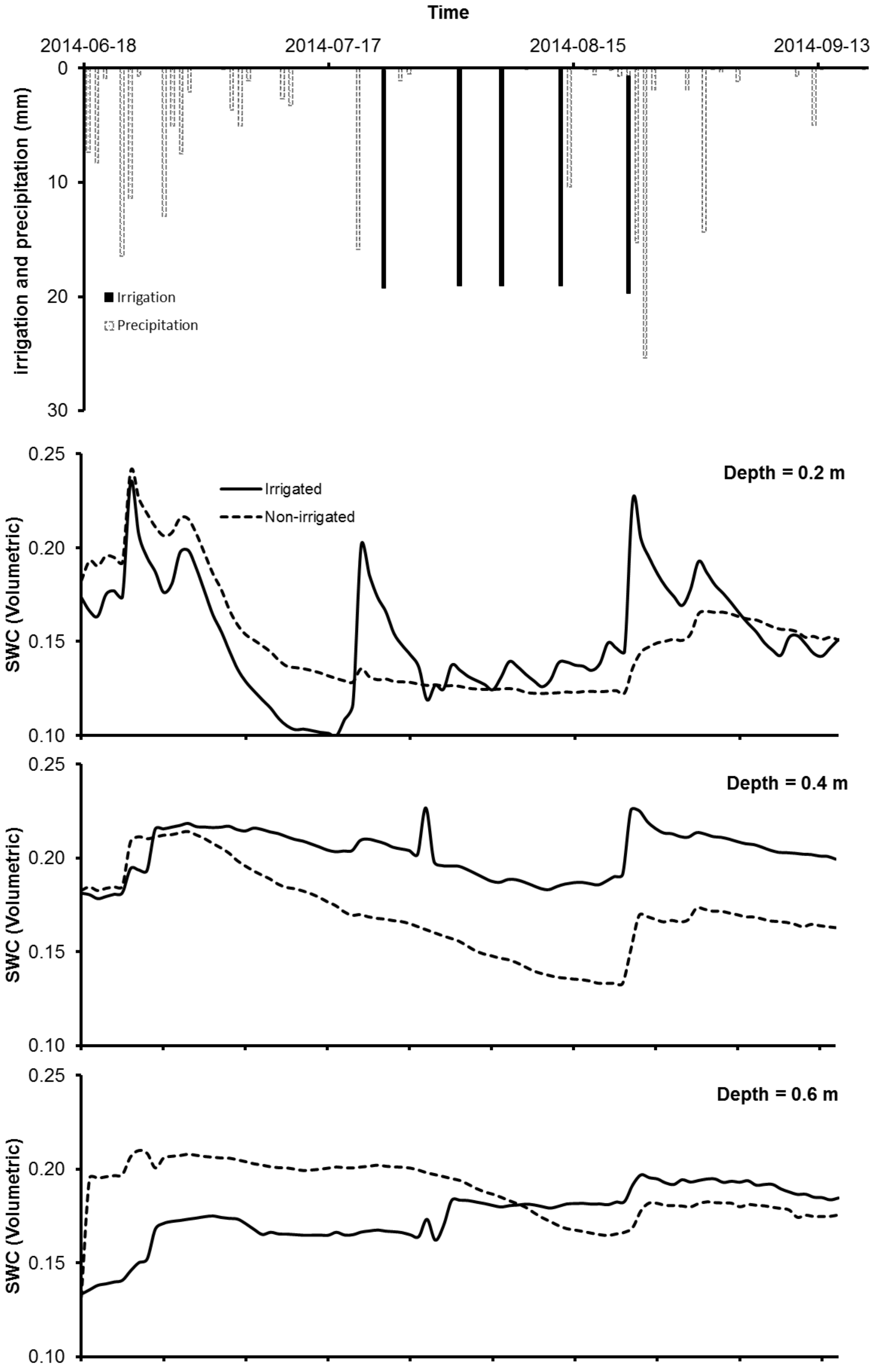

Figure 2.8 Volumetric soil water content (SWC) and recharge in the 2014 growing season.

High yield under dry conditions signifies the importance of upward migration of water from the shallow groundwater table. However, ground water quality may significantly affect the marketable yield and quality of potatoes. These results are in agreement with Cordeiro and Sri Ranjan (2012), who conducted a study in the same location to compare the yield of corn under no-irrigation and with overhead irrigation. They reported no statistical difference between the yields from the control treatment and treatments receiving the overhead irrigation. MASC (2013) reports also support these results. According to these reports Southern Manitoba experienced good crops in 2012 despite the dry weather conditions. In a study conducted by Follett et al. (1974) in sandy loam soil under shallow water table conditions with corn crop, they reported good corn yield in the absence of supplemental irrigation.

2.4 CONCLUSIONS

This study investigated the impact of overhead irrigation on potato yield under Manitoba conditions during two consecutive years. A trend of higher potato yield was observed in irrigated plots compared to non-irrigated plots in both years, although the difference in yield was not statistically significant. Both treatments received moisture through natural precipitation i.e. rainfall. However, both treatments had the potential to receive supplemental moisture from the shallow groundwater table. Better potato yield in irrigated plots showed the importance of soil moisture supply through overhead irrigation at critical stages of development. The irrigation water supplied through overhead irrigation system was sufficient to meet the crop water demand.

Water demand of potato crop corresponds to the stage of growth. In the very beginning of the growing season (sprout development and vegetative growth stages), plant root density is small and the water uptake is also small. Plant root density rapidly increases as the plant development proceeds from tuber initiation to tuber maturation stage. As the soil water within the root zone is rapidly depleted during these stages, upward migration of groundwater is needed to meet the water demand in the absence of rainfall/irrigation. This upward water flux is seen as an increase in soil moisture in the deeper layers. Conducive hydraulic conductivity in the soil profile facilitated the upward water migration leading to a decline in the groundwater table. The upward flux of groundwater to meet the crop water demand led to a lowering of the water table.

Shallow groundwater resources may significantly decrease the need for supplemental irrigation. Major natural sources of recharge to groundwater include rainfall and snowfall. These sources should be managed properly to make effective use of groundwater as a source for crop production. Southern Manitoba receives an annual average precipitation of 533 mm. Out of which approximately 65 % is received through rainfall and the rest is contributed by snowfall. Snowmelt runoff should be minimized and infiltration should be maximized during the snowmelt period to replenish the groundwater that could be available for use by the crops during the critical growth periods. Groundwater quality should be measured to ensure the quality is adequate to get good quality potatoes. Facilitating the upward migration of water at the expense of marketable yield is not desirable.

3. Effect of Soil Moisture Deficit on Marketable Yield and Quality of Potatoes

ABSTRACT: Tuber yield and quality are the two main factors that can increase or decrease the market value of potatoes. Soil moisture availability and nutrient concentration within the potato root zone play a pivotal role in controlling tuber yield and quality. This study was conducted in Southern Manitoba to compare the effects of overhead irrigation (IR) and no-irrigation (NI) on marketable tuber yield and quality during the 2013 and 2014 growing seasons. The total yield of potato was not significantly different between the two treatments in both years. In 2013, the marketable yield of the irrigated (IR) treatment (36.89 MT/ha) was 20% higher ($p = 0.017$) compared to the non-irrigated (NI) treatment (30.74 MT/ha). However, no significant difference in marketable yield was found between the irrigated (39.0 MT/ha) and non-irrigated (43.7 MT/ha) treatments in 2014. Excess nitrate accumulation within the root zone tends to promote the formation of over-sized tubers. Although the incidence of hollow hearts and sugar ends showed a higher trend in the non-irrigated treatment it was statistically not significantly different from the irrigated treatment. Overhead irrigation was found to be economically advantageous to produce better quality potatoes with higher marketable yields.

3.1 INTRODUCTION

The production volume of potato is 368 million tons from 19.3 million hectares which ranked it as the fourth most consumed staple crop in the world (Faberio et al., 2001, FAO, 2012). During the past few decades, potato production has grown to become an important component of the agricultural industry and the provincial economy of Manitoba. It is an important source of vitamin C (ascorbic acid) and has a significant nutritional value in human food (Burlingame et al., 2009). The share of potato in average annual diet of a global citizen is 33 kg on weight basis.

The increase in human population is stimulating the increase in demand for good quality potato tubers. In addition to quantity, potato quality has become important factor based on consumer demand. Potato quality is determined by tuber size, tuber weight, specific gravity, fry color, and brown center/hollow heart incidence. All these parameters collectively determine the marketable yield of tubers. Several factors affect the yield and quality of potato tubers including variety, environmental conditions (Ierna and Mauromicale, 2006), cultural practices (Yang et al., 2001), and water and nitrogen (N) supplies (White et al., 2007). Water and N inputs are the most important factors influencing tuber yield, quality and net return (Alva, 2008; Shock et al., 2007; Li et al., 1999).

Potato tubers are very sensitive to water stress. Water stress intensifies sprouting and malformation (Levy, 1986) and reduces the tuber size (Schafleitner et al., 2007). Other negative impacts of water stress and soil moisture fluctuations include knobbiness, pointed ends, dumbbells and bottle necks (Hooker, 1981), growth cracks (MacKerron and Jefferies, 1985), physiological disorders such as hollow heart and translucent end (Rex and Mazza, 1989), bruise susceptibility and heat stress (Hiller et al., 1985). Potato production can be divided into five growth stages i.e. (I) sprout development, (II) vegetative growth (III) tuber initiation, (IV) tuber bulking, and (V) maturation stage. Flint (1992) reported that potato growth stages might differ in time because they depend on environmental and cultural factors. As potato has a shallow and sparse root system: approximately 85% of the root length is concentrated in the upper 0.3 m of the soil (Iwama, 2008; Wang et al., 2006; Opena and Porter, 1999), water stress at any growth stage leads to a considerable negative impact on potato tuber yield and quality (Ahmadi et al., 2010; Shock et al., 2003; Eldredge et al., 1996; Lynch et al., 1995; Adams and Stevenson, 1990). That is why a continuous water supply to meet the crop water demand at different growth stages is highly recommended for better growth from sprout development to maturity (Ierna et al., 2011; Ierna and Mauromicale, 2006; Ojala et al., 1990; Miller and Martin, 1983). Effect of water stress is different at different growth stages of potatoes (Shock et al., 1993). Water stress during the vegetative growth stage reduces plant height, root expansion and number of tuber sets per plant. Potatoes at tuber initiation and tuber bulking stages are more sensitive to water stress as compared to the sprout development, vegetative growth, and maturity stages (Miller and Martin, 1987a). Water deficit at tuber initiation stage causes reduction in number of tubers produced per plant (MacKerron and Jefferies, 1986) whereas moisture stress at tuber bulking stage, even for a short period produces dumbbell-shaped, knobby or pointed-end tubers (Jefferies and MacKerron, 1993; MacKerron and Jefferies, 1988). If this stress persists for a longer period of time it follows tuber defects, such as internal brown spot (Haverkort, 1982).

In addition to irrigation, N fertilizer can also influence both yield and quality of potato tubers (White et al., 2007; Westermann, 2005). Maximum potato yield is obtained when N is available to plant roots during the periods of peak demands whereas extreme (deficit and/or excess) usage of fertilizer N results in reduced tuber yield and quality. Specific gravity (SG), an important quality determining parameter, decreases with increase in N application rates (Sparrow and Chapman, 2003; Feibert et al., 1998; Porter and Sisson, 1991; Laurence et al., 1985) while high SG of tubers is economically important because it reduces the quantity of oil needed for frying the potatoes (Lulai and Orr, 1979). Low specific gravity, sometimes, results in darker fry color, that may not be acceptable to the processing industry (Porter and Sisson, 1991). However, sugar-ends was reported to be a more important determinant of fry quality (Dahlenburg, 1982) compared to SG (Dahlenberg et al., 1990). The accumulation of sugar in the tip of the tubers leads to brown-tipped fries arising from caramelization of the sugar during frying (Gould and

Plimpton, 1985). Excessive accumulation of nitrates within the tuber root zone may also cause the occurrence of tuber disorders such as hollow heart (HH) in some cultivars of potato (Yang et al., 2001).

Many researchers have studied the effect of water and nutrient supply on potato yield and quality and reported that different cultivars behave differently under water excess or stress conditions (Hassanpanah, 2010; Kashyap and Panda, 2003; Ferreira and Carr, 2002; Panigrahi et al., 2001; Lynch et al., 1995; Shock et al., 1993) and nitrates extremes (Hutchinson et al., 2003; Zvomuya and Rosen, 2001; Maier et al., 1994; Admiraal, 1988). Waddell et al. (1999) and Ojala et al. (1990) reported a considerable decline in total and marketable tuber yields (tubers having less culls and knobs) in Russet Burbank cultivar attributed to increased soil moisture stress. Miller and Martin (1987a) experienced a significant reduction in average tuber size and SG in response to deficit irrigation at tuber initiation stage but no effect was observed on number of tubers produced by Russet Burbank. Painter and Augustine (1976) reported increased number of malformed tubers in Russet Burbank due to water stress during the early growth stages but it did not affect total tuber yield.

McCann and Stark (1989) found increased incidence of hollow heart (HH) at high moisture contents and excess nitrates in the root zone of Russet Burbank cultivar when tubers were 10 mm in diameter i.e. at vegetative growth stage. However, Porter and Sisson (1991) did not experience any increase in HH with rates of applied N in large Russet Burbank tubers while they found highest HH occurrence in large Shepody tubers due to excessive nitrates. Kara (2002) observed the favorable outcomes of nitrogen fertilization on specific gravity, dry matter content, crisps yield, and protein content of potato tubers. Maier et al. (1994) showed that maximum SG of tubers was reached at lower nitrates availability and vice versa. However, Dahlenburg et al. (1990) found lower SG in N-deficient case in potato tubers.

Potato is usually grown on sandy loam soils on the Canadian Prairies, especially in Manitoba. Overhead irrigation is extensively used in Manitoba to irrigate potatoes. Different irrigation methods and their effect on tuber yield and quality have been reported. These methods include plastic mulch (Hou et al., 2010; Wang et al., 2009), drip irrigation (Onder et al., 2005; Wang et al., 2006; Bhardwaj, 2001), and sprinkler irrigation (Shock et al., 2003; Halitligil et al., 2002; Hang and Miller, 1986). Sustainable agriculture demands water conservation and proper fertilizer use to protect water quality and quantity for future generations. Sustenance based on rainfall without supplemental irrigation has been successfully used in a number of crops (Domínguez et al., 2012; Geerts and Raes, 2009; Saeed et al., 2008; DaCosta and Huang, 2006; English and Raja, 1996). However, in case of potatoes many researchers reported reduction in tuber yield and quality with different soil type and tuber cultivar without supplemental irrigation. Cappaert et al. (1994) and Liu et al. (2006) found that potato crop can tolerate deficit soil moisture (DSM) at vegetative growth and maturation stage without significant reduction in tuber yield and quality whereas Fabeiro et al. (2001) reported that DSM during the last part of the growth stage led to lowest tuber production. Ahmadi et al. (2010) showed that DSM has no significant effect on potato yield compared to full irrigation (FI). Liu et al. (2006) studied the effects of FI and DSM on yield of potato at tuber initiation stages. They showed that potato tuber yield decreased significantly under DSM relative to FI that was in contrast with their previous study (Liu et al., 2006) where tuber yield was similar for the FI and DSM. However, some other studies have also reported significant or non-significant tuber yield loss under DSM compared to FI (Ahmadi et al., 2010; Jovanovic et al., 2010; Saeed et al., 2008; Shahnazari et al., 2007).

Although literature describing the impact of water stress and nutrient availability is available for other crops, literature for potato is sparse. The impact of nitrogen on tuber yield and quality under no-irrigation and overhead irrigation has not been investigated under Manitoba conditions. This study evaluates the growth stage specific influences of irrigation (required soil moisture) and no-irrigation (deficit soil moisture or moisture stress) with uniform application of nitrogen fertilizer on yield and quality of Russet Burbank potatoes. The objective of this study was to examine the effects of no-irrigation and irrigation applied through overhead irrigation system (linear move irrigation system) at tuber initiation and tuber bulking stages on marketable yield and quality of Russet Burbank potatoes.

3.2 MATERIALS AND METHODS

3.2.1 Study Site

A field study was conducted in southern Manitoba (49^0 10`N Lat., $-97^o$ 56`W Long., 272-m elevation) located south of Winkler, to evaluate the effects of no-irrigation (NI) and overhead irrigation (IR) on tuber yield and quality under the same nitrogen fertilizer application. Experiment was conducted at Canada Manitoba Crop Diversification Center (CMCDC) farm in 2013 (first year) while Hespler Farm located one km away from CMCDC farm was the experimental location in 2014 (second year). The soil characteristics are similar at both sites. The growing season starts in May and lasts up to September with harvesting done by early September. The major crops in this area are potato, corn and bean.

3.2.2 Climatic Conditions

Natural Resources Canada (1957) has classified the study site as typical humid continental; resulting in dry cold winters with hot frequently dry summers. The average temperature in summer typically ranges from 12 to 22 °C, while in winter reported range is -15 to -25 °C. The study area receives the most heat units for crop production in Manitoba. The 30-year average annual precipitation is 533 mm of which 416 mm is received as rainfall with 342 mm being attributed to the growing season (Environment Canada, 2013). During the growing season supplemental irrigation was applied as needed.

3.2.3 Soil Type

Soil at the experimental sight is coarse-textured loamy sand soil (Smith et al., 1973) with textural distribution of sand 70%, silt 19%, and clay 11% (Cordeiro and Sri Ranjan, 2012). It belongs to Reinland series being classified as Gleyed Rego Black Chernozem (MAFRI, 2010). Average bulk density, field capacity, and porosity were 1450 kg m^{-3}, 28%, 45.3%, respectively.

3.2.4 Experimental Field Design

The impact of two water management treatments comprised of overhead irrigation system (IR) and no supplemental irrigation (NI), on marketable tuber yield and quality was tested using a randomized complete block design (RCBD) consisting of three replicates. In 2013, a field area of 1.2 ha (2.97 ac) was divided into six equal plots of approximately 0.2 ha (0.49 ac) with dimensions of 44.6 m X 40.3 m. In 2014, a comparatively larger field area of approximately 1.29 ha (3.19 ac) was divided into six equal plots with dimensions of 50 m X 44 m. All the plots were planted with Russet Burbank cultivar, the most commonly grown cultivar in Manitoba.

Both treatments had subsurface tile drainage system of same characteristics installed below the ground surface, at 0.9 m depths during the fall of 2009. Drain spacing was kept at 11.1 m. In the first year of study (2013), overhead irrigation was applied using a linear move irrigation system whereas travelling gun was used in the second year (2014) to replenish the soil moisture deficit. The irrigation water was a pumped from a reservoir located nearby the study site, established and maintained by a group of local farmers who capture and store the spring snowmelt runoff. Water quality was tested prior to planting and was found to be suitable for irrigation purpose. C-probe and Watermark sensors were installed at 0.2, 0.4, 0.6, 0.8 and 1.0 m depths from the ground surface at the center of each plot to track soil moisture contents (%) and soil water tension (kPa), respectively, throughout the growing season. Observation wells were installed in the center of each plot to track the fluctuations in water table depth below the ground surface.

3.2.5 Instrumentation and Data Collection

Groundwater level (m) was monitored by water level sensors (WLS) (Solinst Levelogger Junior 3001, Solinst Canada, Ltd., Georgetown, Ontario, Canada) hung inside 2.5 m long piezometers/observation wells, manually installed at the center of each plot. These sensors were set to record the water level every 30 minutes throughout the growing season. A barometric pressure sensor (Solinst Barologger Gold) was also hung inside a stilling well for subsequent barometric correction of the water level sensor data. The data collected through WLS was verified by taking manual reading of ground water level (m) through a water level sensing tape. Capacitance/frequency domain probes (model EC-5, Decagon Devices, Inc., Pullman, Wash.), installed at the center of each plot, were used to monitor volumetric soil moisture contents (%) and soil temperature (°C) continuously throughout the growing season at five different depths (0.2, 0.4, 0.6, 0.8, and 1.0 m). The C-probe provided real time soil moisture and soil temperature data with a logging interval of 15 minutes through the Weather Innovations Network (WIN) website. Soil water tension was tracked at five different depths (0.2, 0.4, 0.6, 0.8, and 1.0 m) by Watermark sensors installed in each plot.

Manitoba Ag Weather Network station (Spectrum Technologies, Inc. Weather Station, 2000 Series) located on site was used to collect precipitation (mm), temperature (°C), wind velocity (km/h), relative humidity (%) and solar radiation data on daily basis. Irrigation water was applied in the irrigated treatment plots through linear move irrigation system (O3000 Orbitor, Nelson Irrigation Coporation, Walla Walla, WA) in 2013 while a travelling rain gun was used in 2014. The reference crop evapotranspiration (ET_0) was calculated on a daily basis using the Penman Monteith semi-empirical equation (Allen et al., 1998). The actual evapotranspiration for different months was estimated by multiplying the reference evapotranspiration by the corresponding crop coefficient (K_c) based on crop developmental stages:

$$\text{Actual Evapotranspiration} = \text{Reference Evapotranspiration } (ET_0) \text{ X Crop Coefficient Factor}$$

$$ET = ET_0 \text{ X } K_c$$

Allowable depletion for the irrigated plots was based on 75% available water holding capacity (AWHC). Irrigation application was triggered when the tensiometer reading exceeded 25 kPa at any of the 0.2, 0.4, 0.6 m soil depth in the irrigated plots. The readings of C Probes and tensiometer from the deeper depths (0.8 and 1.0 m) were considered as criteria to confirm successful irrigation rates. Shock and Wang (2011) have reported that many potato researchers have used tensiometer readings to measure soil matric potential (SMP) and schedule irrigations (Epstein and Grant, 1973; Lynch and Tai, 1989; Wilson et al., 2001; Kang et al., 2004). Wang et al. (2007) has compared five SMP treatments for potato crop and found that an SMP of -25 kPa was the most favorable criterion for potato production and water use efficiency during the various potato developmental stages, while -15 kPa was observed too wet and -45 kPa caused drastic water stress.

The depth of irrigation was based on % volumetric depletion integrated over the depth of the root zone (600 mm). Field capacity was determined from C-probes by saturating the soil prior to installation. Irrigation nozzles were manually turned on/off to ensure no irrigation outside of selected plot boundaries. Irrigation application rates were measured by in-field rain gauges. The irrigation rate was adjusted to replenish the daily ET demand of the potato crop. Soil samples were collected using a soil auger at 0.2, 0.4, and 0.6 m depths (effective potato root zone) at each growth and development stage and analyzed for nitrate concentrations (ppm) at each depth by Cadmium reduction method.

3.2.6 Agronomic Practices

Cultural practices favorable for the production of higher marketable yield having the best tuber quality acceptable to the Manitoba French-fry processing industry were followed (Geisel, 1994). Prior to planting, equal fertilizer rates, determined on the basis of soil test results, were applied to all the six plots by broadcast method and cultivated to incorporate fertilizer with chisel plough. The rate of fertilizers applied for both treatments was 178 kg/ha of N in the form of polymer coated urea (PCU), 67 kg/ha of P in the form of MAP, 89 kg/ha of K in the form of KCl, and 22 kg/ha of S in the form of K_2SO_4. Nitrogen was applied in the form of polymer-coated urea (PCU). Polymer-coated urea also called Environmentally Smart Nitrogen (ESN) urea is a controlled release nitrogen fertilizer source that has the nitrogen granule covered in a thin/semi-permeable polymer coating (Beres et al., 2012; McKenzie et al., 2007). The semi-permeable polymer coating allows water to enter into the granule and dissolve the nitrogen inside based on soil temperature and soil moisture level (Agrium, 2005). This technique facilitates a slow release of nitrogen. About 80% of the nitrogen is released from PCU/ESN urea between 40 and 90 days after application (Agrium, 2005). Potato seeds were planted mechanically at a depth of approximately 5-10 cm with a 4-row planter on formed ridges with seed spacing between the rows of 0.91 m (36 in.) whereas the spacing between the seeds within row was kept as 0.36 m (14 in.). A power hiller was used to do the hilling/ridging to protect the stems of the potato crop from wind effects. The height of ridges was maintained at 0.12 m. Berming was done around the plots following the hilling operation to prevent overland flow between plots and from outside the study area. Fungicides were applied on a weekly basis whereas herbicides and insecticides were applied based on the detection of pests. All the other agronomic practices were carried out in accordance with potato production guidelines. Potatoes were flailed and harvested using a single row potato harvester in the third week of September at physiological maturity on three 20 m length strips per plot with one row above or close to the drain tile, second row along 1/4 spacing and third row along 1/2 spacing of the drains for quality, collected in burlap bags, separated by treatments, and weighed in the field to determine total and marketable yield. Statistical analyses were done using student t-test, ANOVA and JMP software (ver. 8, SAS Institute, Inc., Cary, N.C.).

3.2.7 Post-Harvest Actions

Potato tubers were stored at 7 ^{0}C after harvest for about two months. Each set of samples was washed and weighed before analyzing every quality parameter discussed in this paper. Quality analyses included tuber size, tuber weight, fry color, sugar ends, dark ends, hollow heart incidence, specific gravity, rot detection, green coloration, and marketable yield.

3.2.7.1 Fry Color and Sugar Ends

French fry color was determined for fry quality and sugar end analysis. A set of twenty-five tubers was picked from each replicated treatment, washed, cut into thin slices (1.4 ± 0.1 mm) with an electric slicer, and washed for 1 minute in distilled water to remove surface starch using a magnetic stirrer. The purpose of removing surface starch is that it prevents potato slices from sticking to each other during the process of frying. After washing the slices were dried by gently pressing with a paper towel. The potato slices were deep fried by completely immersing in vegetable oil in an electrical fryer set at 190.6 ^{0}C (375 ^{0}F). After frying, samples were placed on an absorbing tissue paper for 2 minutes and 30 seconds and allowed to cool to room temperature prior to test. Tuber quality was analyzed for sugar ends on the basis of fry color. The sugar ends were identified by the dark discoloration of potato fry ends. The color appearance of each fry was visually assessed and scored using the USDA Munsell French fry color chart (Anonymous, 1988). According to this chart, potato fries with score No. 0 to No. 2 are regarded as good quality tubers. If potato fry is scored No. 3 or 4 with dark ends, they would be having sugar end. Fry colour varies from lighter (000) to darker (4) value. The lighter the fry colour the better the quality. Pritchard and Adam (1994) have simplified the chart ratings by converting 000, 00, 0, 1, 2, 3, and 4 to nonzero ratings i.e. 1, 2, 3, 4, 5, 6, and 7, respectively, where 1 corresponds to lightest fry color. They also reported that a fry color of 3.5 or lower on the 1-7 color scale is the most desirable number for the processing industry in Manitoba.

3.2.7.2 Specific Gravity

Specify gravity was determined by weight in air and weight in water method (Edgar, 1951). For this purpose, randomly selected twenty-five tubers from each replicate were washed and left overnight at room temperature to dry. Next day, tuber samples were weighed (weight in air), immersed in tap water, and then weighed again (weight in water). Weight of tubers in air was divided by the difference between the weight in air and weight in water as indicated by the following formula:

Specific Gravity = Weight of tubers in air (g) / {Weight of tubers in air (g) – Weight of tubers under water (g)}

$$S.G = W_a / (W_a - W_w)$$

3.2.7.3 Hollow Heart

In order to determine hollow heart (also called as brown center, or sugar center) incidence in tuber samples, 25 tubers were taken randomly from each replication. Tubers were sliced into 3 mm thick pieces and hollow heart incidence was assessed by visual judgment of cavities in the center of tubers. The number of tubers with 5 mm or larger sized hollow heart was counted, weighed and the percent incidence was calculated in both treatments.

3.2.7.4 Tuber Size, Weight and Marketable Yield

A representative sample of twenty-five tubers was taken from each replication, washed thoroughly and weighed. These potatoes were graded into 5 sizes: extra-small/undersized also known as culls (<3 oz/ < 85 g), small (3-6 oz/ 85-170 g), medium (6-10 oz/ 170- 284.5 g), large (10-12 oz/ 284.5- 340 g), and extra-large/oversized also known as jumbo (>12 oz/ > 340 g), and weighed each size group. Culls (<3 oz/ < 85 g), jumbo (>12 oz/ > 340 g), and misshapen tubers (knobs) were excluded from the total yield to determine the marketable yield. Percent mean tuber weight of each size group was calculated. Percent weights of small, medium, and large size tubers were added to calculate the percent marketable yield in each size category.

3.2.7.5 Rot Detection and Green Coloration

Potato diseases; rot and green coloration happen when potatoes are not stored properly or they are exposed to light. A set of 25 tubers was taken from each replicate to visually detect the incidence of rot and green coloration. The weight of rotten tubers both by tuber rot or green discoloration was separately done for each incidence and calculated as a percent disease incidence per total sample weight.

3.3 RESULTS AND DISCUSSIONS

3.3.1 Weather Conditions

The study site experienced a different rainfall pattern during the study years (2013 and 2014) as compared to the 30-year rainfall pattern in Southern Manitoba. The mean air temperature during the critical growth stages of potato was also different in the two years. The 2013 growing season (May to September) received 14% higher rainfall (389 mm) compared to the 30-year average (342 mm). During the same period the mean T_{max} was 23.6 ^{o}C and T_{min} was 10.2 ^{o}C with tuber bulking stage having a number of days with > 25 ^{o}C. However, the 2014 growing season was comparatively drier with a total precipitation of 262 mm (24 % less than the 30-year average) and an average T_{max} of 23 ^{o}C, and T_{min} of 9.5 ^{o}C (Fig. 3.1).

During the initial growth stages i.e. sprout development and vegetative growth stages; supplemental irrigation was not required in both years because rainfall was sufficient to meet the crop water demand. As all the six replicated plots received adequate amount of water through rainfall and equal fertilizer rates, plant emergence and development was uniform in all the plots.

In the 2013 growing season, a dry period occurred from the beginning of July (tuber initiation stage) till the third week of August (51 days) (tuber bulking stage) with only 120.6 mm rainfall during this period. The tensiometer readings fell below 25 kPa during several days because the rainfall was not adequate to meet the potato crop water demand. This was exacerbated by high air temperature which remained above 25 ^{o}C and was sometimes > 30 ^{o}C at noon. This high temperature during the tuber bulking stage is harmful for tuber growth (Hou et al., 2010). The potato crop is very sensitive to heat with minimum temperature required for growth and development being 7 °C (45 °F) and the most rapid growth and development occur at 21 °C (70 °F). The growth rate decreases with increasing temperature above 21 ^{o}C (70 °F) under moisture deficit conditions and finally stops at 30 °C (86° F) (MASC, 2013). The high temperature and lack of rainfall during July and early August necessitated the application of 130.5 mm of water through 11 supplemental irrigations using a linear move irrigation system. On an average, the potato crop in Manitoba needs 90 mm of supplemental irrigation (Western Potato Council, 2003). Higher mean temperature during the study period led to supplemental irrigation, which was considerably higher than the average annual moisture deficit of 90 mm of the study site.

In the 2014 growing season, a 30-day dry period occurred from 23 July (tuber initiation stage) to 21 August (tuber bulking stage) with only 14.6 mm rainfall. During this period, supplemental irrigation was applied through five irrigation events to replenish the losses from evapotranspiration (ET). Although 2014 was a comparatively drier year with only 262 mm rainfall during the growing season, the daily mean temperature never rose above 25 ^{o}C except on a few days during the vegetative growth stage. Lower mean temperature during the critical growth stages of tuber initiation (11.4 ^{o}C) and tuber bulking (10.9 ^{o}C), lowered the ET demand in 2014.

The irrigated period spanned over the tuber initiation and tuber bulking stages in both years. Since the potatoes do not need as much water during the maturation stage (Rowe, 1993), no supplemental irrigation was applied during this stage. However, during May, June, and September the potato crop was sustained by rainfall. In 2013, the average depth of water table remained 1.69 and 1.77 m below the ground surface for both the irrigated and non-irrigated treatments, respectively. However, during the 2014 growing season, shallower average water table depth of 1.10 and 1.03 m below the ground surface for irrigated and non-irrigated treatments were observed at a different site than that used in 2013.

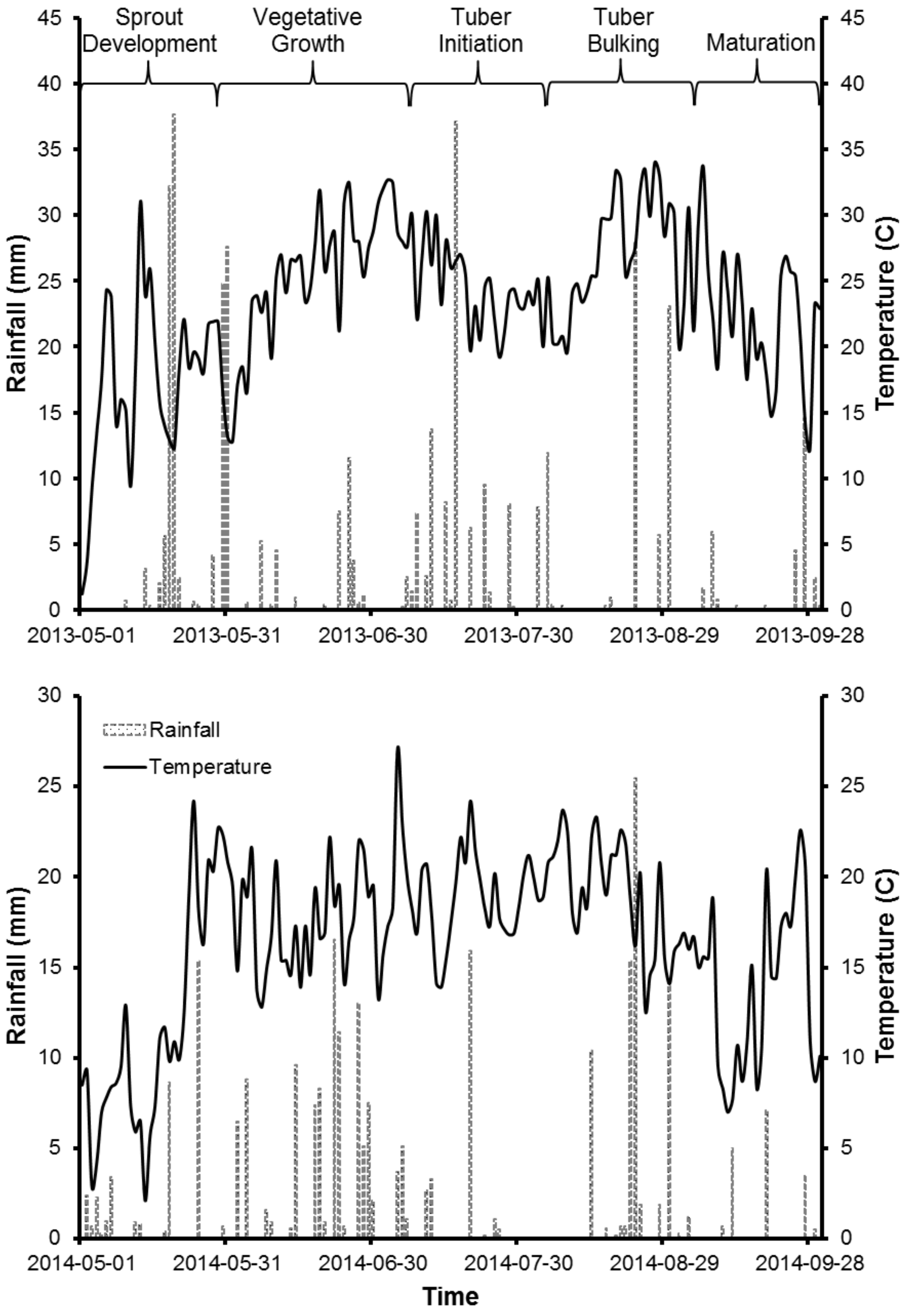

Figure 3.1 Rainfall and daily mean air temperature during the 2013 and 2014 growing seasons at various growth stages.

3.3.2 Nitrate Concentrations

The accumulation of nitrates within the potato root zone (0 to 0.6 m) was determined by analyzing soil samples collected at 0.2 m depth increments. The average nitrate concentrations within the effective root zone at different stages of growth was reported by averaging the nitrate contents of samples obtained at 0.2, 0.4, and 0.6 m depths. The non-irrigated treatment shows a trend of higher nitrate content (ppm) compared to irrigated treatment in both years (Fig. 3.2 and 3.3). In the 2013 growing season, the nitrate content was significantly higher in the non-irrigated treatment between the tuber initiation and bulking stages ($p = 0.023$) and between the tuber bulking and maturation stages ($p = 0.036$). However, in the 2014 growing season, the nitrate content was significantly higher in the non-irrigated treatment ($p = 0.006$) between the tuber bulking and maturation stages only.

In both years, during the vegetative growth stage, all the six replicated plots received adequate amount of water through rainfall. This rainfall was sufficient to facilitate the release of nitrogen from the slow released urea (PCU/ESN urea). Although, irrigated treatment was receiving supplemental water through overhead irrigation during a part of the tuber initiation stage, rainfall depth and mean air temperature was adequate to facilitate the release of nitrogen from PCU/ESN urea in both treatments. In the 2013 growing season, lower rainfall events during the tuber bulking and maturation stages restricted the release of nitrogen from PCU/ESN urea granules in non-irrigated treatment. Adequate moisture and temperature are required for the release of nitrogen from PCU/ESN urea, which the irrigated plots had. However, the moisture content of the non-irrigated plots may not have been adequate to support the release of nitrogen from the PCU/ESN urea leading to the accumulation of higher concentrations of nitrates within the root zone compared to the irrigated plots.

Nitrates, released from PCU/ESN urea, leached below the potato root zone with the water received through precipitation and irrigation in irrigated treatment. However, in non-irrigated treatment, precipitation alone did not result in significant deep percolation leading to the accumulation of nitrates within the root zone. According to groundwater analysis, prior to the study, average nitrates concentration in the groundwater was found to be 55 ppm. Therefore, the non-irrigated plots may have pulled the nitrates-rich water from the shallow water table through capillary rise to meet the crop water demand during the dry period. This upward migration of nitrates from the water table resulted in excessive accumulation of nitrates in the potato root zone. This hypothesis is in agreement with Patel et al. (2001).

In the 2014 growing season, soil moisture and mean air temperature was adequate to facilitate the release of nitrogen from the slow released urea (PCU/ESN urea) during vegetative growth, tuber initiation, and tuber bulking stages in both treatments. However, an approximately consistence concentration of nitrates at these stages in the non-irrigated treatment indicates that rate of releasing the nitrogen from PCU/ESN urea was very slow compared to the irrigated treatment. During these stages, unutilized nitrates may have accumulated within the potato root zone. The deficit soil moisture during the maturation stage restricted the release of nitrogen from PCU/ESN urea in non-irrigated treatment leading to the accumulation of higher concentrations of nitrates within the root zone compared to the irrigated plots during the maturation stage. The non-irrigated plots also may have pulled the nitrates-rich water from the shallow water table through capillary rise to meet the crop water demand during the dry period. It resulted in increase in the nitrate contents within the root zone.

The high accumulation of nitrates within the potato root zone in the non-irrigated treatment compared to the irrigated treatment may be attributed to three factors: (1)

comparatively less favorable conditions for release of nitrogen from PCU/ESN urea, (2) upward flux of groundwater due to dry conditions, and (3) comparatively lower percolation in the absence of recharge through irrigation. Potato needs higher concentration of nitrates during vegetative growth and tuber initiation stages while only traces of nitrates are required at tuber bulking stage. Excessive nitrates concentration at tuber bulking stage may cause drastic yield reduction and is a threat to tuber quality.

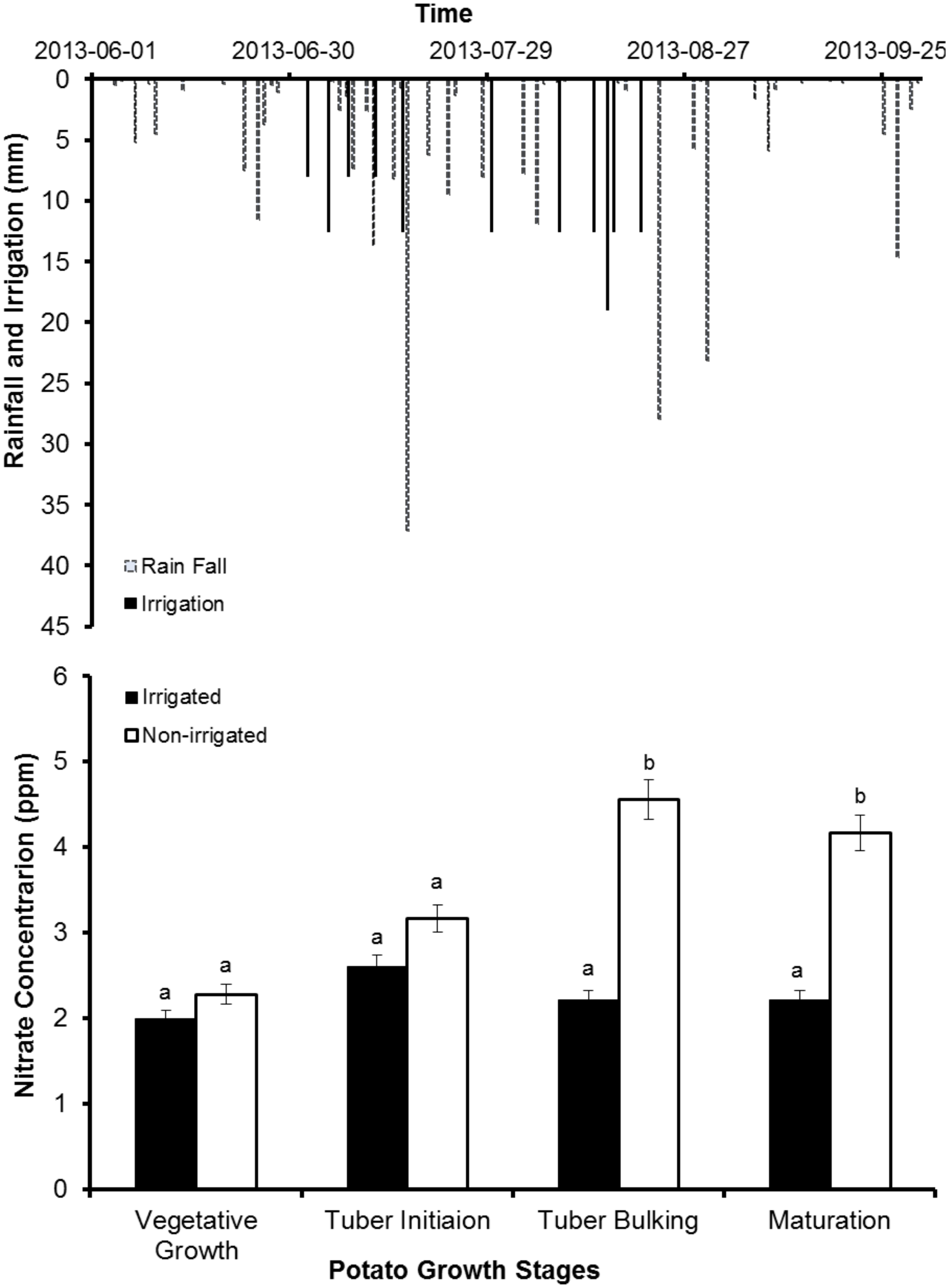

Figure 3.2 Response of nitrate concentration to water recharge (rainfall + irrigation) during the 2013 growing season at various growth stages

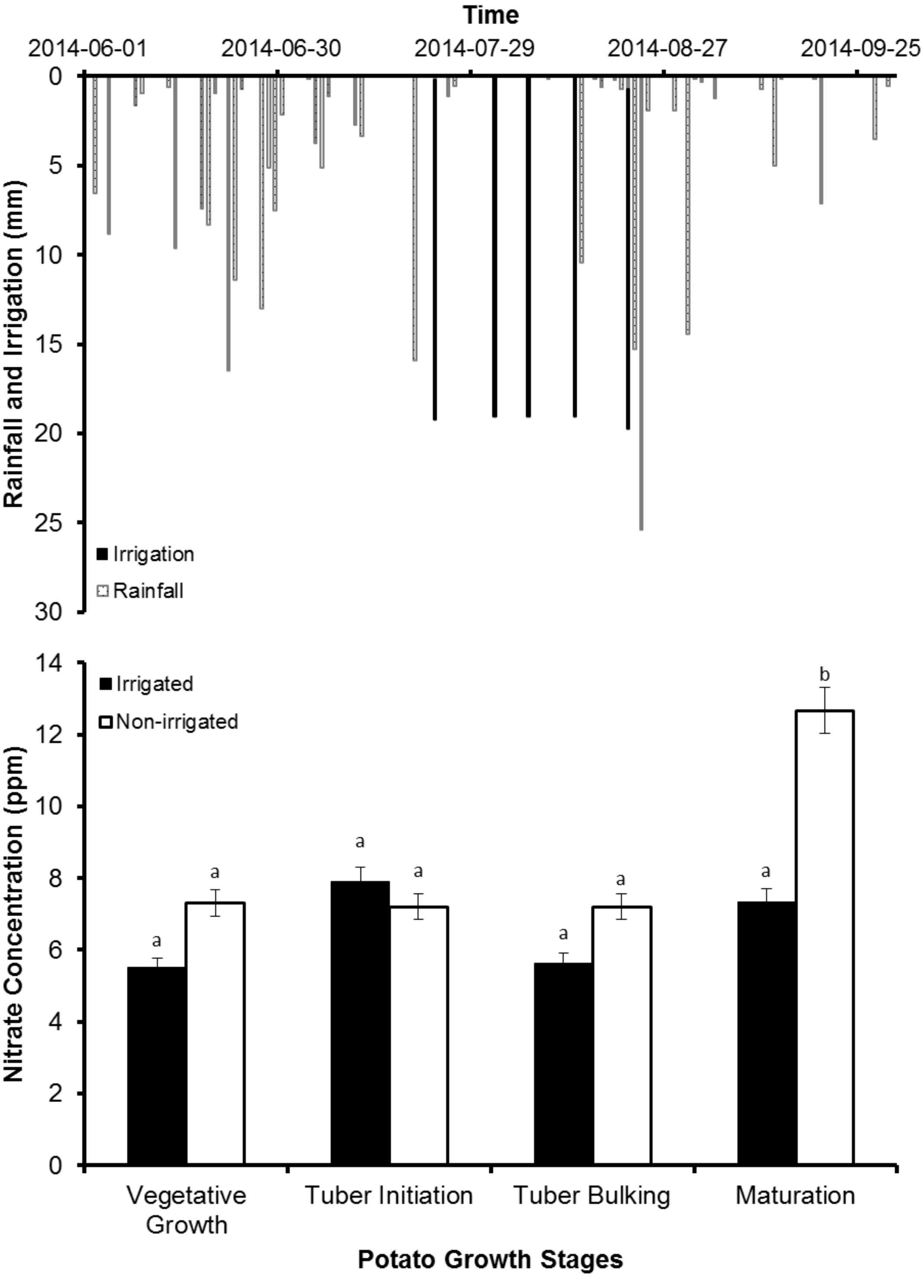

Figure 3.3 Response of Nitrate concentration to water recharge (rainfall + irrigation) at different growth stages during the growing season 2014.

3.3.3 Total and Marketable Yield

Yield data were analyzed using ANOVA, and means were compared using Student's t-test at the 0.05 significance level. The difference in total yield for the irrigated (IR) and non-irrigated treatments was found to be statistically not significant in both years. However, the economically important component is the marketable yield, which excludes under-sized (< 3 oz), over-sized (> 12 oz), and misshapen potato tubers. In 2014, yields were higher than in 2013 across both of the treatments. Several factors including change in the study location, weather conditions, and initial groundwater levels might have led to the higher yield in the 2014-growing season.

In the 2013 growing season, the irrigated treatment (IR) had significantly higher (p = 0.044) percentage (71.21%) of acceptable tubers (3 oz -12 oz) (Fig. 3.4a). The percent non-marketable potatoes (undersized/misshapen + oversized potatoes) was significantly higher (p = 0.044) in non-irrigated treatment (38.28 %). In the 2014 growing season, although the percent acceptable tubers were higher in the non-irrigated treatment (70.75%) compared to the irrigated treatment (62.01%), the difference was not statistically significant (Fig. 3.4b). The total percent non-marketable potatoes was higher in the irrigated treatment (37.99%) compared to the non-irrigated treatment (29.25%) but the difference was not statistically significant. Oversized tubers are less desirable to the French fries processing industry. The over-sized tubers have excessively long fry strip length and a portion of the fry strip is lost during processing. That is why over-sized potatoes are excluded from the marketable yield.

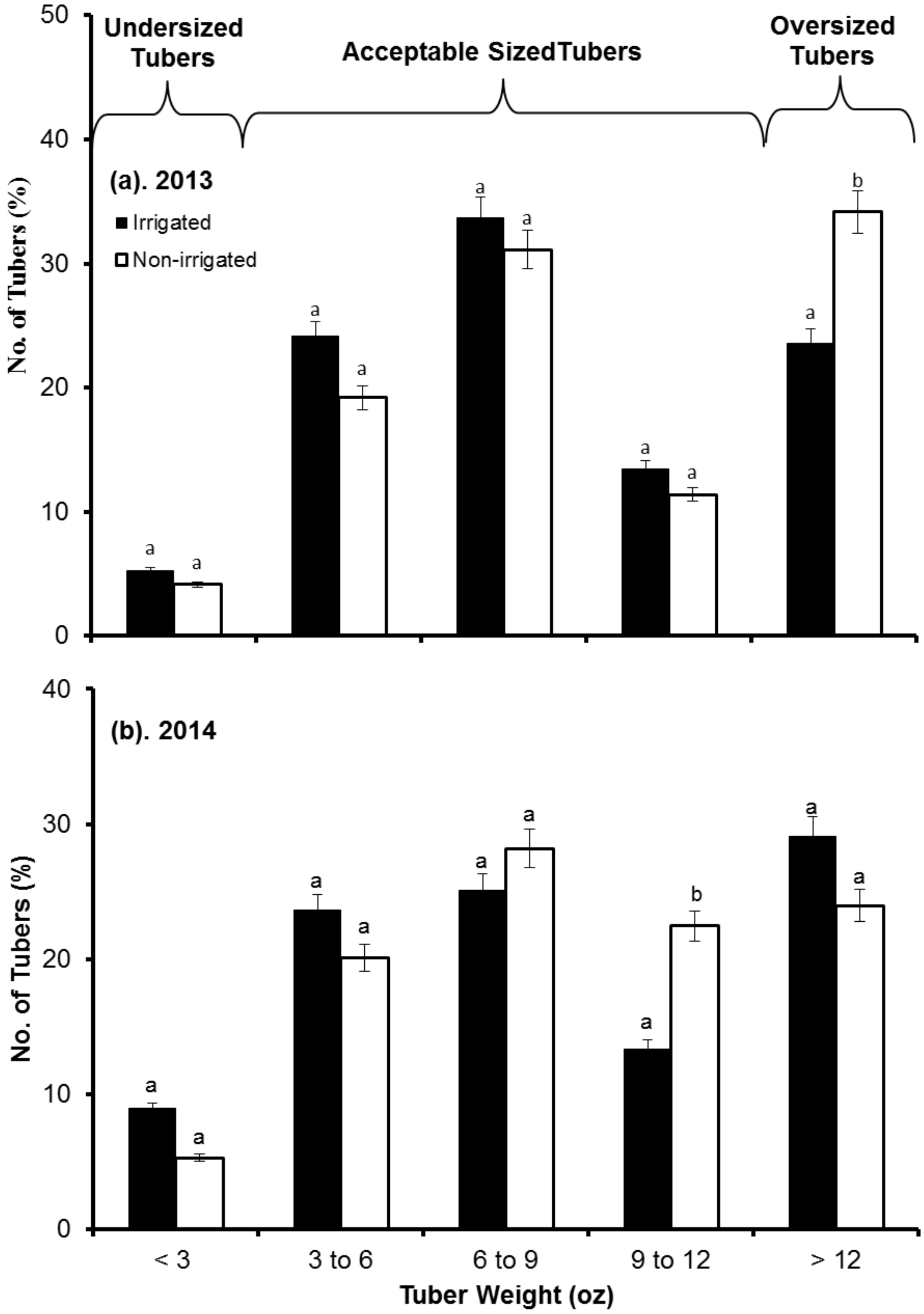

Figure 3.4 Percent Tuber Size Distribution by Tuber weight (oz) during the (a). 2013 and (b). 2014 growing seasons.

When comparing marketable yields, the irrigated (IR) treatment (36.89 MT/ha) was significantly higher (p = 0.017) than the non-irrigated (NI) treatment (30.74 MT/ha) in the 2013 growing season (Fig. 3.5). Supplemental irrigation resulted in ~17 % lower yield of non-acceptable tubers (undersized, oversized, and knobs). Oversized tubers had significant contribution (34.15%) to the total un-acceptable tubers (38.28%) in the non-irrigated treatment. A dry period with 72.2 mm of rainfall was experienced approximately 70 days after planting, which corresponded to the time of tuber initiation and expansion. Tuber growth is known to peak at 70 days after planting and decrease thereafter (Hur and Shin, 2000). The lack of moisture in the non-irrigated plots led to upward migration of groundwater containing higher nitrates, which accumulated within the root zone. This additional N supplementation received from the groundwater may have induced rapid tuber growth, which resulted in higher incidences of oversized tubers.

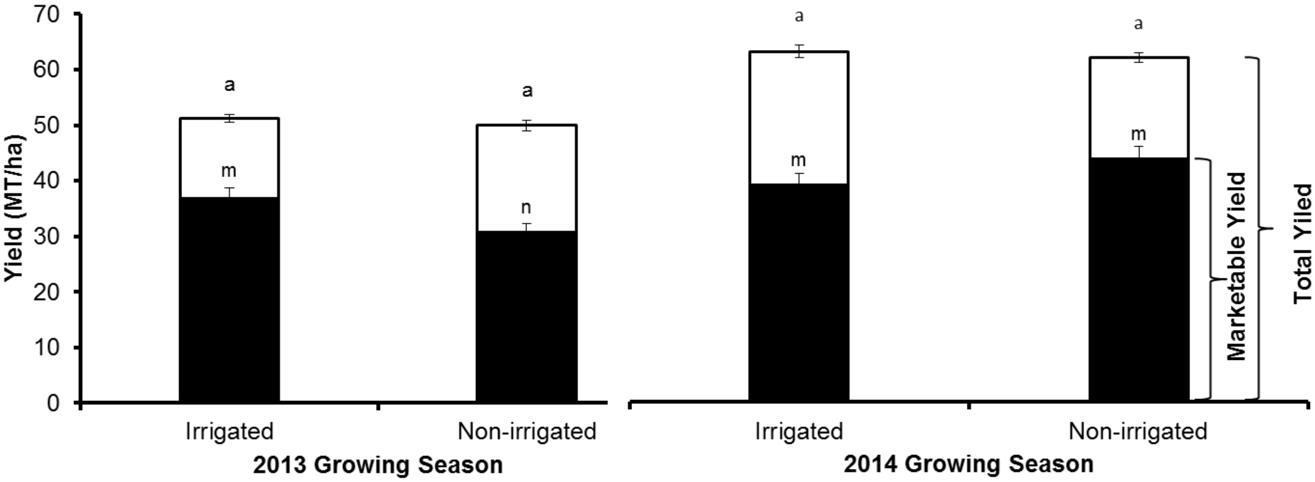

Figure 3.5 Total and Marketable Yield (MT/ha). Adequate moisture and nutrients availability within the potato root zone resulted in higher marketable yield in irrigated treatment as compared to non-irrigated treatment.

An adequate concentration of nitrates was available to the plant roots to support the vegetative growth for both treatments. However, excessive soil N accumulation within the plant root zone in the non-irrigated (NI) treatments during the later stages of growth suppressed tuber bulking and decreased marketable yield. Although the upward movement of nitrates in the non-irrigated treatment resulted in comparable total yield it had an adverse impact on marketable yield. Similar results were also reported by Kang et al. (2001) who examined nutrient uptake and leaching under different fertilizer treatment for corn and potato. Lower marketable potato yield and grade in response to deficit soil moisture were in agreement with results reported by Cappaert et al. (1992), Hang and Miller (1986), Martin and Miller (1983a), Miller and Martin (1983, 1987b), and Stark and McCann (1992).

In the 2014 growing season, marketable yield of the non-irrigated (NI) treatment (43.68 MT/ha) was higher than the irrigated (IR) treatment (38.99 MT/ha) but the difference was not statistically significant (Fig. 3.5). Comparatively lower marketable yield in the irrigated treatment may be attributed to the contribution of shallow groundwater towards the potato root zone. Supplemental irrigation improved the hydraulic conductivity of the soil within the root zone of the irrigated plots making it conducive for the upward migration of groundwater. The accumulation of high concentration of nitrates within the potato root zone from the groundwater may have led to the deterioration of quality of the tubers in the irrigated treatment. On the contrary, the dry conditions in the non-irrigated plots may have resulted in a lower hydraulic conductivity leading to a reduction in the upward water flux from the water table and the consequent lower influx of nitrates from the groundwater.

Figure 3.6 shows the variation in water table depth from the ground surface as an average for the three replicates in relation to the recharge events (precipitation and overhead irrigation) in

2014. A 30-day dry period from August 25 to September 25 (mid bulking to maturation stage) with only 30.9 mm rainfall resulted in upward movement of groundwater in the irrigated plots leading to a lowering of the water table. A decline in groundwater level in the irrigated plots starting from the mid of tuber bulking stage, confirms the contribution from the groundwater. The dry conditions and a higher hydraulic conductivity in the irrigated plots at this stage supported the upward migration of groundwater. Excessive nitrate concentrations during the tuber bulking and maturation stages led to the early maturity of tubers. As a result, tubers of class 9-12 oz size (acceptable size) are significantly lower (p = 0.030) in the irrigated treatment. Tubers of class >12 oz size (un-acceptable size) are comparatively higher in irrigated treatment but the difference wass not statistically significant.

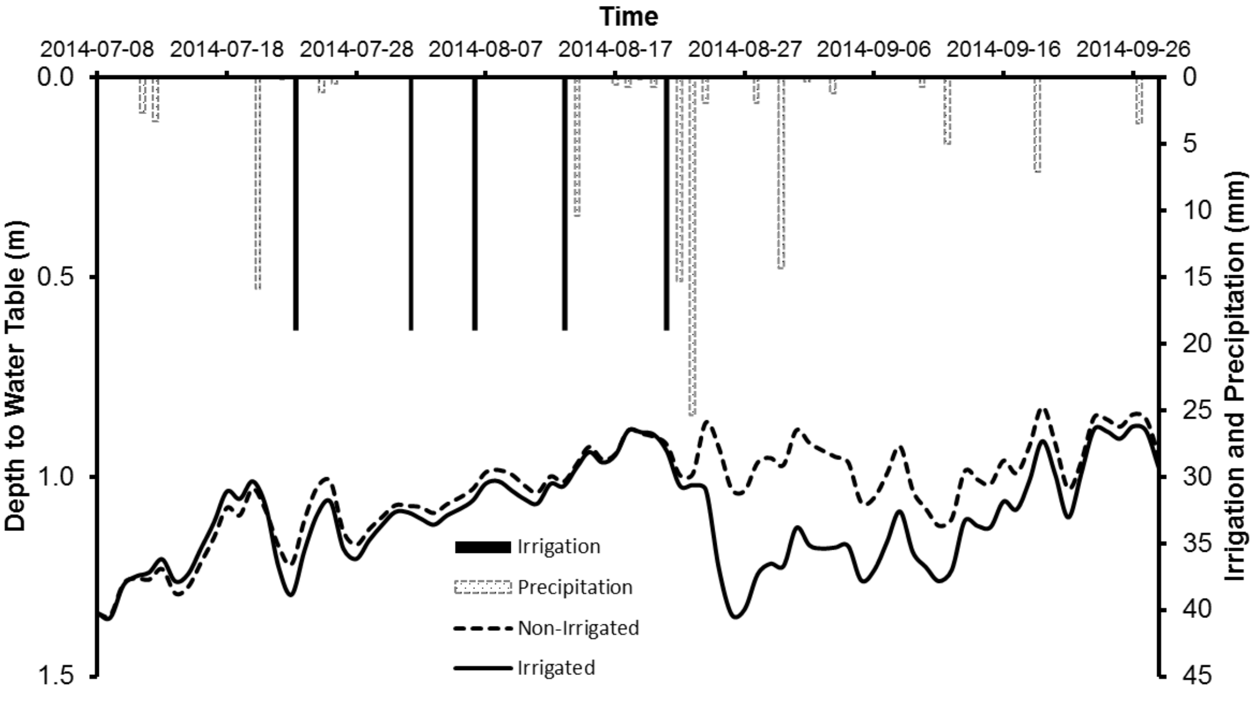

Figure 3.6 Water table depth, precipitation, and irrigation amounts during the 2014 growing season.

3.3.4 Potato Fry Color and Sugar Ends

Fry quality and sugar ends were determined by fry color analysis. Figure 3.7 shows the distribution of potato fry color as determined using the USDA Munsell french fry color chart. Potato fries with score No. 0-2 had light brown fry color with no dark end discoloration. However, potato fries with score No. 3 and 4 had brown color with dark ends. When glucose concentration exceeds the threshold of 1.6 mg/g, the fry color in Russet Burbank potato is considered to be in the unacceptable range (3 or 4) (Pitchard and Adam, 1994). Dark discoloration of fry ends occurs due to the accumulation of sugar at the long end of the tubers. Although statistically not significant, the irrigated treatment had a higher % of tubers in the acceptable range (0-2 Munsell color). In the 2013 growing season, potatoes with dark ends were found to be higher in non-irrigated treatment (46.66%) compared to irrigated treatment (40.45%). However, this difference was not statistically significant. In the 2014 growing season, a higher % of tubers with score No. 0 and 3 were found in non-irrigated treatment, while a higher % of tubers with score No. 2 were found in irrigated treatment but the difference was not statistically significant.

Extreme water stress conditions at critical growth stages influence the tuber yield, size, and external and internal quality as well. Water stress during the tuber bulking stage causes dark stem-end fry color (Eldredge et al., 1996). However, a moderate early season water stress is beneficial for potato fry color. Shock et al. (1992) reported that a moderate moisture stress before the tuber initiation stage improved the tuber fry color. A comparatively high percentage of unacceptable fry color score in non-irrigated treatment during the 2013 growing season may be attributed to the water stress conditions at tuber bulking stage. In the 2014 growing season, a moderate water stress before the tuber initiation stage having a number of days with > 20 ^{o}C and only 24 mm rainfall led to the improved fry color in both treatments.

Water stress accompanied by excessive nitrate accumulation within the potato root zone affects the sugar balance by disturbing the enzymatic process (Pitchard and Adam, 1994). Russet Burbank is the main cultivar grown for the Manitoba French-fry processing industry. Therefore, it is important to maintain the sugar level in Russet Burbank potato at standard levels to achieve fry color number (0-2), which is acceptable to the Manitoba french fry processing market. These results are in agreement with Wilbur (1979). Lynch et al. (1995) reported that generally early and/or mid-season water stress reduces the sugar ends in fries. They also reported that the effect of early and mid-season moisture stress on sugar ends also depends on other environmental factors. On the contrary, Painter et al. (1975) reported no fry color differences between potatoes irrigated at 25% available moisture season long and those irrigated at 65% available moisture.

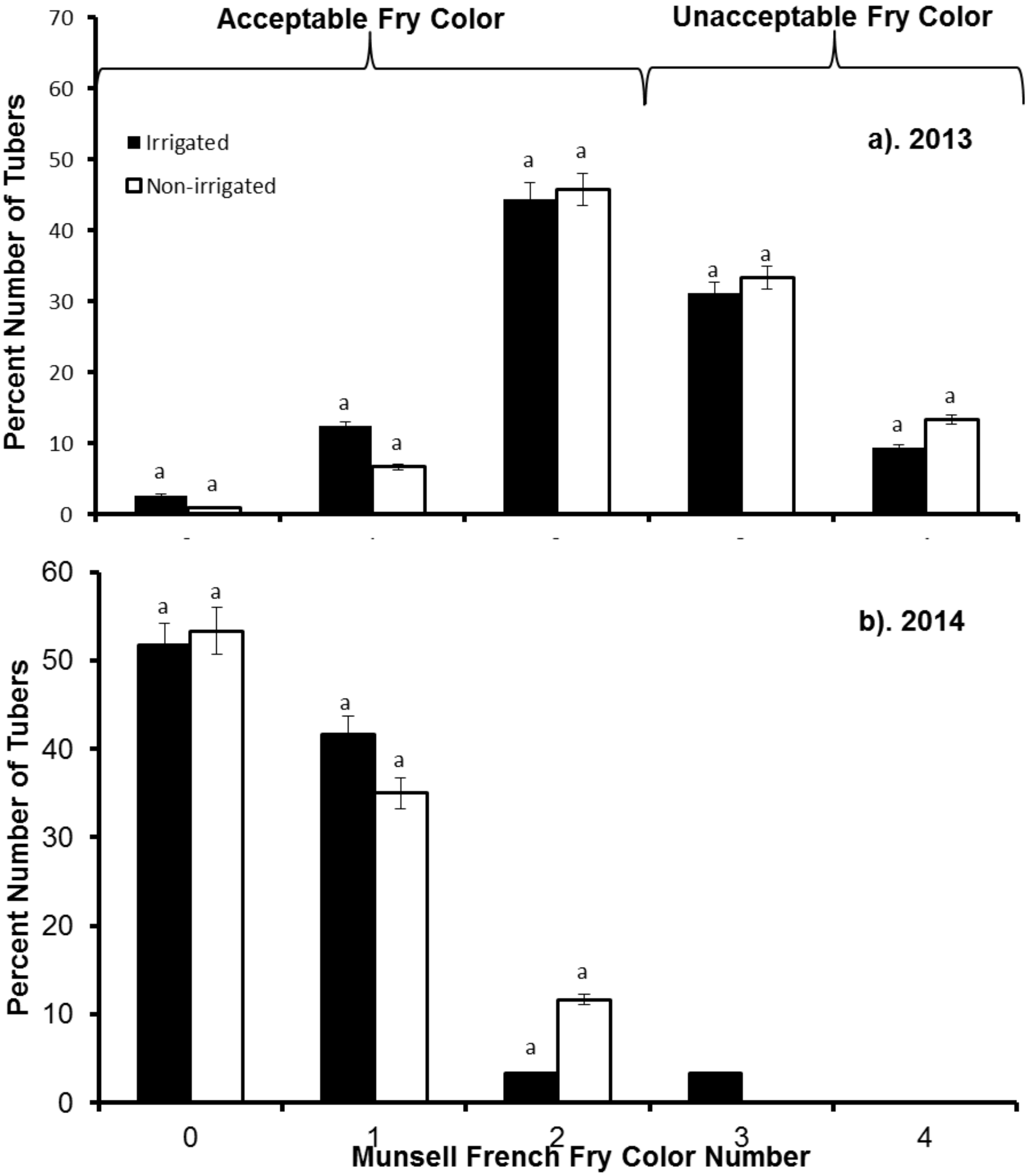

Figure 3.7 Distribution of potato fry color using the USDA Munsell french fry color chart.

3.3.5 Specific Gravity

In the 2013 growing season, the specific gravity of tubers from the irrigated treatment (1.081) was higher than non-irrigated treatment (1.079). A slightly lower specific gravity was found in the irrigated treatment (1.085) than the non-irrigated treatment (1.087) in the 2014 growing season. However, the difference in specific gravity was not statistically significant in both years. It shows that the deficit soil moisture and higher N concentration did not have a significant impact on the specific gravity of tubers. These results are in agreement with earlier reports (Zelalem and Nigussie, 2009: Lynch et al., 1995: Shock et al., 1993, 1992, Ojala et al., 1990). Miller and Martin (1987b) reported a reduction in specific gravity of Russet Burbank cultivar by deficit irrigation at 80 % of ET on sandy soil. Likewise Stark and McCann (1992) reported the same results in silt loam soil. In contrast some researchers observed an increase in specific gravity in Russet Burbank cultivar under deficit irrigation in sandy soil (Eldredge et al., 1996; Stark and McCann, 1992; Hang and Miller, 1986; Martin and Miller, 1983b). The water content of potatoes decreases with the increase in specific gravity. Therefore higher specific gravity in irrigated plots is an indicator of improved properties for frying and better flavor.

3.3.6 Hollow Heart

In both years, hollow heart symptoms (HHS) were not found in any of the treatments in undersized and small tubers. However, HHS were relatively higher in the non-irrigated treatment in medium, large and oversized tubers as compared to the irrigated treatment. However, the differences were not statistically significant. Oversized tubers were more affected compared to medium- and large-sized tubers. Accumulation of excess nitrates within the potato root zone during tuber initiation and tuber bulking stages led to the early maturity of tubers and also increases in tuber size. Since the incidence of hollow heart was higher in oversized tubers, the size of the tubers was found to be an important determinant. The higher incidence of hollow heart in the deficit irrigation treatment in this study is similar to the results reported by Yang et al. (2001). Potatoes with hollow heart are not acceptable to the processing industry and do not have market value. Based on relatively higher incidence of hollow heart in response to the non-irrigated treatment, the deficit irrigation for potato crop is not recommended. Many researchers have adopted several ways to avoid or reduce hollow heart incidence. Yang et al. (2001) attempted cultural practices to reduce the tuber size by planting potato at a higher density and inducing higher competition among plants.

3.3.7 Green Coloration

If the potatoes are stored at room temperature, and/or exposed to natural, artificial, or fluorescent lights, the color of potato skin and upper layers starts to turn green. If this condition is prolonged, green color penetrates deep into the potato tuber and makes its taste bitter (Idaho Potatoes, 2014). As potatoes were stored in a dark place at recommended temperature, no incidence of green coloration was found in potato samples.

3.4 CONCLUSION

This study compared the effects of two different water management treatments on marketable yield and quality of potato tubers under Manitoba conditions during two consecutive years. The rainfall pattern and mean air temperature during the different growth stages of potato was different in the two years. The 2013 growing season was comparatively wet and warm, while the 2014 growing season was comparatively drier and cooler. Deficit soil moisture and excessive nitrate accumulation within the potato root zone of the non-irrigated treatment resulted in significant reduction in marketable yield in 2013. Despite the total yield for irrigated (IR) treatment being 2.4 % higher than non-irrigated treatment (NI) it was not statistically significantly different. However, the marketable yield for the irrigated treatment was significantly higher by 20 % compared to the non-irrigated treatment. No significant difference was found either in total or marketable yield in 2014.

In 2013, the high temperature with low rainfall from tuber initiation to maturity led to moisture stress conditions and affected marketable yield of non-irrigated treatment. Increased evapotranspiration due to high temperatures and the absence of rainfall led to the upward migration of nitrates with the groundwater, and slow rate of release of nitrogen from PCU/ESN urea in the non-irrigated plots. In 2014, deficit soil moisture within the root zone of the non-irrigated treatment led to slow rate of release of nitrogen from PCU/ESN urea leading to the accumulation of the unutilized nitrates within the root zone. Supplemental irrigation improved the hydraulic conductivity of the soil within the root zone of the irrigated plots making it conducive for the upward migration of groundwater. The migration and accumulation of high concentration of nitrates within the potato root zone from the groundwater may have led to the deterioration of quality of the tubers in the irrigated treatment. As a result, both treatments suffered from nitrate stress and no significant difference was found in the marketable yield of both treatments.

The nutrient imbalance stimulates increased tuber size at the expense of marketable yield. Over-sized tubers do not have market value due to losses in processing of long fry strip length and dark fry color. Therefore, french-fry processing industry rejects under-sized and over-sized tubers from the growers. A uniform light brown fry color is acceptable to the market. The degree to which yield was affected depended on soil moisture content, temperature range and nitrate concentrations. Growing potatoes with the aim of getting maximum marketable yield requires that all the essential nutrients must be supplied at the right rate and at the right time. Proper supply of irrigation water to plant roots leads to the even distribution of nitrates, helps to optimize yields, size distribution and quality of both seed, and consumption grade tubers. Water stress at tuber bulking stage in 2013 harmed the french-fry color, while a moderate water stress before the tuber initiation stage, being beneficial with respect to french-fry color, improved the fry color in both treatments in 2014.

Many factors are involved in determining the total nutrient requirement of tubers e.g. cultivar variety, soil type, moisture availability, method of irrigation application and environmental conditions. Among these, all can be carefully controlled except the environmental conditions such as rainfall, temperature, and sunlight. The main consideration is to manage those factors that can be controlled and keep the plants in the best condition to withstand whatever environmental stresses they may encounter. Year round supply of potatoes meeting the specifications of the processing industry is a challenge. The grower wants to generate highest quality potato with the objective of getting a high return on investment. Therefore, deficit soil moisture at tuber initiation and tuber bulking stages are unacceptable for growers as well as the processing industry because of its negative impact on marketable yield and quality.

4. Impact of Overhead Irrigation on Nitrogen Dynamics within the Potato Root-Zone

ABSTRACT: Nitrogenous fertilizer plays a significant role in improving potato yield and quality. Impact of overhead irrigation and no-irrigation on nitrates dynamics within the potato root-zone was studied in the 2013 and 2014 growing seasons in Manitoba. Polymer coated urea (PCU) was used as fertilizer nitrogen source. In 2013, nitrate leaching potential from the effective root-zone was significantly higher during tuber initiation ($p = 0.01$), and tuber bulking ($p = 0.04$) stages in the non-irrigated treatment. However, in 2014, nitrate leaching potential from the effective root-zone was found significantly higher during tuber bulking stage ($p = 0.03$). Tuber initiation and tuber bulking stages are sensitive with respect to soil moisture and nutrients. In both years, supplemental irrigation was applied to the irrigated treatment during the tuber initiation, and tuber bulking stages. Overhead irrigation and rainfall facilitated the release of nitrogen from PCU/ESN urea in the plant-available-form in the irrigated treatment. However, lower rainfall during the same stages slowed the release of nitrogen from PCU granules in the non-irrigated treatment. This high concentration of nitrates was not available to the plants and accumulated within the root-zone and leaching down with subsequent rainfall events. Comparatively lower soil moisture and unfavorable temperature conditions for the release of nitrogen from PCU granules affected both treatments in 2014. Water deficit conditions are not favorable for the release of nitrate from PCU which has a negative impact on potato production.

4.1 INTRODUCTION

Potato (*Solanum tuberosum* L.) is a widely grown crop in the Canadian Prairies. It is a high maintenance crop due to high nutrient inputs and the need for efficient water management (Western Potato Council, 2003; Guenthner et al., 1999). Canadian Prairies accounts for 38% of the total potato production area in Canada, with the majority in Manitoba (Statistics Canada, 2011). Manitoba is the second largest potato producer among all the Canadian provinces with an estimated potato planting area of 33,000 ha (Statistics Canada, 2011). Potato yield is influenced by many soil properties including soil texture (Redulla et al., 2002; Cambouris et al., 2006; Shillito et al., 2009; Po et al., 2010), soil water content (Starr et al., 2008), organic matter content (Reeves, 1997), soil temperature (Zebarth and Rosen, 2007), and soil-nitrogen concentration (Gheysari et al., 2009).

The importance of fertilizers in improving the crop yield and quality can never be underestimated. Nitrogen (N), potassium (P) and phosphorus (K) are the predominant fertilizers, generally applied to meet the crop nutrients demand, if the native soil supplies of these nutrients are limited (Westermann, 2005). Nitrogen (N) is one of the essential fertilizers that affects plant growth and plays a significant role in optimizing the crop yield (Wienhold et al., 1995; Li et al, 2007). Of the total N utilization in Canada, 82% is used in the three Prairie Provinces i.e. Manitoba, Saskatchewan, and Alberta (Agriculture and Agri-Food Canada 2002).

The addition of nitrogenous fertilizers to the agricultural systems has an impact on the composition of air which is 79% nitrogen. The N in the air is present in the form of N_2 molecules, which is not directly available to the plants. That is why inorganic or mineral fertilizers are supplied to the plants to meet the crop nutrients demand. These fertilizers supply a form of N, called fixed nitrogen, that plants can easily uptake. In an inorganic fertilizer, N in the form of ammonium ion (NH_4^+) is converted into nitrite ions (NO_2^-) by soil bacteria of the Nitrosomonas species through biological oxidation (Nitrification). The nitrite ions are further converted into nitrate ions (NO_3^-), the plant available form, at soil temperature above 10 °C by the Nitrobacter species. Nitrate is highly soluble and eventually leaches down into the deeper soil layers because of its low adsorption capacity in the soil. If soil becomes water saturated causing anaerobic conditions, Nitrate-Nitrogen (NO_3-N) may be lost to the atmosphere through a reduction process called denitrification. Complete conversion from NH_4^+ to NO_3^- takes place within a month of application.

$$NH_4^+ \leftrightarrow NO_2^- \leftrightarrow NO_3^-$$

Like all other crops, a substantial amount of fertilizer-N is required to get the optimum yield and quality of potato tuber and to tolerate the diseases as well. In addition to nitrogenous fertilizers, irrigation management also plays a significant role in improving the crop yield. Potato tubers are very sensitive to water stress. Yield may be significantly reduced by water deficit (Mahdian and Gallichand, 1997; Cambouris et al., 2006). On the other hand, excessive water application may result in respiration stress (Crawford and Braendle, 1996) and denitrification (Zebarth and Rosen, 2007). Maximum potato production is achieved when the soil moisture is sustained at an optimum level (Ojala et al., 1990) and N is frequently available during the peak demand period within the potato root-zone (Stark et al., 1993). In order to achieve high potato yield with minimum water quality impact, both nitrogen and water management should be taken into account.

A combination of fertilizer application and irrigation management during the early growth stages of potato affects the tuber yield. Both over- and under-application of irrigation water and nitrogenous fertilizers, affect the nitrogen dynamics within the potato root-zone. The highly soluble NO_3-N will be leached below the root-zone due to excessive water application. That is why over-application of irrigation water causes contamination of ground water and surface water by leaching and surface run off, respectively. However, the total N uptake by plants is also substantially restricted by water deficits (Tarkalson et al., 2006)

Intensive over-application of fertilizer is one of the main contributors to lower yield and elevated NO_3-N concentrations in groundwater. If the excess N is not utilized by the crop, N may accumulate within the root-zone in the form of NO_3-N which can leach below with a rainfall or supplemental irrigation event causing an increase in the NO_3-N concentrations in the groundwater (Darwish et al., 2003). If the soil becomes saturated, this nitrogen may be lost to the atmosphere in the form of nitrous oxide (N_2O) gas by denitrification (Beauchamp, 1997), which destroys the stratospheric ozone contributing to global warming (Ravishankara et al., 2009). Nitrate leaching in the agricultural soil is influenced by many factors such as the irrigation system/applicator (Power et al., 2000; Darwish et al., 2003), irrigation management (Diez et al., 2000; Martin et al., 1994; Pang et al., 1997; Schepers et al., 1995), N fertilizer management (N rate, application method, and splitting) (Tarkalson et al., 2006; Diez et al., 2000; Moreno et al., 1996), soil characteristics (Sogbedji et al., 2000), and rainfall patterns (Klocke et al., 1999). Soil thickness and distance between the bottom of the root-zone and groundwater table also plays a role in determining the potential for ground water contamination. If the plants roots are closer to the water table, nitrate leaches into the groundwater more easily.

The results from numerous studies have proven that excessive irrigation and heavy rainfall are the main drivers of NO_3-N losses from plant root-zone (Tamini and Mermoud, 2002, Jalali, 2005; and Wallis et al., 2011). This loss can be controlled by irrigation management (that subsequently governs the volume of subsurface drainage water) and fertilizer management (Zhu and Chen, 2002; Gheysari et al., 2009; Tamini and Mermoud, 2002). The timing and scheduling of irrigation directly affects nitrate leaching. A proper water management can minimize N losses from the plant root-zone and improve the N uptake. Tarkalson et al., (2006) reported that if there is a significant difference between the irrigation supplies and the evapotranspiration demand of crop, the application of N fertilizers assessed for full irrigation may result in “unintentional” over application of N fertilizers causing the potential for N losses. O’Neill et al. (2004) found higher yield with N application coupled with sufficient irrigation supply and lower yield under deficit irrigation. They reported 23% increment in average yield with adequate verses deficit irrigation supply and dramatically 100% yield increase for adequate versus deficit N levels in the Great Plains of the United States. Soil type and soil physical properties also affect nitrate leaching potential. Previous studies indicate lower nitrate leaching potential in silt loam soils (Saxton et al., 1977) and higher potential in sandy loam soils (Ritter et al., 1990).

Many researchers have studied the effect of irrigation water management on N-dynamics in different crops and found that N uptake, translocation, distribution and accumulation within the root-zone are influenced by irrigation. Garabet et al. (1998), changed the soil moisture content within the wheat root-zone by irrigating to 33%, 66%, and 100% of full irrigation. The N-uptake in wheat was 9 kg-ha^{-1} smaller with 100% of full irrigation compared to 66% of full irrigation, showing that increasing the amount of irrigation decreased the total N uptake in wheat. Weed and Kanwar (1996) observed a pattern of accumulation of NO_3-N within the soil profile and it’s leaching for different crops. Deep-rooted crops had a lower nitrate leaching potential because they have the ability to uptake NO_3-N from deeper depths.

Potatoes require comparatively less N during the early part of the growing season i.e. sprout development, and vegetative growth stages compared to the later part i.e. tuber initiation, and tuber bulking stages. Excessive N application during the early part of the growing season leads to delay onset of the tuber initiation stage, and decrease the yield. Potato requires an adequate and steady supply of N from tuber formation to bulking. Therefore, potato growers apply approximately 25-50 % of the total recommended N at the beginning of the growing season and the remainder is applied at the tuber initiation stage. Although this scheduling improves the yield and quality of tuber, it is costly and labor intensive. Controlled release nitrogen (CRN), also known as polymer coated urea (PCU), and environmentally smart nitrogen (ESN) is a cost effective N application source. A micro-thin polymer coat facilitates the release of N at a controlled rate and minimizes N losses from the soil. The rate of N release from PCU is controlled by soil temperature and soil water content. When water is applied to the soil by supplemental irrigation and/or rainfall, it enters into the polymer coated fertilizer granule and dissolves the N into soluble form within the granule. As temperature increases, this nitrogen solution moves out through the polymer coated fertilizer granule into the soil solution in the plant available form (Agrium, 2005).

Russet Burbank is a commonly grown potato in Manitoba. Farmers usually apply supplemental irrigation by overhead irrigation systems. Many studies have investigated the effect of N application on yield and overall N balance in the soil under different irrigation treatments (Liu et al., 2003; Ju et al. 2006). However, very little research to assess the nitrogen dynamics within the potato root-zone under overhead irrigation application in the presence of shallow groundwater table has been reported. There is only one study that compared the effects of irrigation vs. no-irrigation on N losses from agricultural fields by measuring the N_2O gas emissions (Horvath et al., 2010). Many studies have reported about NO_3-N behavior in coarse textured soils (Delgado et al. 2001; Ziadi et al. 2011). However, there is very little information on nitrates in loam-textured soils. The objective of this study was to examine the effects of no-irrigation and irrigation applied through overhead irrigation systems (self-propelled linear move irrigation system, and travelling rain gun) on nitrogen dynamics within the potato root-zone in a loamy sand soil, and to analyze the nitrate leaching potential below the root-zone.

4.2 MATERIALS AND METHODS

4.2.1 Study Site

Field experiments were conducted during 2013 and 2014 growing seasons in southern Manitoba on uniformly flat commercial farms located south of Winkler (49° 10′ N Lat., -97° 56′ W Long., 272-m elevation). In order to avoid pathogen carryover, separate experimental sites were used in both years. In 2013, experiment was conducted at Canada Manitoba Crop Diversification Center (CMCDC) farm while Hespler farm located one km away from CMCDC farm was the experimental location in 2014.

4.2.2 Soil Type

Soil characteristics, agronomic practices and drainage systems of the study site were reported previously (Cordeiro and Sri Ranjan, 2012). The soil at the experimental site is sandy loam soil with textural percentage of sand 70%, silt 19%, and clay 11% and is imperfectly drained. This soil belongs to the Reinland series being classified as Gleyed Rego Black Soil (MAFRI. 2010). Representative soil samples were collected from different plots in the spring prior to the plot establishment to assess the required rate of nutrients N, P, K and S.

4.2.3 Climatic Conditions

Average annual precipitation (AAP) of this area is 533 mm of which rainfall accounts for 416 mm. According to Environment Canada (2013), the growing season (May to September) rainfall is 342 mm on an average in this study location. This amount of rainfall is not sufficient to meet the entire crop water demand especially in the highly moisture deficit months of June and July. That is why requisite amount of supplemental irrigation is applied to replenish this gap.

4.2.4 Experimental Design

Plots were arranged in a randomized complete block design (RCBD) replicated three times. Each season, two water management treatments comprising of overhead irrigation system and no supplemental irrigation were tested to evaluate the effect of overhead irrigation on nitrogen dynamics within the potato root-zone, and nitrate leaching potential below the root-zone. Total field area, field divisions and dimensions, and mean of overhead irrigation are given in Table 4.1 for both years.

Table 4.1. Experimental field dimensions and mean of overhead irrigation for study years 2013 and 2014.

Year	Field Area (ha)	No. of Plots	Plot Area (ha)	Plot Dimensions (m^2)	Overhead Irrigation Mean
2013	1.2	6	0.20	45X40	Linear Move Irrigation System
2014	1.3	6	0.22	50X44	Travelling Rain Gun

All the plots were planted with the Russet Burbank cultivar, which is the most commonly grown cultivar in Manitoba. A reservoir located about 3 km west of the research site was used as a source of supplemental irrigation water. Water quality was tested prior to the plot establishment. Nitrate concentrations and electrical conductivity were found to be ≤ 0.2 mg L^{-1} and 0.55 dS m^{-1}, respectively, making it appropriate for irrigation purpose.

4.2.5 Instrumentation and Data Collection

Weather data including rainfall (mm), temperature (°C), relative humidity (%), solar radiations, and wind velocity (km/h) were collected using an onsite weather station (Spectrum Technologies, Inc. Weather Station, 2000 Series). Piezometers were installed at the center of each plot and water level sensors (WLS) (Solinst Levelogger Junior 3001, Solinst Canada, Ltd., Georgetown, Ontario, Canada) were hung inside each piezometer to record the groundwater level at 30 minutes interval throughout the growing season. C-probe and Watermark sensors were installed at 0.2, 0.4, 0.6, 0.8 and 1.0 m depths from the ground surface at the center of each plot to track volumetric soil moisture contents (%) and soil water tension (kPa), respectively, throughout the growing season. Irrigation application was triggered when the tensiometer reading exceeded 25 kPa at any of the 0.2, 0.4, 0.6 m soil depth in the irrigated plots. Irrigation water was applied in the irrigated treatment plots through linear move irrigation system (Orbitor 3000, Nelson Irrigation Corporation, Walla Walla, WA) in 2013 while a travelling rain gun was used in 2014. The depth of irrigation was based on % volumetric depletion integrated over the depth of the root-zone (600 mm). Field capacity was determined from C-probes by saturating the soil prior to installation. Irrigation nozzles were manually turned on/off to ensure no-irrigation outside of selected plot boundaries. Irrigation application rates were measured by in-field rain gauges. The irrigation rate was adjusted to replenish the daily ET demand of the potato crop. Evapotranspiration (EC) was determined using Penman Monteith’s equation.

4.2.6 Nitrate Concentration

Soil nitrate concentration was determined by Strickland and Parsons (1968) cadmium (Cd) reduction method using an auto-analyzer due to its efficient speed and accuracy (greater than 90%) (Huffman and Barbarick, 1981: Skjemstad and Reeve, 1978). Representative soil samples within 1.0 m below the ground surface were taken at 0.2 m intervals to determine the NO_3-N concentration at the beginning of each growth stage. Soil samples were stored in a refrigerator prior to the analysis. Before beginning the analysis, soil samples were subjected to air-drying for 24 hours and then ground. The ground soil was sieved with a sieve mesh size of 1.0 mm. Dissolved 15 g KCl in 1 L of deionized water to prepare nitrate-extracting solution. Scooped 5 g of soil into a plastic cup, added 12.5 mL of nitrate extracting solution and stirred for 15 minutes to prepare a solution of 2.5:1 (extract:soil) extraction ratio. The mixture was filtered through filter paper (Osmonics Inc., Fisher Scientific; Pittsburgh, PA) into a plastic cup. Filtered solution was passed through a granulated cadmium-column containing copperized-Cd that reduces nitrate (NO_3) to nitrite (NO_2).

$$NO_3^- + 2H^+ + 2e^- \rightarrow NO_2^- + H_2O$$

The nitrite (both original soil nitrate and nitrite from reduced from nitrate) was measured colorimetrically following reaction with a diazotizing reagent called sulfanilamide coupled with [N- (1-napthyl) - ethylenediamine dihydrochloride]. As a result a pinkish-purple color develops that is measured between the wavelengths of 510 and 550 nm. The absorbance of the solution is directly proportional to the concentration of nitrite + nitrate in the sample.

4.2.7 Electrical Conductivity

Electrical conductivity was measured to investigate the salinity status. The EC (dS/m) was multiplied by a factor of 670 mg L^{-1} dS^{-1} m to calculate total dissolved salts (mg/L) (Whipker and Cavins, 2000). In order to determine the electrical conductivity of soil within 1.0 m depth below the ground surface, soil samples taken at 0.2 m intervals were air dried for 24 hours, ground, and sieved through a 1 mm Mesh size. Deionized water was added to 50 g of soil while stirring with a spatula to make a saturated paste. At saturation, the soil paste starts to glisten. The paste was transferred onto a filter paper lining a Buchner funnel. The Buchner funnel was placed on a 250 mL vacuum flask and suction was applied with a mechanical suction pump for 30 seconds. The saturated paste extract collected into the vacuum flask was used for the EC measurement. A Conductivity Meter (YSI Model 32, Yellow Springs Instrument Co., Inc., Ohio, USA) was calibrated for temperature compensation using the reference temperature of 25°C. For this purpose, the standard potassium nitrate (KNO_3) solution was used following the manufacturer's instructions. Rinsed the conductivity cell with deionized water, dipped it into the saturated paste extract present in the beaker, and read the EC of the saturated paste extract in dS/m.

4.2.8 Nitrate Leaching Potential

Although soil coring provides information on soil nitrate concentration within the soil profile, it is not adequate to calculate the concentration of nitrates leached below the root-zone (Willian and Nielsen, 1989). However, percolation depth combined with soil nitrate concentration can be used to determine the nitrate leaching potential within the effective root-zone. Water balance equation was used to determine the daily water percolation (mm).

Percolation = Rainfall + Irrigation – Change in Soil Water Storage – Evapotranspiration

$$P = R + I - \Delta S - ET$$

When $(R + I) > (\Delta S + ET)$ percolation will occur. Manitoba Ag Weather Network station (Spectrum Technologies, Inc. Weather Station, 2000 Series) located on site was used to collect rainfall (mm) data on a daily basis. Irrigation depth (mm) was measured at the experimental site.

Evapotranspiration (mm) was determined on a daily basis using Penman Monteith's equation. The crop water demand changed with daily weather conditions and potato growth stage. Change in soil water storage (mm) within the effective root-zone of potato (0.6 m) was determined on a daily basis by measuring the volumetric soil water content. Since soil samples were taken at the beginning of each growth stage, daily nitrate concentrations between two consecutive sampling dates were calculated by linear interpolation. It was assumed that the nitrogen added from rainfall/irrigation water, was negligible.

4.2.9 Groundwater Sampling

Groundwater samples were taken from each replicated plot following the potato harvest in both years for analysis of nitrate, electrical conductivity, and total dissolved solids (TDS) in groundwater. Observation wells installed in six replicated plots were purged thrice by an inertial pump; a manually operated groundwater sampling assembly consisted of a riser tube coupled with a foot-valve. After purging, groundwater samples were collected by inertial pump by repeatedly lowering and raising the tubing. Foot-valve permits the groundwater to get into the tube that may be discharged from the outer end. The purpose of purging observation wells before sampling is to remove the stagnant water from well casing, and allow groundwater adjacent to the well to flow into the observation well. This technique enables the collection of more representative sample of the aquifer. Samples were collected in 250 mL plastic bottles, kept refrigerated before analysis.

4.2.10 Agronomic Practices

Russet Burbank tubers were mechanically planted in hills on 17 May 2013 and 13 May 2014 at a spacing of 0.91 m (36 in.) between rows and 0.36 m (14 in.) within the row. Fertilizer rates, determined on the basis of soil test results, were applied uniformly in all the six replicated plots in both years. Fertilizers were broadcasted and cultivated with chisel plough to incorporate into soil. Pre-sowing broadcasted fertilizers were the only source of mineral nutrient input to the soil. Nitrogen was applied in the form of polymer coated urea (PCU) so that the required N may be available to plant at each growth stage due to its controlled release mechanism. Application rate and portion applied is given in Table 4.2 for both years.

Table 4.2. Fertilizers application rates for study years 2013 and 2014.

Nutrient	Source	Application Rate
Nitrogen (N)	Urea: ESN blend	178 kg ha^{-1}
Phosphorus (P)	Monoammonium Phosphate (MAP)	68 kg ha^{-1}
Potassium (K)	Potassium chloride (KCl)	90 kg ha^{-1}
Sulphur (S)	Potassium sulfate (K_2SO_4)	23 kg ha^{-1}

A power hiller was used to do the hilling/ridging to protect the stems of the potato crop from wind effects. The height of ridges was maintained at 0.12 m. Berming was done around the plots following the hilling operation to prevent overland flow between plots and from outside the study area. Fungicides were applied on a weekly basis whereas herbicides and insecticides were applied based on the detection of weeds and pests. All the other agronomic practices were carried out in accordance with the potato production guidelines. Potatoes were flailed and harvested using a single row potato harvester in the third week of September at physiological maturity. Three 20 m long strips per plot with one row above or close to the drain tile, second row along ¼-spacing and third row along ½-spacing of the drains were harvested. The potatoes were weighed in the field for yield. Statistical analyses were done using student t-test, ANOVA and JMP software (Ver. 8, SAS Institute, Inc., Cary, N.C.).

4.3 RESULTS AND DISCUSSION

4.3.1 Weather Conditions and Nitrate Dynamics

The 2013 growing season was warmer and wetter while the 2014 growing season was cooler and drier compared to the 30-year average growing season weather conditions for this area. The 30-year average rainfall, average minimum and maximum air temperature during the growing season (May to September) for this area is reported as 342 mm and 12 to 22 °C, respectively (Environment Canada, 2013). The 2013 growing season had comparatively higher average temperature and higher rainfall at each growth stage compared to that in 2014 (Fig. 4.1). In the 2013 growing season, rainfall depth and average minimum and maximum air temperature were recorded as 389 mm (47 mm higher than 30-year average) and10.2 °C to 23.6 °C, respectively. The rainfall depth and average minimum and maximum air temperature for the 2014 growing season were recorded as 262 mm (80 mm lower than 30-year average) and 9.5 °C to 23 °C, respectively. Supplemental irrigation was applied during tuber initiation and tuber bulking stages in both years to meet the crop water demand. In 2013, irrigated treatment received 130.5 mm of supplemental irrigation at 11 different times throughout the growing season. A total of 95.2 mm supplemental irrigation was applied through 5 irrigation events during the 2014 growing season.

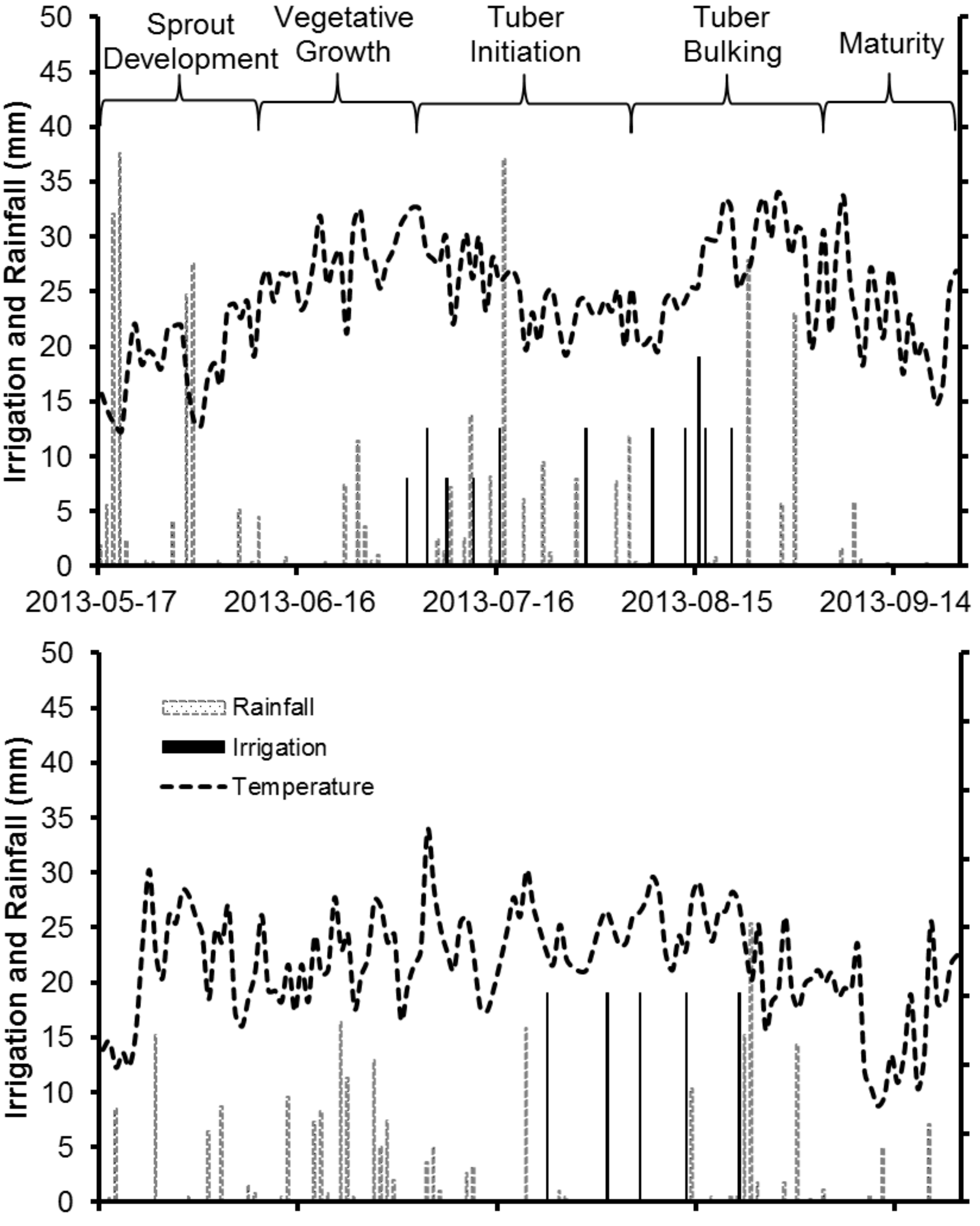

Figure 4.1 Daily recharge and daily average air temperature in the 2013 and 2014 growing seasons at different growth stages.

The nitrate concentrations at 0.2, 0.4, 0.6, 0.8 and 1.0 m depths from ground surface at vegetative growth, tuber initiation, tuber bulking, and maturation stages during the 2013 and 2014 growing seasons are shown in figure 4.2. Although, the non-irrigated plots showed a trend of higher nitrate content within the potato root-zone compared to the irrigated plots during both years, in 2013 the difference at vegetative growth, tuber initiation, and maturation stages was not statistically significant. However, the nitrate content was significantly higher in the non-irrigated treatment at 0.2 ($p = 0.004$) and 0.4 m ($p= 0.019$) depths at tuber bulking stage in 2013 while the difference in nitrate concentrations was not significantly different at deeper depths (0.6, 0.8 and 1.0 m). Although the nitrate contents were higher in the non-irrigated treatment from vegetative growth stage to maturation in 2014 the differences were not statistically significant. When comparing both growing seasons, nitrate content in both treatments were higher in the 2014 growing season at each growth stage compared to 2013.

Nitrogen was applied in the form of polymer-coated urea (PCU), a controlled release nitrogen fertilizer source. It has nitrogen granules covered in a thin/semi-permeable polymer coating (Beres et al., 2012; McKenzie et al., 2007). Soil water is absorbed by the granule which dissolves the nitrogen inside to releases it at a specific temperature and soil moisture level (Agrium, 2005). About 80% of the nitrogen is released from PCU/ESN urea between 40 and 90 days after application. This period spans over the beginning of tuber initiation stage to mid of tuber bulking stage.

Potato requires modest nitrate and soil moisture in the beginning of the growing season i.e. at sprout development and vegetative growth stages compared to the subsequent growth stages. In both years, rainfall was sufficient to meet the crop water demand at the early stages. Temperature conditions and soil moisture level remained favorable to the release of required quantity of nitrogen from PCU in both treatments (Fig. 4.2a and 4.2e). Supplemental irrigation was applied during tuber initiation, and tuber bulking stages in both years. In 2013, both treatments received a total of 116 mm rainfall at tuber initiation stage. However, irrigated treatment received additional moisture through 41 mm of supplemental irrigation. An average temperature of 25 °C during the tuber initiation stage and 116 mm rainfall facilitated the release of nitrogen from PCU in both treatments (Fig. 4.2b). However, comparatively higher nitrate content within the 0.2 m depth in the non-irrigated treatment may have been due to the accumulation of unutilized PCU. Tuber bulking stage was drier with an average temperature of 27 °C (sometimes reaching > 30 °C at noon) and 67 mm rainfall. A total of 69 mm supplemental irrigation was applied during this stage. Thus, high temperature and ET, and correspondingly lower soil moisture could not have been favorable for the release of nitrogen from PCU in the non-irrigated treatment (Fig. 4.2c). As a result, the PCU did not fully release the nitrate in the non-irrigated treatment within the root-zone. Therefore, the nitrate content was significantly higher in the non-irrigated treatment at 0.2 ($p = 0.004$) and 0.4 m ($p= 0.019$) depths. Polymer coated urea may release a maximum of 80% of the total nitrogen during the period of sprout development to mid-bulking stage and remaining is released after that. The site received a total of 0.7 mm rainfall during maturation stage with an average temperature of 22 ^{o}C. Since the potatoes do not need as much water during the maturation stage (Rowe, 1993), no supplemental irrigation was applied during this stage. About 20% of the total PCU nitrogen may have been released during this stage. The decrease in nitrate content at 0.2 m depth and increase at 1.0 m depth in non-irrigated treatment may be attributed to leaching down of unutilized nitrogen with percolation caused by rainfall (Fig. 4.2d). An upward flux of nitrate rich shallow groundwater to meet the crop water demand may also have contributed to the higher nitrate content in the non-irrigated treatment.

In 2014, both treatments received a total of 23.7 mm rainfall at tuber initiation stage. However, irrigated treatment received 38 mm additional water by supplemental irrigation. The average recorded temperature, during this stage, was 19 °C. Lower temperature (sometimes falling below15 °C) and lower recharge may have slowed the release of nitrogen from PCU in both treatments (Fig. 4.2f). In the irrigated treatment, moisture received from rainfall and irrigation dissolved the nitrogen into soluble form within the granule but the temperature conditions could not support the release of adequate nitrogen from the PCU granules. However, in the non-irrigated treatment, which received only 23.7 mm, rainfall was not sufficient even to dissolve the PCU granules to release the nitrogen. Therefore, comparatively lower nitrate accumulation was observed in the non-irrigated treatment. Both treatments suffered from nitrate stress at this stage. Tuber bulking stage had an average temperature of 22 °C and 73 mm rainfall. A total of 57 mm supplemental irrigation was applied during this stage. A comparatively higher temperature and soil moisture level, between tuber initiation and tuber bulking stages, supported the release of dissolved nitrogen from PCU granules in the plant-available-form in both treatments (Fig. 4.2g). However, comparatively higher unutilized nitrates were found in the non-irrigated treatment. A total of 13 mm rainfall received during the maturation stage and average temperature remaining at 12 °C may not have been sufficient to release the remaining quantity of nitrogen from PCU. Comparatively better moisture availability to the irrigated treatment facilitated the higher release of nitrogen from PCU that could be utilized by the plants (Fig. 4.2h).

There may be several other reasons of comparatively higher nitrates in the 1.0 m depth below the ground surface. In the non-irrigated treatment, less percolation took place due to dry conditions leading to accumulation of nitrate within the root-zone. According to pre-sowing groundwater analysis, nitrate concentration in groundwater was found to be 55 ppm and 70 ppm in 2013 and 2014 growing seasons respectively. An upward flux of nitrate rich shallow groundwater may have increased the nitrate contents within the potato root-zone.

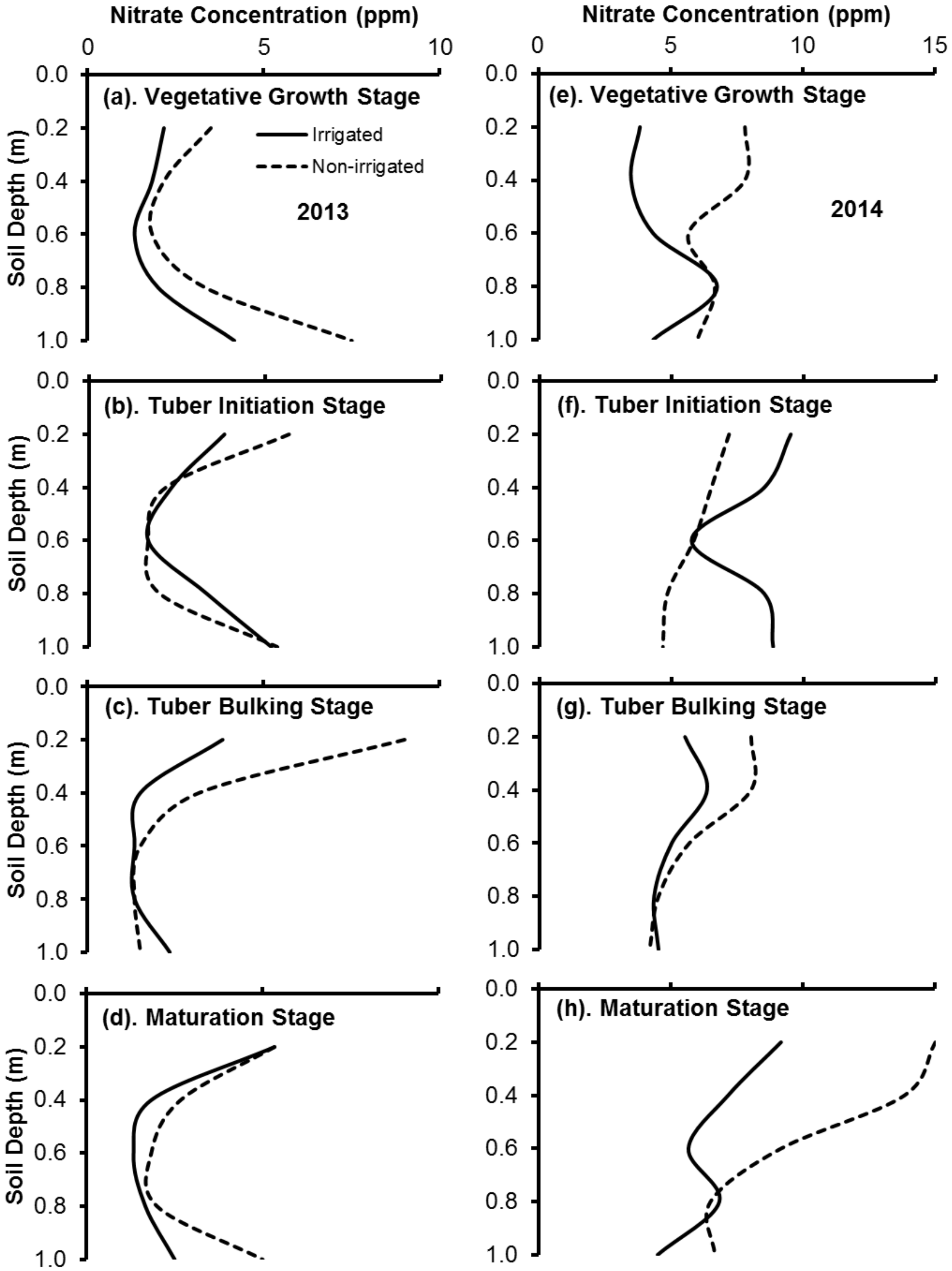

Figure 4.2. Nitrate Dynamics within 1.0 m Soil Depth during the Growing Seasons 2013 and 2014.

4.3.2 Nitrate Leaching Potential

The risk of nitrogen loss from soil increases with increase in the time it resides as unutilized nitrates within the root-zone. Nitrate accumulated within the root-zone has the ability to leach down below the effective root-zone with percolating water because of its high solubility. Daily percolation (mm) from the effective root zone (0.6 m) of irrigated and non-irrigated treatments during the 2013 and 2014 growing seasons are shown in figures 4.3 and 4.4, respectively. A pattern of daily percolation varied from vegetative growth to maturation stage with respect to rainfall and/or supplemental irrigation events. In the irrigated treatment, percolated water was from both rainfall and irrigation while only rainfall contributed to percolation in the non-irrigated treatment. As a result, more water percolated from irrigated plots compared to non-irrigated plots. In 2013, total percolation below the effective root-zone was 245.5 and 129.6 mm for irrigated and non-irrigated treatment, respectively. However, a comparatively lower percolation of 187.6 and 106.8 mm was estimated for the irrigated and non-irrigated treatment, respectively from vegetative growth to maturation stage in the 2014 growing season. Although more water percolated from the irrigated treatment, the higher concentration of unutilized nitrates in the non-irrigated treatment may contribute more to nitrate leaching.

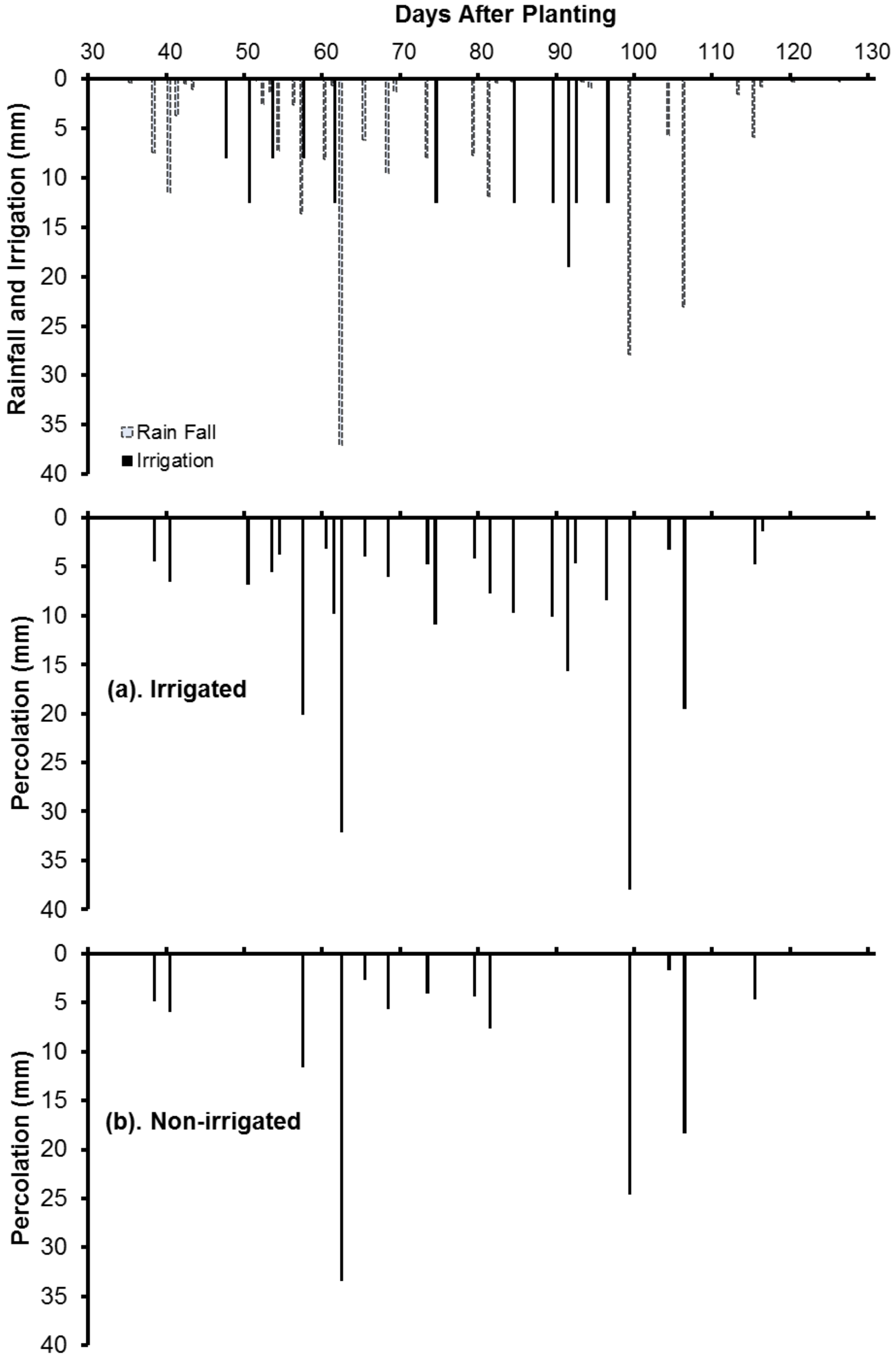

Figure 4.3. Estimated percolation below the effective root-zone during the 2013 growing season.

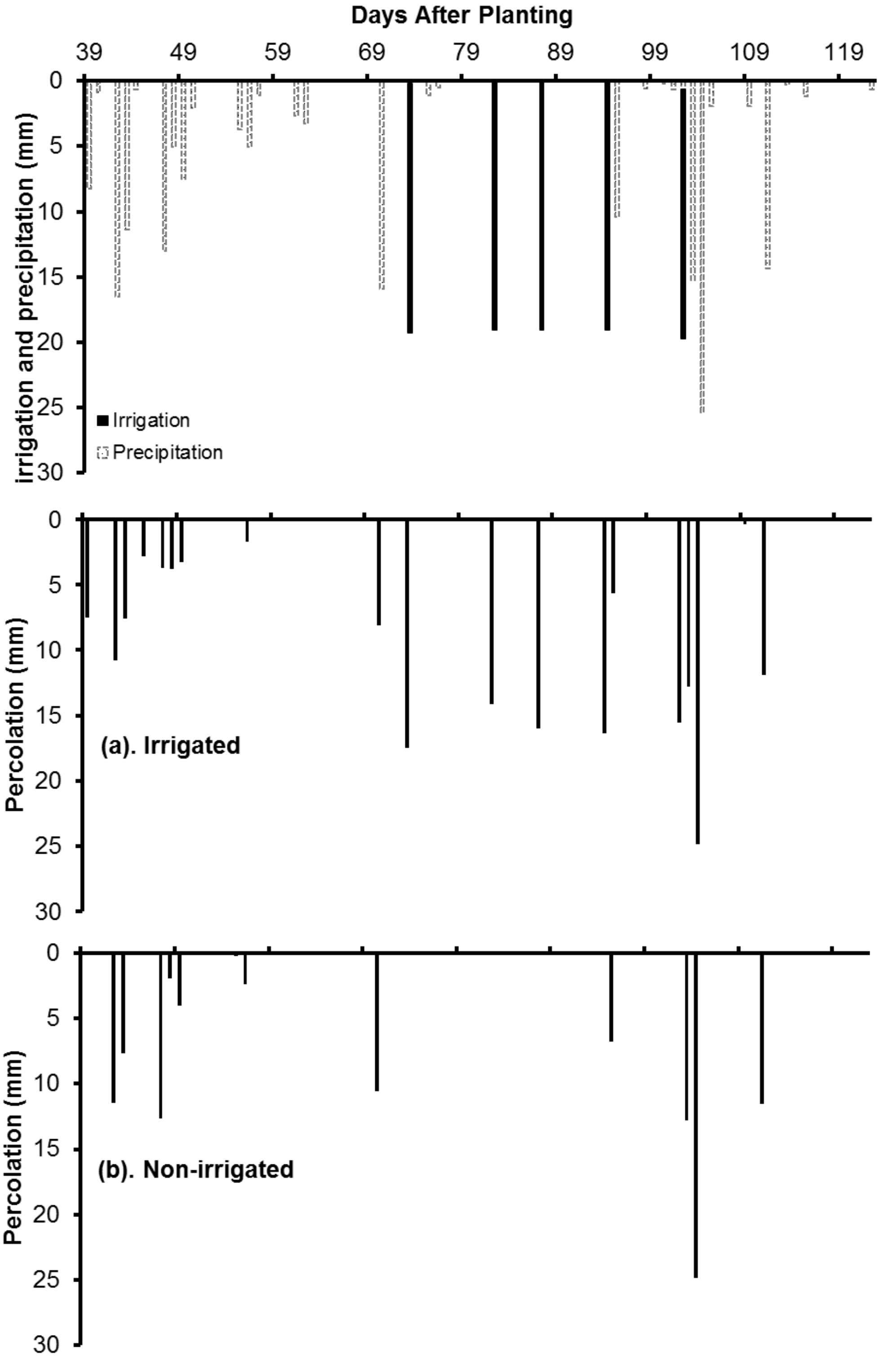

Figure 4.4. Estimated percolation below the effective root-zone during the 2014 growing season.

In order to compare the nitrate leaching potential between the treatments, during a particular growth stage, three rainy days each from vegetative growth, tuber initiation, and tuber bulking stages were selected. Rainy days were selected because percolation was taking place simultaneously in both treatments during this particular period. Significant percolation as well as nitrate leaching did not occur during the maturation stage. Selected number of days after planting (DAP) and corresponding rainfall, and percolation for the 2013 growing season are given in table 4.3.

Table 4.3 Percolation (mm) caused by rainfall (mm) on selected number of day after planting (DAP) in the 2013 growing season

Day After Planting (DAP)	Rainfall (mm)	Percolation (mm)	
		Irrigated	Non-irrigated
38	7.5	4.6	4.5
79	7.8	4.5	4.2
106	23.1	19.6	18.4

Nitrate concentration within the effective root-zone of potato at each selected DAP is shown in figure 4.5a. A significantly higher concentration of nitrates was found within the effective root-zone in the non-irrigated treatment at 79 ($p = 0.01$) (tuber initiation stage) and 106 DAP ($p = 0.04$) (tuber bulking stage) compared to the irrigated treatment. Nitrate leaching potential depends on depth of water drained below the root-zone (percolation) and the total amount of nitrogen within the effective root zone. Significantly higher nitrate accumulation within the effective root-zone of the non-irrigated treatment may increase the nitrate losses with percolating water at tuber initiation, and tuber bulking stages. Approximately 85% of the total growing season percolation occurred during tuber initiation, and tuber bulking stages in the non-irrigated treatment. Although nitrate concentration was also higher at 38 DAP (vegetative growth stage) in the non-irrigated treatment, the difference was not statistically significant.

Selected number of day after planting (DAP) and corresponding rainfall and percolation for the 2014 growing season are given in table 4.4.

Table 4.4 Percolation (mm) caused by rainfall (mm) on selected number of day after planting (DAP) in the 2014 growing season

Day After Planting (DAP)	Rainfall (mm)	Percolation (mm)	
		Irrigated	Non-irrigated
41	16.5	11.49	10.79
69	15.9	10.58	8.08
110	14.4	11.94	11.52

Nitrate concentrations at selected DAP are shown in figure 4.5b. A significantly higher concentration of nitrates was found within the effective root-zone in the non-irrigated treatment at 110 DAP (p = 0.03) (tuber bulking stage) compared to the irrigated treatment. Nitrate leaching potential increased due to the higher nitrates accumulated during the tuber bulking, and maturation stages. Approximately 60% of the total growing season percolation occurred during tuber bulking stage in the non-irrigated treatment. Although nitrate concentration was also higher at 41 (vegetative growth stage), and 69 DAP (tuber bulking stage), the difference was not statistically significant.

In both years, during the vegetative growth stage, all the six replicated plots received only rainfall contributing to percolation. This rainfall was sufficient to facilitate the release of nitrogen from the slow released urea (PCU/ESN urea). Therefore, all the six replicated plots had similar concentration of nitrates within the root-zone at this stage. In the 2013 growing season, the irrigated treatment received supplemental water through overhead irrigation during tuber initiation, and tuber bulking stages. Supplemental irrigation, in addition to rainfall facilitated the adequate release of nitrogen from PCU/ESN urea in the irrigated treatment. However, lower rainfall events during the same stages decreased the release of nitrogen from PCU/ESN granules in the non-irrigated treatment causing it to accumulate and leach below the below the root-zone with subsequent rainfall events. As adequate moisture was available to the irrigated treatment, adequate nitrogen was released from PCU/ESN granules, which was utilized by the plants resulting in lower contribution to the percolating water below the root-zone.

In the 2014 growing season, first irrigation event took place at 72 DAP (tuber initiation stage) while the selected rainy day during the tuber initiation stage was 69 DAP. Both treatments were receiving only rainfall to meet the crop water demand until 69 DAP. Therefore, nitrate concentrations within the effective root-zone were not statistically significantly different from each other at 69 DAP. Supplemental irrigation was applied during the tuber bulking stage. As a result, a significantly higher nitrates accumulation was found within the root-zone of the non-irrigated treatment compared to the irrigated treatment. More nitrates may have been leached with the percolating water in the non-irrigated treatment. These results are in agreement with Zvomuya et al. (2003), Hill (1986), Errebhi et al. (1998) and Gasser et al. (2002). Waddell et al. (2000) also found significantly reduced nitrates leaching potential from PCU under sprinkler irrigation. The drier than average weather conditions in 2014 may have resulted in lower nitrate leaching potential compared to the 2013 growing season.

As nitrates are readily soluble in water, nitrate leaching potential is directly linked to soil water dynamics within the effective root-zone. The potential risk of nitrate leaching increases with the accumulation of excessive nitrates within the root-zone combined with excessive irrigation and/or intense rainfall on well-drained sandy soils having low water-holding capacity (McNeal et al., 1995).

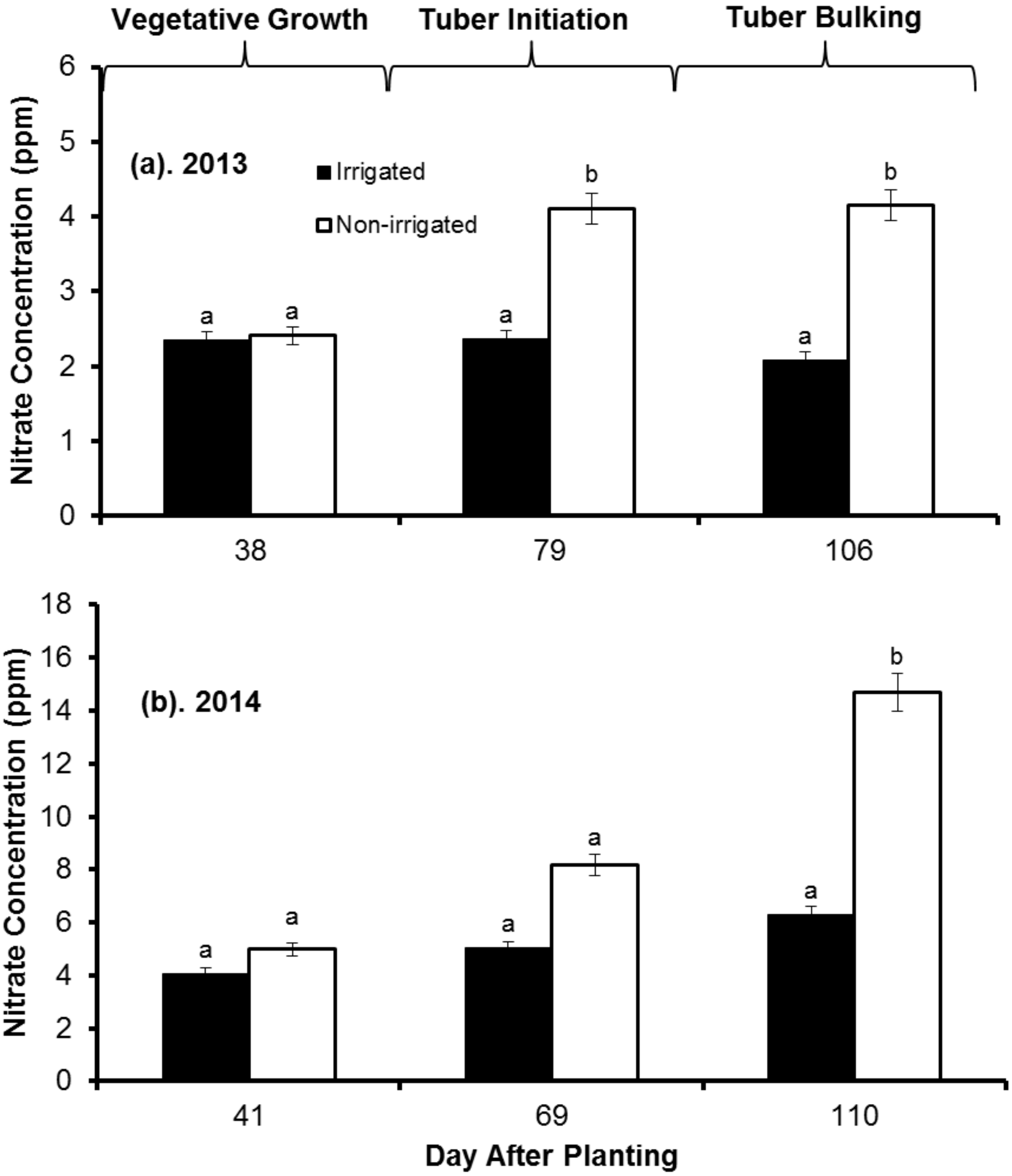

Figure 4.5 Nitrate leaching potential at selected rainy days at different growth stages in 2013 and 2014.

4.3.3 Soil and Groundwater Electrical Conductivity

Electrical conductivity (EC) of the pore water extract is used as a measure of salinity. Potatoes are sensitive to salinity (Maas and Hoffman, 1977) and yield decreases with increase in salinity. Soil EC within the potato root-zone (0 - 1.0 m) at different growth stages, and groundwater EC after potato harvesting, for the 2013 and 2014 growing seasons are shown in figure 4.6 and 4.7, respectively.

Soil EC was not significantly different in both treatments during the vegetative growth and tuber initiation stages in both years. In 2013, the soil EC was found to be significantly higher in the slightly saline limit (2 - 4 dS/m) for the non-irrigated treatment at tuber bulking ($p = 0.03$), and maturation ($p = 0.04$) stages. Soil EC exceeding the non-saline limit (0 - 2 dS/m) leads to higher osmotic potential around the roots that affects water uptake by the plants. In 2014, similar to the 2013 growing season, a significantly higher soil EC was found in the non-irrigated treatment at tuber bulking ($p = 0.05$) and maturation ($p = 0.04$) stages. The range of soil EC was within the slightly saline limit in both treatments in all of the stages except for the irrigated treatment in the tuber bulking stage where the soil EC was within non-saline limit. Groundwater EC was found to be within the slightly saline limit in both treatments which was not statistically significantly different.

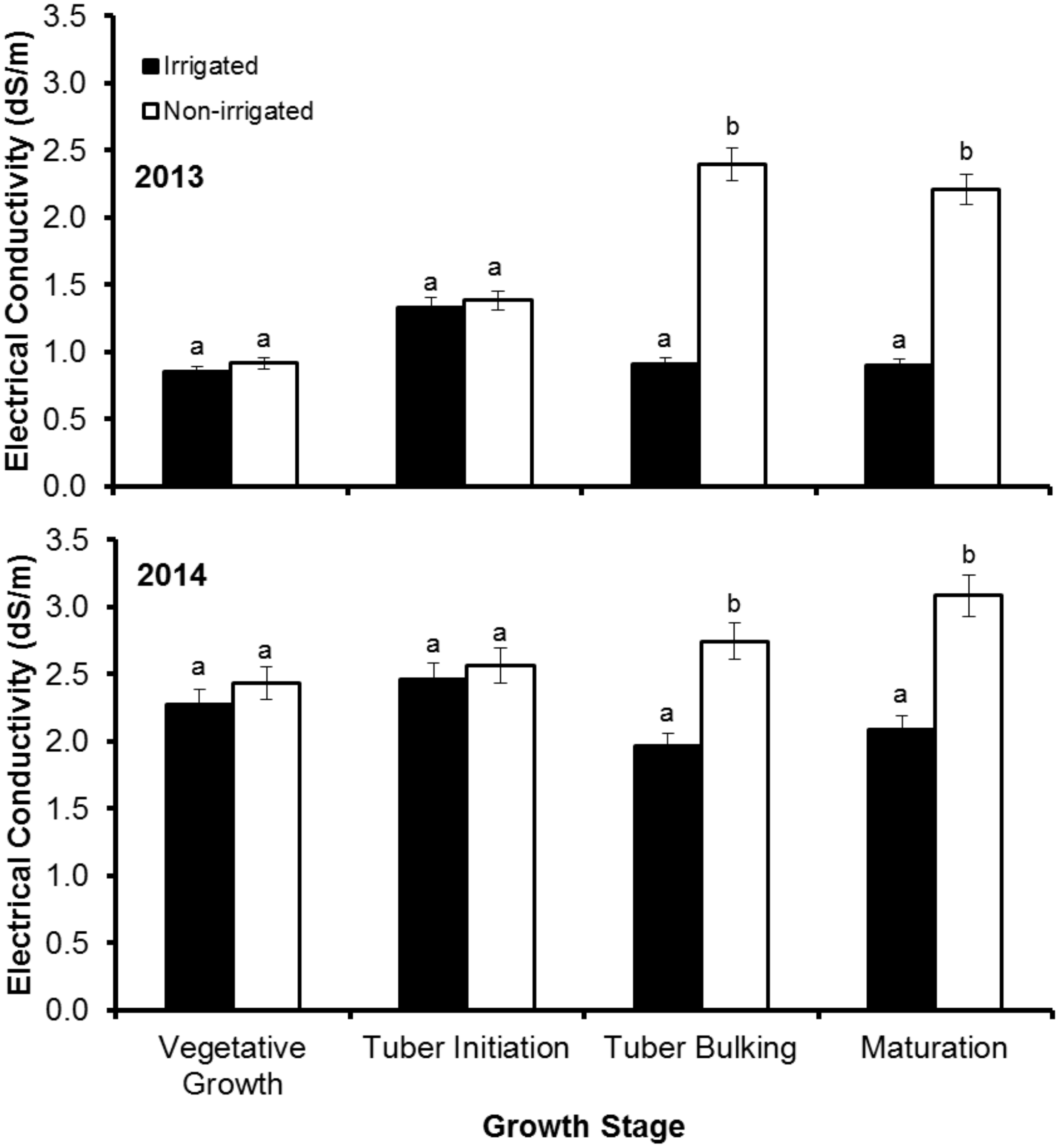

Figure 4.6 Electrical conductivity of soil within the potato root-zone at different growth stages.

Sufficient soil moisture availability from the beginning of growing season to tuber initiation stage facilitated the adequate release of nitrogen from PCU granules in both treatments. A part of the released nitrogen was utilized by the plant roots and part of it leached below the root-zone with percolating water. Lower rainfall with higher temperature and ET necessitated the need for supplemental irrigation at tuber bulking stage. However, supplemental irrigation was available only to the irrigated treatment. Adequate moisture supplied to replenish the daily ET resulted in the release of higher proportion of nitrogen from PCU in the irrigated treatment compared to the non-irrigated treatment. However, in the non-irrigated treatment, comparatively higher nitrogen accumulated within the PCU granules due to the lack of water available to release the nitrates. Supplemental irrigation was not applied at maturation stage because potato water requirement decreases at this stage. The moisture received through rainfall and irrigation previously, supported the release of nitrogen from PCU at maturation stage in the irrigated treatment. However, prolonged dry conditions could not facilitate adequate release of nitrogen from PCU in the non-irrigated treatment possibly leading to a higher soil EC.

Groundwater EC was not statistically significantly different between the treatments in both years. However, groundwater EC was found to be within the non-saline limit in 2013 while groundwater EC approached the slightly saline limit in 2014 in both treatments increasing the potential for nitrates to leach below.

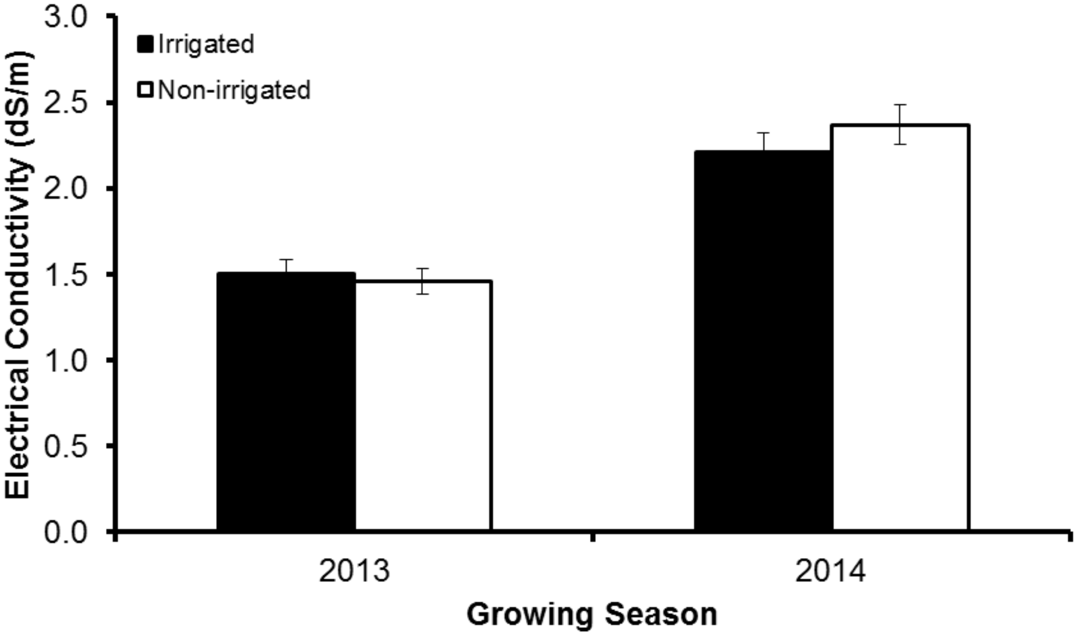

Figure 4.7. Electrical conductivity of groundwater after harvest in 2013 and 2014.

As water EC (dS/m) is multiplied by a factor of 670 mg L^{-1} dS^{-1} m to calculate total dissolved salts (TDS) (mg/L) (Whipker and Cavins, 2000), TDS in water is proportional to water EC. In 2013, TDS for irrigated and non-irrigated treatment were found to be 964 and 935 mg/L, respectively while TDS for irrigated and non-irrigated treatment were found to be 1414 and 1517 mg/L, respectively in 2014. Higher migration of nitrates from potato root-zone to groundwater in both treatments increased the dissolved salts and salinity level as well in the groundwater. Shallow groundwater generally has comparatively higher nitrate concentration at the top which decreases gradually with depth due to dilution (Mueller and Helsel, 1996). The nitrate rich shallow groundwater may also have contributed to root-zone of the non-irrigated treatment via upward flux during the water stress periods, transferring the nitrates to the potato root-zone. However, the potential of upward flux of nitrate rich groundwater may have been comparatively less in the irrigated treatment because the irrigated treatment was receiving supplemental irrigation. These results are in agreement with Hubbard et al. (1986) and Hill (1986).

4.4 CONCLUSION

Impact of overhead irrigation and no-irrigation on nitrate dynamics within the potato root-zone was studied in Southern Manitoba. In the 2013 growing season, nitrate leaching potential from the effective root-zone was found significantly higher at 79 (tuber initiation stage) ($p = 0.012$), and 106 DAP (tuber bulking stage) ($p = 0.036$) in the non-irrigated treatment. However, in 2014, nitrate leaching potential from the effective root-zone was found to be significantly higher at 110 DAP (tuber bulking stage) ($p = 0.027$). Tuber initiation and tuber bulking stages are sensitive to irrigation and nutrients stress. In 2013, supplemental irrigation was applied to the irrigated treatment during the tuber initiation, and tuber bulking stages. Overhead irrigation and rainfall coupled with favorable temperature facilitated the release of nitrogen from PCU/ESN granules in the plant-available-form. However, lower rainfall during the same stages slowed the release of nitrogen in the plant available form from the PCU/ESN granules in the non-irrigated treatment. This accumulated nitrate may have been available to leach below the root-zone with the rainfall events. In 2014, supplemental irrigation was applied to the irrigated treatment from late tuber initiation to the mid of tuber bulking stages. As a result, significantly lower amounts of nitrates leached below the root-zone in the irrigated treatment compared to the non-irrigated treatment. The 2014 growing season was comparatively drier with lower temperature and lower rainfall. Supplemental irrigation, applied through overhead irrigation system, was sufficient to meet the crop water demand but soil water content and lower temperature were not adequate for the release of nitrogen from the PCU granules. As a result, both treatments suffered from nitrate stress. The nitrate rich shallow groundwater may also have contributed to the root-zone of the non-irrigated treatment via upward flux during the water stress periods, transferring the nitrates to the potato root-zone.

Sufficient soil moisture coupled with favorable temperature conditions is required for the release of required quantity of nitrates from the granules of polymer coated urea (PCU) that may be efficiently supplied through overhead irrigation system. In addition to crop water demand, soil moisture necessary to facilitate the release of nitrates from PCU should also be taken into account. Relying on moisture supplied only through rainfall for potato production is not recommended, especially when (i) using polymer coated urea and (ii) facing shallow groundwater conditions.

5. SUMMARY AND CONCLUSION

In southern Manitoba, Russet Burbank potato cultivar yield during the 2013 and 2014 growing seasons were compared under overhead irrigation and no-irrigation. Overhead irrigation was supplied through linear move irrigation system and travelling rain gun in 2013 and 2014, respectively. The main objectives of the study were to evaluate the impact of both treatments on potato yield, marketable yield, quality and nitrogen dynamics within the potato root-zone.

Main conclusions are given below:

1. A trend of higher potato yield was observed in irrigated plots compared to non-irrigated plots in both years, although the difference in yield was not statistically significant. The irrigation water supplied through overhead irrigation system was sufficient to meet the crop water demand in the irrigated treatment. A water balance analysis conducted within the root-zone during rainy and rain-free periods showed that groundwater contribution may have met some of the crop water demand. Upward flux of the shallow groundwater table to the root-zone had a significant influence on potato yield. High yield even under dry conditions shows the importance of upward migration of water from the shallow groundwater table. Better potato yield in irrigated plots showed the importance of soil moisture supply through overhead irrigation at critical stages of development.
2. The marketable yield, economically important component, of the irrigated treatment (36.89 MT/ha) was 20% higher ($p = 0.017$) compared to the non-irrigated treatment (30.74 MT/ha). However, no significant difference of marketable yield was found between the irrigated (39.0 MT/ha) and non-irrigated (43.7 MT/ha) treatments in 2014. The 2013 growing season was comparatively wet and warm, while the 2014 growing

season was comparatively drier and cooler. Deficit soil moisture and excessive nitrate accumulation within the potato root-zone of the non-irrigated treatment resulted in significant reduction in marketable yield in 2013. Excessive nitrate accumulation may be attributed to upward flux of nitrate rich groundwater and unutilized nitrogen within the PCU granules, which could not be available to the plants. In 2014, supplemental irrigation improved the hydraulic conductivity of the soil within the root-zone of the irrigated plots making it conducive for the upward migration of groundwater. The migration and accumulation of high concentration of nitrates within the potato root-zone from the groundwater may have led to the deterioration of quality of the tubers in the irrigated treatment. As a result, both treatments suffered from nitrate stress and no significant difference was found in the marketable yield of both treatments.

3. In 2013, nitrate leaching potential from the effective root-zone was found significantly higher at 79 (tuber initiation stage) ($p = 0.012$), and 106 DAP (tuber bulking stage) ($p = 0.036$) in the non-irrigated treatment. However, in 2014, nitrate leaching potential from the effective root-zone was found to be significantly higher at 110 DAP (tuber bulking stage) ($p = 0.027$). Tuber initiation and tuber bulking stages are sensitive to irrigation and nutrients stress. Overhead irrigation and rainfall coupled with favourable temperature facilitated the release of nitrogen from PCU/ESN granules in the plant-available-form. However, lower rainfall during the same stages slowed the release of nitrogen in the plant available form from the PCU/ESN granules in the non-irrigated treatment. This accumulated nitrate may have been available to leach below the root-zone with the rainfall events.

6. RECOMMENDATIONS

1. Better marketable yield obtained under overhead irrigation system signifies the importance of irrigation in potato production in Manitoba.

2. In addition to crop water demand, soil moisture necessary to facilitate the release of nitrates from PCU should also be taken into account. Relying on moisture supplied only through rainfall for potato production is not recommended, especially when (i) using polymer coated urea and (ii) facing shallow groundwater conditions.

3. Although shallow groundwater resources may significantly decrease the need for supplemental irrigation the quality of the groundwater should be considered. Major natural sources of recharge to groundwater should be managed properly to make effective use of groundwater as a source for crop production.

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