



Profitability of Supplemental Irrigation and Soil Dewatering for Potato Production in Atlantic Canada: Insights from Historical Yield and Weather Data

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Abstract

Highly variable and unpredictable precipitation in humid regions makes water management important for consistent potato production. This study assessed the influence of supplemental irrigation (SI) and soil dewatering on potato productivity and profitability in Prince Edward Island, Canada. The average yields of Russet Burbank (RB), Shepody, Kennebec and Goldrush cultivars from 2000 to 2020 (excluding 2018) were conceptualized as the results of an un-replicated experiment with growing season (GS) precipitation representing water supply treatment. GS precipitation varied from 155 to 479 mm, with an average of 338 mm. Yield increased with increasing GS precipitation in the 155–257 mm range (Rainfall Zone 1; 3/20 seasons), became relatively insensitive to GS precipitation in the 258–425 mm range (Rainfall Zone 2; 12/20 seasons), and decreased as GS precipitation increased from 426 to 479 mm (Rainfall Zone 3; 5/20 seasons). Yields responded to GS precipitation following second-order polynomial regressions, with GS precipitation explaining 69%, 65%, 29% and 50% of yield variation for RB, Shepody, Kennebec and Goldrush cultivars, respectively. These yield regression equations predict that SI using a center-pivot system would produce a positive profit in the first half of Rainfall Zone 1 regardless of field size and in the second half of Rainfall Zone 1 in fields over 40 ha. SI would not produce a positive profit in Rainfall Zone 2 regardless of field size because precipitation was high enough that additional water supply would not have resulted in sufficient yield gains to offset the cost of SI. Soil dewatering would be beneficial for optimal production in Rainfall Zone 3 in which precipitation was excessive. The annual variation in precipitation, unpredictability of SI requirements, and unprofitability in most seasons, present a significant financial barrier for the widespread implementation of SI. On the other hand, the gross income gained from increased yields by soil dewatering would fully cover the cost of tile drain installation after only two to three extremely wet seasons, making tile drainage a good investment for consistent production. This study demonstrates that historical rain-fed yield and weather data can be used to assess the economics of potato production with SI and soil dewatering, and provides important insights on potato water management in a humid temperate climate.

La precipitación altamente variable e impredecible en las regiones húmedas hace que el manejo del agua sea importante para la producción constante de papa. Este estudio evaluó la influencia del riego suplementario (SI) y la deshidratación del suelo en la productividad y rentabilidad de la papa en la Isla del Príncipe Eduardo, Canadá. Los rendimientos promedio de los cultivares Russet Burbank (RB), Shepody, Kennebec y Goldrush de 2000 a 2020 (excluyendo 2018) se conceptualizaron como los resultados de un experimento no replicado con precipitación del ciclo de cultivo (GS) que representa el tratamiento del suministro de agua. La precipitación GS varió de 155 a 479 mm, con un promedio de 338 mm. El rendimiento aumentó con el aumento de la precipitación GS en el rango de 155 a 257 mm (Zona 1; 3/20 estaciones), se volvió relativamente

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insensible a la precipitación GS en el rango de 258–425 mm (Zona 2; 12/20 estaciones), y disminuyó a medida que la precipitación GS aumentó de 426 a 479 mm (Zona 3; 5/20 estaciones). Los rendimientos respondieron a la precipitación GS después de regresiones polinómicas de segundo orden, con la precipitación GS explicando 69%, 65%, 29% y 50% de la variación de rendimiento para los cultivares RB, Shepody, Kennebec y Goldrush, respectivamente. Estas ecuaciones de regresión de rendimiento predicen que el SI utilizando un sistema de pivote central produciría un beneficio positivo en la primera mitad de la Zona 1, independientemente del tamaño del campo, y en la segunda mitad de la Zona 1 en campos de más de 40 ha. SI no produciría una ganancia positiva en la Zona 2, independientemente del tamaño del campo, porque la precipitación fue lo suficientemente alta como para que el suministro adicional de agua no hubiera resultado en suficientes ganancias de rendimiento para compensar el costo del SI. La deshidratación del suelo sería beneficiosa para una producción óptima en la Zona 3 en la que la precipitación fue excesiva. La variación anual en la precipitación, la imprevisibilidad de los requisitos de SI y la falta de rentabilidad en la mayoría de las estaciones, presentan una barrera financiera significativa para la implementación generalizada de SI. Por otro lado, el ingreso bruto obtenido del aumento de los rendimientos por deshidratación cubriría completamente el costo de la instalación del drenaje de baldosas después de solo dos o tres temporadas extremadamente húmedas, lo que hace que el drenaje de baldosas sea una buena inversión para una producción constante. Este estudio demuestra que el rendimiento histórico y los datos meteorológicos se pueden utilizar para evaluar la economía de la producción de papa con SI y deshidratación, y proporciona información importante sobre el manejo del agua de la papa en un clima templado húmedo.

Keywords Tuber yield · Precipitation · Frequency · Profit · Evapotranspiration

Introduction

As the world's third most important food crop in terms of human consumption after wheat and rice, potatoes play a significant role in world food and nutrient security (Devaux et al. 2020). Water management has important economic implications for potato growers (Djaman et al. 2021; Satognon et al. 2021). Potato crops are sensitive to moisture variation in the root zone (van Loon 1981; Opena and Porter 1999; Unlu et al. 2006; Obidiegwu et al. 2015). Water supply below optimal potato plant growth need can adversely influence tuber yield and quality (Shock et al. 1998; Cantore et al. 2014; King et al. 2020). Excess soil moisture can delay planting by making fields inaccessible, and damage the crop due to inadequate aeration that results in a lack of oxygen, biochemical toxicity, and/or nutrient deficiency (Epstein and Grant 1973; Cappaert et al. 1992; Evans and Norman 1999). Growing season (GS) precipitation in a humid climate can vary from substantially lower to substantially higher than optimal potato growth need and is highly unpredictable (Porter et al. 1999; Sexton et al. 2008). For example, total rainfall from June to August from 1980 to 2009 in the potato production areas of Maine, US, was normally distributed with a mean of 284 mm (standard deviation = 60 mm), varying from a low of 142 mm to a high of 480 mm. The optimum amount for potato production is 328 mm (Silver et al. 2011). The large water deficit (186 mm) in the dry seasons and surplus (152 mm) in the wet seasons suggest that consistent potato production requires both supplemental irrigation (SI) and soil dewatering (Benoit and Grant 1985). Climate change has led to more extreme weather events including more frequent droughts and excessive rainfall (Cook et al.

2014; Romero-Lankao et al. 2014), making SI and soil dewatering increasingly important for consistent production in a humid climate.

Making informed water management decisions requires an understanding of the influence of SI and dewatering on productivity and profitability. Several studies have assessed the influence of SI on potato tuber yield in a humid climate. In an experiment conducted in Maine, US, during 1993–1995, Porter et al. (1999) found that SI significantly increased total tuber yields by 10 Mg/ha (36%) in 1994 and 11.6 Mg/ha (37%) in 1995, while significantly reducing specific gravity and increasing tuber size. Marketable tuber yields were observed to increase from 25.6 Mg/ha without SI to 30.7 Mg/ha with SI (1995–1997) in New Brunswick, Canada (Bélanger et al. 2000). Aggregating data from trials conducted during 1992–2003 at the Aroostook Research Farm in Maine, Sexton et al. (2008) reported that SI increased average yield by 17% (i.e. 5 Mg/ha). However, Xing et al. (2012) observed little impact on tuber yield from SI in an experiment (2000–2003) in New Brunswick, Canada. Afzaal et al. (2020) found that SI significantly increased total tuber yield in 2019, but not in 2018, in a study in Prince Edward Island (PEI), Canada. Silver et al. (2011) provided a detailed assessment of the cost of SI in Maine, US, but included limited information about the benefits of SI. These previous studies demonstrated an interest in SI in the potato-producing areas in the humid northeast regions of the US and Atlantic Canada but produced inconsistent results about yield response to SI and limited economic information about SI. While several efforts have been made to understand the influence of SI on potato production in a humid climate,

research about the impacts of soil dewatering has been limited. In a two-year (2010–2011) study in Manitoba, Canada, Satchithanatham et al. (2012) observed that free-drain dewatering combined with overhead irrigation significantly increased tuber yield in 2011 but not in 2010. It is not known if their results are applicable in regions with different soils and climate.

A common limitation among the aforementioned water management experiments is that they were conducted in a limited number of seasons (All took place over less than four years except for one 12-year study). In contrast to an arid or semiarid environment, short-term experiments cannot characterize potato yield response to a wide range of water supply in a humid environment due to the difficulty in implementing various water supply treatment levels with uncertain precipitation. SI water supply has to be reduced as GS precipitation increases, and vice versa (Allen and Lambert 1971). As such, the contribution of SI to potato productivity and profitability when GS precipitation falls outside of the range of the experimental seasons are expected to be different (Shaykewich et al. 2002; Sexton et al. 2008; Silver et al. 2011). As a result, the existing studies cannot provide insights for seasons with rainfall outside their experimental ranges, and therefore cannot be used to assess the long-term profit frequency of SI. Knowing the annual distribution of productivity and profitability of water management is important for growers as SI requires long-term investment. Similarly, short-term dewatering experiments cannot assess the profit frequency of dewatering. Long-term experimental data are needed to assess the influence of SI and dewatering on farm profitability and associated frequency.

This study assessed the economic effects of SI and dewatering for potato production in PEI. In the absence of long-term experimental data, historical rain-fed yield and weather data were used to simulate long-term experimental results. Specifically, the 2000–2020 (excluding 2018) average provincial yields of Russet Burbank (RB), Shepody, Kennebec and Goldrush cultivars were conceptualized as the results of a long-term un-replicated experiment with GS precipitation representing water supply treatments. The specific objectives were to (1) characterize yield responses of the four cultivars to water supply using historical rain-fed yield and weather data, (2) assess the reliability of the yield-determining equations and (3) evaluate the profitability of SI and dewatering and associated frequency for the four cultivars. The regression equations relating the yields to GS precipitation were used to predict annual yield gains or losses resulting from SI or dewatering for calculating gross income. The costs of SI from Maine, US (Silver et al. 2011), after currency and inflation adjustments and accounting for the local price of tile drain installation, were utilized for the cost–benefit analysis.

Materials and Methods

Study Area

PEI is located on the eastern coast of Canada and covers an area of 5670 km². The island's land surface is rolling with slopes varying from 7 to 14% (MacDougall et al. 1988). The island is entirely underlain by a sandstone formation with a thickness of 1200–1600 m comprised of a sequence of Permo-Carboniferous terrestrial red beds (van de Poll 1983). This formation is overlain by a layer of glacial till (0–10 m). Soils derived from the glacial till are sandy (loam, sandy loam or loamy sand) and relatively uniform as a result of relatively consistent geology across the island (MacDougall et al. 1988). The soils have organic matter typically ranging from 1.5% to 3.5% (Nyiraneza et al. 2017) and pH between 5 and 7.2. The annual average growing degree days above 5 °C is 1600 with May to September average degree days above 10 °C being 800. The average January air temperature is -8 °C and the average July air temperature is 19 °C. The frost-free period varies from 100 to 160 days.

Despite being the smallest province in Canada, PEI is one of the largest potato producers in the country, accounting for about 25% of national potato crop production (Agriculture and Agri-Food Canada 2010–2020). The annual production area has varied between 33,570 ha (2013) and 37,460 ha (2008) in recent years, corresponding to about 6% of the total land area (i.e. 20% of all cropland) in PEI and 24% of annual potato production area in Canada (Agriculture and Agri-Food Canada, 2010–2020). Potatoes rank as the number one source of farm revenue from crops in PEI, representing 78% of total crop cash receipts in PEI and 23% of Canada's total international exports of potatoes (PEI Department of Agriculture and Land 2020). The most widely-grown varieties are Russet Burbank, Goldrush, Superior, Yukon Gold, Red Norland, Shepody, Kennebec and a number of proprietary varieties. Approximately 60% of the potatoes are destined for processing, 30% go to the fresh market through retail or food service and 10% are grown for seed purposes. Potato growers typically adopt the minimum 3-year rotation length as mandated by the Province and follow local industry standard management practices (Bernard et al. 1993; PEIAIC 2022). Traditionally, growers mainly planted barley and forages (e.g. red clover or a mix of red clover and one or two perennial grass species) as the rotation crops. In recent years, growers have included more diverse annual crops such as spring wheat, soybean, corn, buckwheat and brown mustard, or perennial hay/grass crops in the rotations. Growers usually start to plant potatoes in the middle of May and harvest the crops in October, depending on the

maturation requirement of each specific cultivar (Parent et al. 1967; PEIAIC 2022). Potato production in PEI is predominately rain-fed. While interest in SI is growing, it is currently limited to only about 6% of annual potato production area due to a provincial moratorium on new irrigation wells (unpublished data). The moratorium has been in place since 2002 because of concerns about the effect of increased irrigation extraction on drinking water availability and groundwater discharge-dependent ecosystems (Afzaal et al. 2020). SI is expected to expand following the lifting of the moratorium in 2022. Tile drains are installed on < 5% of potato production land (unpublished data).

Data Sets

The cultivar-based average marketable yield data for RB, Shepody, Kennebec and Goldrush cultivars collected by the PEI Agricultural Insurance Corporation (PEIAIC) from 2000 to 2020 were used for this study. PEIAIC collects annual cultivar-based potato yield data from about 180 participating farms (representing the majority of potato farms in PEI) to calculate benchmark cultivar-based yields for crop production insurance compensation purposes. The four selected cultivars are widely grown in North America; RB is a long-season cultivar grown mainly for processing into french fries; Shepody, Kennebec and Goldrush are all mid-season cultivars and are grown primarily for making french fries, chipping and the fresh market, respectively. Yield data from 2018 were excluded because extremely wet soil conditions in the fall of 2018 prevented growers from harvesting their full crops.

The PEIAIC yield data are based on verified final production counts, defined as the remaining marketable crop after cullage is subtracted from the overall yield. PEIAIC determines the cultivar-based marketable yield for each participating farm by conducting yield sampling and then combines the data from all participating farms into a province-wide average marketable yield (PEIAIC 2022). If a farmer is storing the potatoes, PEIAIC calculates the volume and measures the density to find a weight. If a farmer has sold the potatoes, PEIAIC uses scale tickets of the measured weight of each load delivered. The total yield for each farm can be calculated using one or both of these methods. The acreage is calculated by the insurance agents. The data from each individual farm are confidential. Upon request, PEIAIC provided the province-wide average data for this study. The cultivar-based averages are used to determine production insurance compensation when yield losses occur that are beyond the policy holders' control. The dataset is considered to be reliable, as the insurer and insured are bonded by an agreement (PEIAIC 2022) and inaccurate data could lead to serious financial and legal consequences for both parties.

The meteorological data, including daily precipitation and air temperature, used in this study were retrieved from Environment and Climate Change Canada's (ECCC 2020) weather stations at Harrington (46°20'37"N, 63°10'11"W), Summerside (46°26'28"N, 63°50'17"W) and New Glasgow (46°24'32.08"N, 63°21'01.04"W). Missing data points were filled in using available data from a nearby ECCC station. Effective rainfall (i.e. daily rainfall > 5 mm or ≤ 5 mm daily precipitation where there are five days of rainfall in succession) accounted for over 86% of total GS precipitation on average, with a range from 78% (2001) to 94% (2002). Using effective GS rainfall instead of total GS precipitation did not change the yield correlations (data not presented). Therefore, total precipitation, rather than effective, was used to relate precipitation to yield in this study.

Statistical Analysis

The PEIAIC provincial average rain-fed yield data were treated as the results of an un-replicated water supply experiment with precipitation representing water supply treatment level. Polynomial and linear regressions were performed separately for each cultivar using annual yield as the dependent variable and total GS precipitation and monthly precipitation in the GS as independent variables. The yield data were related to precipitation data from each of the three weather stations (Harrington, Summerside and New Glasgow) separately, as well as to the average of the three stations. The regression equations that best fit the data were adopted as final yield-determining equations for the cost–benefit analysis. The significance of correlation was assessed through an ANOVA test of regression. The influences of other biophysical factors (e.g. field management, soil and other weather variables) were not considered.

Reliability Assessment of Yield-Determining Equations

The reliability of the yield-determining equations from the statistical analysis was tested by comparing the optimum water supply rates as indicated by the inflection points (i.e. the highest yields) on the yield-determining equations with the average potential evapotranspiration of the potato plant (ET_c). The underlying principle is that water supply at ET_c level represents the optimal water supply that is expected to produce the highest yields if other cultural practices are managed well (Allen et al. 1998). In other words, the yield-determining equations were considered reliable if the optimal water supply rates determined from the regression equations matched the ET_c value and the crop factors used for the ET_c calculation matched the empirical values in literature (Doorenboss and Pruitt 1977; Allen et al. 1998; Kashyap and Panda 2001; Kadam et al. 2021). Available soil water left over from previous seasons

was not explicitly counted towards net GS water supply as a similar amount of soil water was carried out into the following season. Soil drainage and runoff are limited in GS in this area and thus were neglected in water balance analysis. The GS was defined as June 1 to September 30, which is typical for potato crops in this broader region (Parent et al. 1967; Benoit and Grant 1985; Bélanger et al., 2000).

ET_c for each potato growth stage was estimated using the stage-wise crop factor (K_c) multiplied by the potential evaporation (ET_0), which was estimated using the Linacre equation (Linacre 1977) using meteorological data from the Harrington weather station (ECCC 2020). The Linacre equation was used instead of the Penman–Monteith equation recommended by the FAO (Allen et al. 1998) because some input data required for the Penman–Monteith equation were not available. The stage-wise potato crop factors (K_c) from literature were: 0.42–0.8 for the initiation stage (0–25 days, May 15–June 10), 0.8–1.1 for the development stage (30 days, June 11–July 10), 1.1–1.27 for the mid-season stage (45 days, July 11–August 25), and 0.57–1.01 for the late season (30 days, August 26–September 25) (Doorenboss and Pruitt 1977; Allen et al. 1998; Kashyap and Panda et al. 2001; Kadam et al. 2021).

Cost–Benefit Analysis

In the absence of local data and on account of similar production conditions, the costs of SI in Maine, US, were used to estimate the costs of SI in PEI. Silver et al. (2011) estimated the costs of SI in Maine, US, by factoring in capital costs (equipment, interest), water development (pond construction, permitting, engineering) and operating and maintenance costs (labor, power, repair). They annualized the total capital cost over the life of the equipment to give a uniform annual capital cost payment with interest included. They estimated the costs for hose reel traveler systems and center-pivot systems with and without water development costs for 20-, 40- and 80-ha field size categories, as all these parameters influence the overall cost. They also took into account a variable component reflecting the demand for irrigation water, which is dependent on rainfall. They calculated the annual operating costs for each field size for each system and then added the annualized capital cost.

The costs for center-pivot systems with and without water development for 20- and 40-ha field size categories were used in this study. This is because 1) although 61% of potato production area in PEI is made up of <20-ha fields, SI is not likely to be economically viable using current irrigation technology in fields of this size (Silver et al. 2011); 2) 20- and 40-ha field sizes are representative for SI considerations because 37% of PEI's potato land area is made up of 20- to 80-ha sized fields. Fields > 80 ha cover only 2% of potato production area (unpublished PEI government data); 3) the

costs for hose reel traveler systems were similar to those for center-pivot systems (Silver et al. 2011), and therefore were not considered separately. The average annual costs at 2010 prices associated with a center-pivot system with water development for 20- and 40-ha fields were \$1792 USD/ha and \$1005 USD/ha, respectively. Without water development, the costs dropped to \$891 USD/ha and \$553 USD/ha for the same field sizes. The respective ownership costs accounted for 79.8%, 80%, 59.4% and 66.2% of the total costs. These costs were also adjusted for inflation using an annual inflation average of 1.78% (USinflationcalculator 2020), converted into Canadian currency using the 2018 conversion rate (1.3) and used for the cost–benefit analysis. The costs reflected the prices for average SI water application (152 mm or 6 inches). Since operation costs increase with increasing amounts of irrigation applied, the annual costs of SI (SIC) were adjusted proportionally with irrigation rate by using the average price of unit SI water application, which was calculated as,

$$SIC = \begin{cases} \frac{OWS-x}{152} \times UWC + AOC, & x < OWS; \\ AOC, & x \geq OWS. \end{cases} \quad (1)$$

where UWC is the cost for average SI water use (\$542.2/ha and \$300.2/ha for 20- and 40-ha field size), AOC is the annual ownership cost (\$2142.8/ha and 792.7/ha for 20-ha with and without water development, and \$1206.2/ha and \$531/ha for 40-ha with and without water development), x is the total GS (Jun.–Sep.) rainfall (mm), and OWS is the average optimal GS water supply for the potato plant (mm), which was determined from the yield regression equations from “Statistical analysis” section.

The annual gross income from SI was calculated by multiplying the annual yield gains from SI with potato sale prices. Potential marketable yield gains or losses (Δy) from SI or lack of dewatering were predicted using the cultivar-based yield-determining equations $f(x)$ from “Statistical analysis” section, by considering GS precipitation to be SI water supply and assuming that similar SI and precipitation rates create a similar yield response. Specifically,

$$\Delta y = f(OWS) - f(x) \quad (2)$$

where Δy is the annual marketable yield gain or loss from irrigating or not dewatering, $f(x)$ is the cultivar-based yield regression equation from “Statistical analysis” section, OWS is the cultivar-based optimal GS water supply, and x is the GS precipitation.

The predicted yields represent expected values and do not account for any errors in the yield-determining equations. To characterize the sensitivity of gross income to yield variation, which the yield-determining equations do not account for, the highest and lowest potential yields from SI were assumed to equal the maximum and minimum yields for the four cultivars observed when GS precipitation was close to

the optimum water level (i.e. quasi-optimum water supply rate). These yields were used to simulate the highest and lowest yield gains from SI by deducting the observed rain-fed yields in a specific year in the sensitivity analysis. Water management scenarios corresponding to GS precipitation frequencies of 5%, 10%, 50% and 95% rainfall depth duration (RDD) were also considered. The equations used to calculate maximum (Δy_{max}) and minimum (Δy_{min}) marketable yield gains from SI were,

$$\Delta y_{max} = \text{Max}(y|_{x=OWS}) - y_{obs} \quad (3)$$

$$\Delta y_{min} = \text{Min}(y|_{x=OWS}) - y_{obs} \quad (4)$$

where $\text{Max}(y|_{x=OWS})$ or $\text{Min}(y|_{x=OWS})$ is a function to determine the maximum or minimum yield from observed rain-fed yields when x is close to the cultivar-based optimal water supply (OWS), y_{obs} is the observed rain-fed marketable yield at a specific GS rainfall level (e.g. 5% RDD). If multiple observed values were available, the average yield was used.

Since the focus was on the influence of SI on profitability, it was assumed that SI was only applied in the seasons when GS precipitation was \leq the average optimum water supply (i.e. water supply at the maximum yield) for the four cultivars as determined from the yield regression equations in Sect. 2.3. Soil dewatering was not considered in the SI cost–benefit analysis (i.e. scenarios with SI and dewatering coexisting were not considered). Gross income was calculated as Δy , Δy_{max} and Δy_{min} multiplied by the potato sale price. Wholesale prices at the farm gate were used for the gross income analysis because they were considered more representative than sale prices (PEI Department of Agriculture and Land 2020), which fluctuate from year to year with the market (Agriculture and Agri-Food Canada 2010–2020). Using 2018 sale price as a comparable reference, the available sale prices (2006 to 2018) were adjusted for inflation using an average annual inflation of 1.7% (Statistics Canada 2020). The prices varied from \$187/Mg to \$291/Mg, with an average price of \$258/Mg (Agriculture and Agri-Food Canada 2010–2020). The 2018 price (\$254/Mg) was used as the average price for sake of simplicity, as it was the closest to the average price. The lowest, average and highest prices were considered in the gross income analysis under various yield scenarios.

In the cost–benefit analysis, if and when GS rainfall exceeded the thresholds for optimal potato growth, it was assumed that marketable tuber yields reach the maximum level with soil dewatering but decrease with increasing GS rainfall without dewatering by following the yield-determining equation for each cultivar. The yield gain from dewatering was calculated using Eq. (2). The gross income of dewatering was calculated as the yield gain multiplied by the potato sale price. The cost of tile drain installation quoted

to the senior author by a local contractor (Simmons Drainage and Supply Ltd.) was \$2500/ha in PEI in 2018. The net profit of dewatering was calculated by subtracting the cost of installation from the gross income of dewatering.

Results

Precipitation

Annual precipitation averaged 1098 mm with 25% as snow during 2000–2020, with a range of 787 mm (2001) to 1393 mm (2014) (Table 1). Monthly precipitation averages varied within 70–127 mm, with the highest values occurring in October–December (Fig. 1). Precipitation averages in June, July, August and September were 81, 75, 80 and 101 mm, respectively. Monthly precipitation averages in the GS were relatively similar, but the annual variation was large, as shown by the high standard deviations (Fig. 1). GS precipitation varied from 155 mm (2001) to 479 mm (2008) and averaged 338 mm, with a standard deviation of 84 mm (Fig. 1; Table 1). The large annual variation in monthly and GS precipitation indicates inconsistent water supply to the potato plant year-to-year without irrigation and soil dewatering.

Yield Response to Growing Season Precipitation

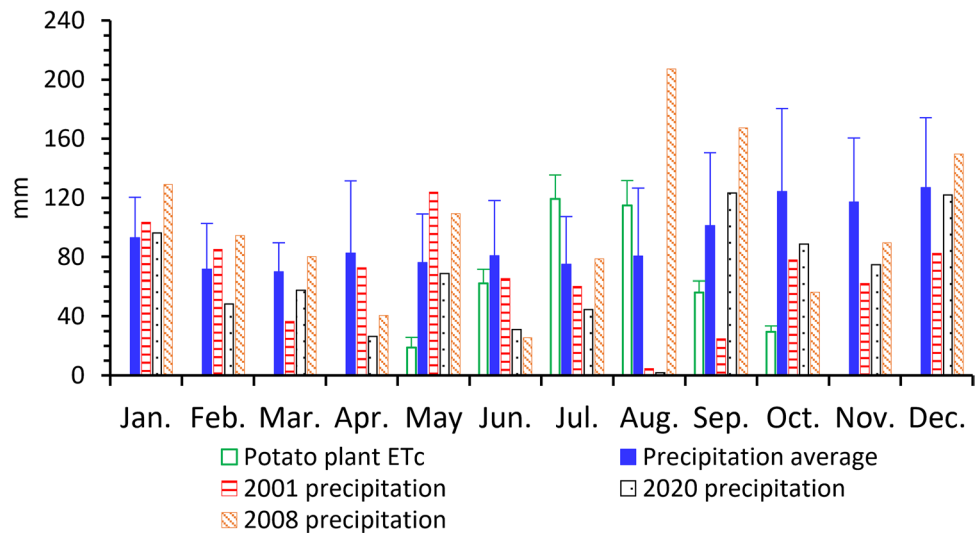
GS precipitation from Harrington (x_h), Summerside (x_s) and New Glasgow (x_{ng}) was linearly correlated: $x_s = 0.766x_h + 89.989$ ($R^2 = 0.6$); $x_{ng} = 0.8445x_h + 104.34$ ($R^2 = 0.76$). All the correlations were significant ($p < 0.001$), suggesting that rainfall is relatively uniform among the three stations despite some spatial variation and measurement errors (the original precipitation data sets from Summerside and New Glasgow had more missing data points than Harrington) as indicated by R^2 being below 1. Because of the strong collinearity, tuber yields correlated with GS precipitation from one station should follow a similar correlation with GS precipitation from the other two stations and with the average of the three stations. For instance, RB yields (y) responded to Harrington GS precipitation by following a second-order polynomial equation (Figs. 2, 3, 4, 5 and Tables 1–2). RB yields were also correlated with the GS precipitation at Summerside, New Glasgow and with the average (x_a) of the three stations by following second-order polynomial equations: $y = -0.0003x_s^2 + 0.1909x_s - 3.1342$ ($R^2 = 0.57$), $y = -0.0002x_{ng}^2 + 0.2027x_{ng} - 10.632$ ($R^2 = 0.59$), and $y = -0.0003x_a^2 + 0.2251x_a - 10.601$ ($R^2 = 0.67$). The four yield-determining regression equations for RB were similar and each of the correlations was significant ($p < 0.001$). This means that each of the equations could be used to predict RB yield response to water supply but would produce

Table 1 Potato marketable yields, precipitation and evapotranspiration

Year	RB (Mg/ha)	Shepody (Mg/ha)	Kennebec (Mg/ha)	Goldrush (Mg/ha)	GS prec. (mm)	GS ET _c (mm)	GS water deficiency /excess (mm)	Annual prec. (mm)
2000	29.8	24.8	22.4	28.2	296	346	-50	1038
2001	16.3	15.6	18.8	17.0	155	377	-222	787
2002	32.7	28.8	29.3	29.0	426	343	83	1297
2003	30.5	27.2	24.5	31.4	257	362	-105	1024
2004	33.1	28.8	30.5	28.7	310	339	-28	987
2005	31.8	26.6	27.3	28.9	302	362	-59	1115
2006	33.2	28.4	30.9	33.1	326	356	-30	1092
2007	29.9	29.4	23.8	26.4	358	329	30	946
2008	26.8	21.6	17.9	23.5	479	320	159	1198
2009	27.1	26.5	28.2	27.4	470	343	127	1253
2010	29.8	27.0	21.0	27.7	458	359	99	1212
2011	28.9	26.6	24.8	28.9	355	341	14	1319
2012	28.2	25.0	24.1	22.1	333	368	-47	954
2013	28.4	26.1	25.0	26.0	326	359	-33	1032
2014	31.1	23.6	26.4	28.0	329	355	-26	1377
2015	31.0	26.6	22.5	27.4	316	348	-31	1350
2016	32.0	29.9	25.6	27.7	328	358	-30	1056
2017	30.1	27.2	32.0	25.7	300	365	-65	925
2019	31.4	24.2	27.5	23.9	426	348	78	1208
2020	28.0	22.2	22.5	18.5	201	373	-173	783
Ave	29.5	25.8	25.3	26.5	338	353	-16	1098
Stdev	3.6	3.3	3.8	3.9	84	14	94	176

GS-Growing season; Prec.-precipitation; Weather data were from Harrington (ECCC 2020) with missing data filled using data from Charlotte-town Airport weather station (46°17'21"N, 63°7'9"W) (ECCC 2020)

Fig. 1 Means with standard deviations of monthly precipitation and potential evapotranspiration for the potato plant (ET_c) for 2000–2020 and monthly precipitation for representative dry (2001, 2020) and wet (2008) years at Harrington



slightly different predictions. Another difference between the four regression equations is that the optimal water supply rate for RB from the New Glasgow Eq. (506 mm) is higher, while the values from the Summerside (318 mm) and average precipitation (375 mm) equations were similar

to the Harrington value (357 mm). Nevertheless, the weather data from Harrington were chosen for characterizing tuber yield responses to GS precipitation for the four cultivars mainly because these data created the best correlations and were considered representative of average meteorological

Fig. 2 Russet Burbank (RB) marketable yield (y) responses to growing season precipitation (x) from Harrington (2000–2020, with 2018 excluded) (Standard errors of coefficients of x , x^2 and intercept are 0.0351, 0.000052 and 5.8)

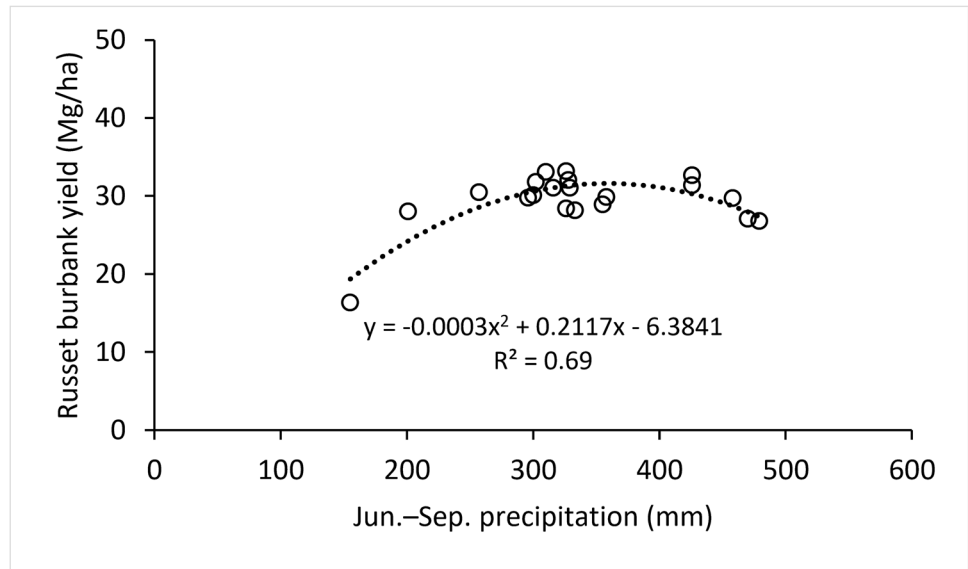
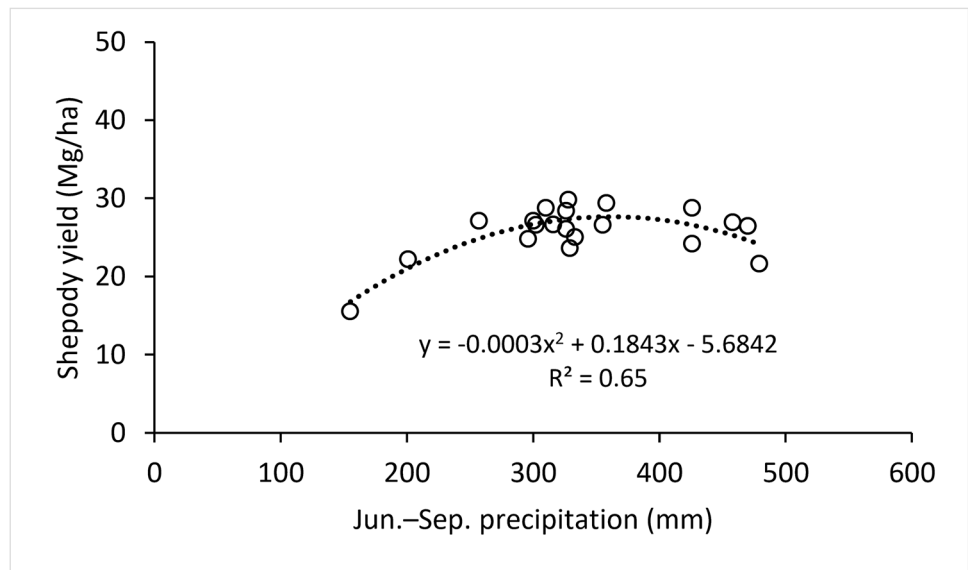


Fig. 3 Shepody marketable yield (y) responses to growing season precipitation (x) from Harrington (2000–2020, with 2018 excluded) (Standard errors of coefficients of x , x^2 and intercept are 0.0339, 0.00005 and 5.6)



conditions due to Harrington's central location on the island. Data for Shepody, Kennebec and Goldrush are not presented.

The yield responses of the four cultivars to GS precipitation all followed second-order polynomial regressions with best fits, with GS precipitation explaining 69%, 65%, 29% and 50% of the yield variation for RB, Shepody, Kennebec and Goldrush, respectively (Figs. 2–5 and Tables 1–2). Yield generally increased with the initial increments of GS precipitation (i.e. water supply), became relatively insensitive to water supply within the 258–425 mm range and then decreased as water supply exceeded the point where the maximum yield (i.e. optimum yield) is located. This general yield response pattern is consistent with the typical crop water production functions as shown by English (1990)

and Foster and Brozović (2018). The regression equations (Figs. 2–5) are also very similar to the typical potato water production functions in literature (Ross 2006; Yuan et al. 2003; Karam et al. 2014) and are consistent with the experimental results of potato irrigation observed by Shaykewich et al. (2002) in Manitoba, Canada and Crosby and Wang (2021) in Wisconsin, US. The key difference is that these regression equations can be used to assess the frequency of GS precipitation and associated yield occurring within a long time period while the crop water production functions in literature cannot because they were derived from short-term experiments. Water supply in the 20 seasons can be divided into three zones: insufficient (Rainfall Zone 1: 155–257 mm, 3 out of 20 seasons), medium (Rainfall Zone 2: 258–425 mm, 12 out of 20 seasons), which produced

Fig. 4 Kennebec marketable yield (y) responses to growing season precipitation (x) from Harrington (2000–2020, with 2018 excluded) (Standard errors of coefficients of x , x^2 and intercept are 0.0568, 0.000084 and 9.4)

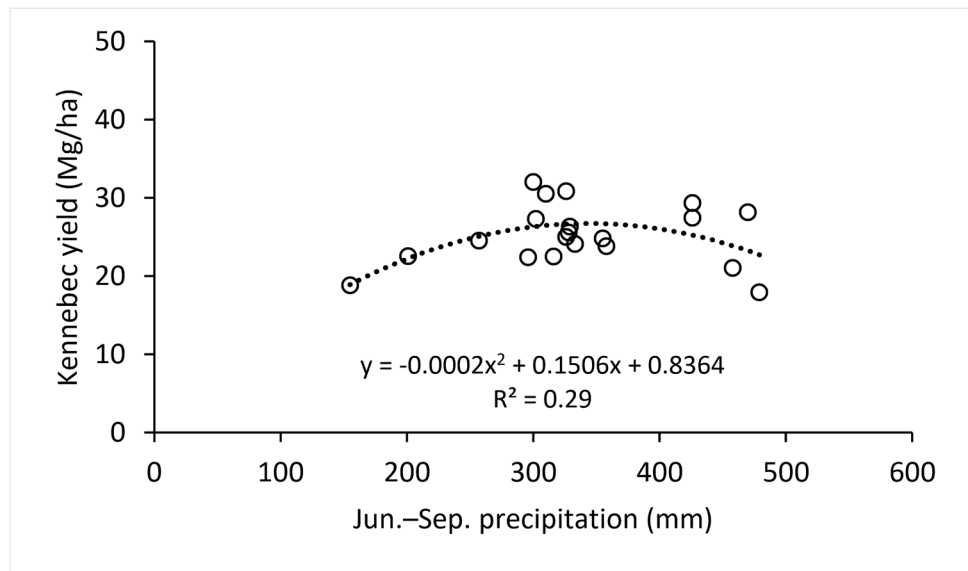
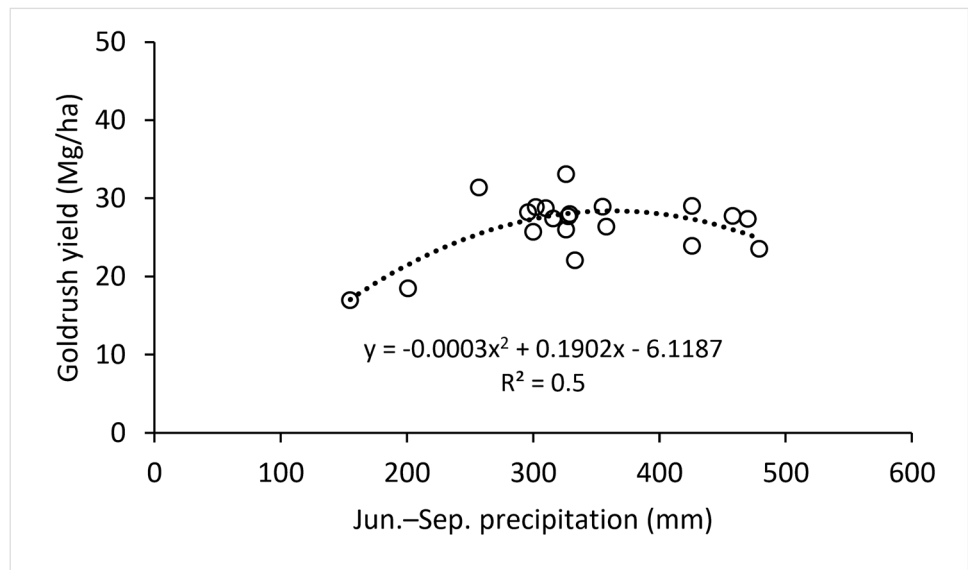


Fig. 5 Goldrush marketable yield (y) responses to growing season precipitation (x) from Harrington (2000–2020, with 2018 excluded) (Standard errors of coefficients of x , x^2 and intercept are 0.0487, 0.000072 and 8)



high yields including the maximum (i.e. optimum) yields but included less variation, and excessive (Rainfall Zone 3: 426–479 mm, 5 out of 20 seasons). These historical data suggest that consistently producing high potato yields in this humid region requires not only irrigation to supplement water when precipitation is insufficient, but also a drainage system to dewater soil when precipitation is excessive.

Although the response patterns for the four cultivars are generally similar, there are a few differences that are relevant to water management. Firstly, GS precipitation explained a different percentage of yield variation for each cultivar, with RB being the highest (69%), followed by Shepody (65%) and Goldrush (50%), and Kennebec being the lowest (29%). This indicates that RB, Shepody and Goldrush are more sensitive to GS water supply than Kennebec. Secondly, Shepody,

Kennebec and Goldrush had similar yields with the same water supply rates, while RB generated between 11 and 17% more yield than the other three cultivars (Table 1), likely due to its longer growth period. Lastly, the optimum GS water supply rates as indicated by the inflection points on the response curves (Figs. 2–5) were 353, 307, 376 and 317 mm for RB, Shepody, Kennebec and Goldrush, respectively.

Reliability of the Yield-Determining Equations

The estimated weekly ET_0 values (Fig. 1) were numerically similar to the values ($ET_0 = 7–14$ mm/w around 10°C ; $14–28$ mm/w for under 20°C ; $28–49$ mm/w for over 30°C) for a humid temperate region as reported by Allen et al. (1998) and in a similar climate in Maine, US (Sexton et al.

Table 2 Results of second-order polynomial regression analysis

Independent variable	Russet Burbank yield (Mg/ha)			Shepody yield (Mg/ha)		
	R ²	Standard error	p value (ANOVA)	R ²	Standard error	p value (ANOVA)
Jun.–Sep. precipitation	0.69	2.1	<0.001	0.65	2	<0.001
May precipitation	0.29	3.2	0.05	0.2	3.1	0.15
Jun. precipitation	0.08	3.7	0.5	0.19	3.1	0.17
Jul. precipitation	0.01	3.8	0.9	0.08	3.3	0.5
Aug. precipitation	0.28	3.2	0.06	0.47	2.5	0.047
Sep. precipitation	0.24	3.3	0.1	0.2	3.1	0.14
Oct. precipitation	0.14	3.5	0.26	0.1	3.3	0.4
	Kennebec yield (Mg/ha)			Goldrush yield (Mg/ha)		
	R ²	Standard error	p value (ANOVA)	R ²	Standard error	p value (ANOVA)
Jun.–Sep. precipitation	0.29	3.5	0.05	0.5	2.9	0.002
May precipitation	0.05	3.9	0.6	0.2	3.7	0.13
Jun. precipitation	0.26	3.5	0.08	0.25	3.6	0.08
Jul. precipitation	0.05	3.9	0.6	0.2	3.7	0.14
Aug. precipitation	0.32	3.3	0.03	0.36	3.3	0.02
Sep. precipitation	0.08	3.9	0.5	0.11	3.9	0.35
Oct. precipitation	0.06	3.9	0.6	0.31	3.4	0.04

2008) and New Brunswick, Canada (Bélanger et al. 2000; Xing et al. 2008). The ET_0 values were considered reliable for estimating potential evapotranspiration (ET_c) of the potato plant.

Using a K_c of 0.7 for initiation, 0.7 for the development stage, 1 for midseason and 0.6 for late season, results in a GS ET_c of 353 mm, which is very close to the optimal water supply rates for the four cultivars (317–376 mm) as shown above. These K_c values were either slightly lower than, or equal to, the lower bound of values in literature. Most of the K_c values in literature were estimated for a sub-humid climate while these fitted values were derived from a humid climate, which may explain the difference. The GS ET_c (353 mm) for the potato plant was similar to the value (331 mm) determined by Parent and Anctil (2012) in Quebec, Canada and lower than the values (375–400 mm) in Manitoba, Canada (Shaykewich et al. 2002).

Given that the yield regressions were statistically significant and similar to the typical potato water production functions in literature, that the optimal water supply rates derived from the regression equations were very close to the ET_c , and that the ET_c was similar to values in literature, the regression equations based on precipitation data from Harrington were considered acceptable for predicting yield responses to water supply for the cost–benefit analysis. GS ET_c for each year is listed in Table 1 and monthly ET_c averages are included in Fig. 1. The GS ET_c corresponded to 12.1, 21.4, 28.2 and 13.6 mm of water supply per week

for the initiation, development, midseason and late season stages, respectively, which can be used as a reference for SI scheduling and groundwater allocation for SI in this region.

Yield Responses to Monthly Precipitation

Monthly precipitation in the GS influenced annual potato yields differently depending on the month and variety, because the optimum water demand of the potato plant varies with growth stage (Table 2). Precipitation in May did not influence the yields of Shepody, Kennebec or Goldrush, but high precipitation negatively influenced RB yields ($p=0.05$). In May, potato plant water deficiency (calculated as the difference between precipitation and ET_c) typically did not occur, as potatoes were recently planted or just starting to germinate and water use by the plant (ET_c) was lower than precipitation (Fig. 1). The low probability of water deficiency in May explains why precipitation in May did not influence the yields of the three mid-season cultivars (Shepody, Kennebec and Goldrush). However, excessive soil moisture in May can lead to delayed planting in the absence of soil dewatering, which shortens the growing period and negatively influences the yield of the long-season RB cultivar. In June, when potato plants are establishing, water deficiency was also unlikely to occur, as ET_c was lower than precipitation (Fig. 1). Consequently, precipitation in June did not affect potato yields. In July, when tubers initiate, potato plants were relatively sensitive

Table 3 Costs of SI under 20- and 40-ha field sizes with or without water development

GS precipitation scenario	Rep. year	GS precipitation (mm)	SI/dewatering (mm)	Cost for 20-ha field with water development (\$/ha)	Cost for 40-ha field with water development (\$/ha)	Cost for 20-ha field without water development (\$/ha)	Cost for 40-ha field without water development (\$/ha)
Lowest (5% RDD)	2001	155	183	2796	1568	1445	892
Low (10%RDD)	2020	201	137	2631	1477	1281	802
Optimal average		338	0	2143	1206	793	531
Highest (95%RDD)	2008	479	-141	2143	1206	793	531

Costs are 2018 prices in Canadian Dollars; GS-growing season; RDD-rainfall depth duration; Rep.-Representative

to water stress and water deficiency was as high as 44 mm on average (Fig. 1). However, precipitation in July did not have a significant effect on yields for the four cultivars (Table 2). Given that precipitation typically exceeded ET_c in May and June (Fig. 1) in this humid region, some of the excess precipitation in May and June could have been stored in soil and carried over into July. This carried-over soil moisture may have mitigated the impacts of a precipitation shortage in July, making potato plants less sensitive to precipitation during this month. Precipitation in August significantly influenced yields for all four cultivars, following second-order polynomial regressions (Table 2). This is probably because potato tubers bulk in August, when plants are most sensitive to water stress (Sexton et al. 2008). Water deficiency averaged 34.5 mm and reached 110 mm in August alone in an extremely dry (2001) and very dry (2020) year (Fig. 1). Precipitation in September significantly influenced RB yield, following a second-order polynomial regression, but did not influence the other three cultivars. Having sufficient water supply in September likely increased RB yield by providing more growth time for the long-season cultivar. Precipitation in October did not influence yields for any of the four cultivars, which is not surprising as potatoes are typically harvested in October in this region.

Costs and Benefits of Supplemental Irrigation

The annual costs of SI for 20-ha and 40-ha field sizes with water development are presented in Table 3 and Figs. 6 and 7. Annual costs decrease with decreasing SI water application, levelling off at the annual ownership cost when GS rainfall reaches the average optimal level ($OWS = 338$ mm) and SI is not needed. The gross incomes, as predicted by the yield-determining equations under various water management and sale price scenarios, are shown in Fig. 6 and Table 4. The gross incomes represent increased gross benefit from SI alone, since growers have to pay all other production costs (e.g. seeds, fertilizer and pesticides) regardless of SI. Deducting the costs from the gross incomes gives the net profits of SI. At the average potato sale price (\$254/Mg) and average SI water use of 152 mm (i.e. GS rainfall equals 186 mm), SI has to increase potato yield for a 20-ha and a 40-ha field above 5.2 Mg/ha and 3.3 Mg/ha in order to generate a net profit without water development and above 10.6 Mg/ha and 5.9 Mg/ha with water development.

The general trend with the costs and benefits of SI (Fig. 6 and Table 4) is that the higher the GS rainfall, the lower the gross income, with net profit gradually diminishing as GS rainfall increases to the 10% RDD level in most cases. Specifically, if water development is not required and a higher-than-average price is applied, SI would produce a net profit for all four cultivars in an extremely dry year (e.g. 2001, 5% RDD), regardless of field size,

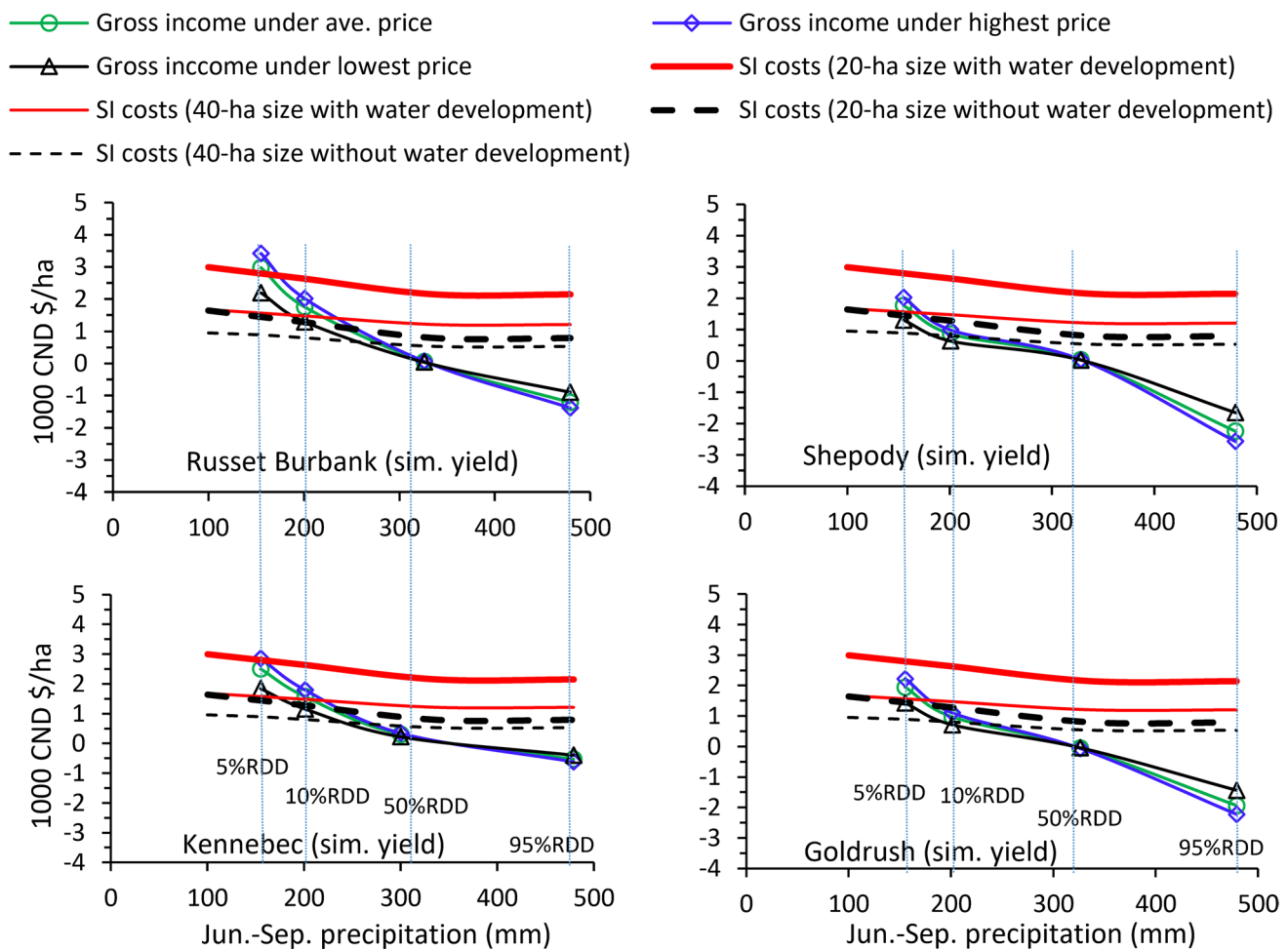


Fig. 6 Comparisons of costs and benefits of SI based on yields predicted by the yield-determining equations (i.e. sim. yield) in Figs. 2–5 (All are 2018 prices in Canadian Dollars)

compared to rain-fed production (Fig. 6). In a very dry year (e.g. 2020, 10% RDD), SI would generate \$926/ha, \$28/ha, \$737/ha and \$136/ha net profit for RB, Shepody, Kennebec and Goldrush, respectively, for a 40-ha field at the average sale price and without water development. In comparison, for a 20-ha field, SI would generate only \$476/ha and \$287/ha net profit for RB and Kennebec, and lose \$422/ha and \$314/ha for Shepody and Goldrush, respectively. SI would create little net profit, depending on the cultivar, as GS precipitation increases beyond the 10% RDD point (i.e. 2020 level). Regardless of field size, sale price or water development, SI would produce a financial loss for all cultivars in a normal year (e.g. 2006, 50% RDD) because the yield gains from SI would be very low (Figs. 2–5) and the annual ownership costs (ranging from \$531/ha/year to \$2143/ha/year, depending on field size and water availability) would be high even though the operation costs would be low due to lower water applications. SI would result in a financial loss in 13 of the 20 study

seasons since rainfall rates were close to the optimum water supply levels. Overall, the financial gains from SI in the two very dry seasons (2001 and 2020) (RB = \$4739/ha, Shepody = \$2632/ha, Kennebec = \$4064/ha and Goldrush = \$2909/ha based on the average sale price) would not be enough to offset the financial losses from SI in the 20 seasons. In other words, the overall gross incomes would be lower than the accumulated ownership costs, which ranged from \$10,620/ha to \$42,860/ha depending on field size and water availability, not to mention the accumulated annual operation costs. As GS precipitation exceeds the optimum water supply levels, which occurred in 25% of the 20 seasons, dewatering, rather than SI, is needed to achieve the optimum yield. As expected, if the lowest potato price is applied, the economic returns under the above scenarios would be consistently worse than using the average price, and vice versa (Fig. 6). However, using the highest price would still not result in consistent net profit as GS precipitation increases beyond the 10%

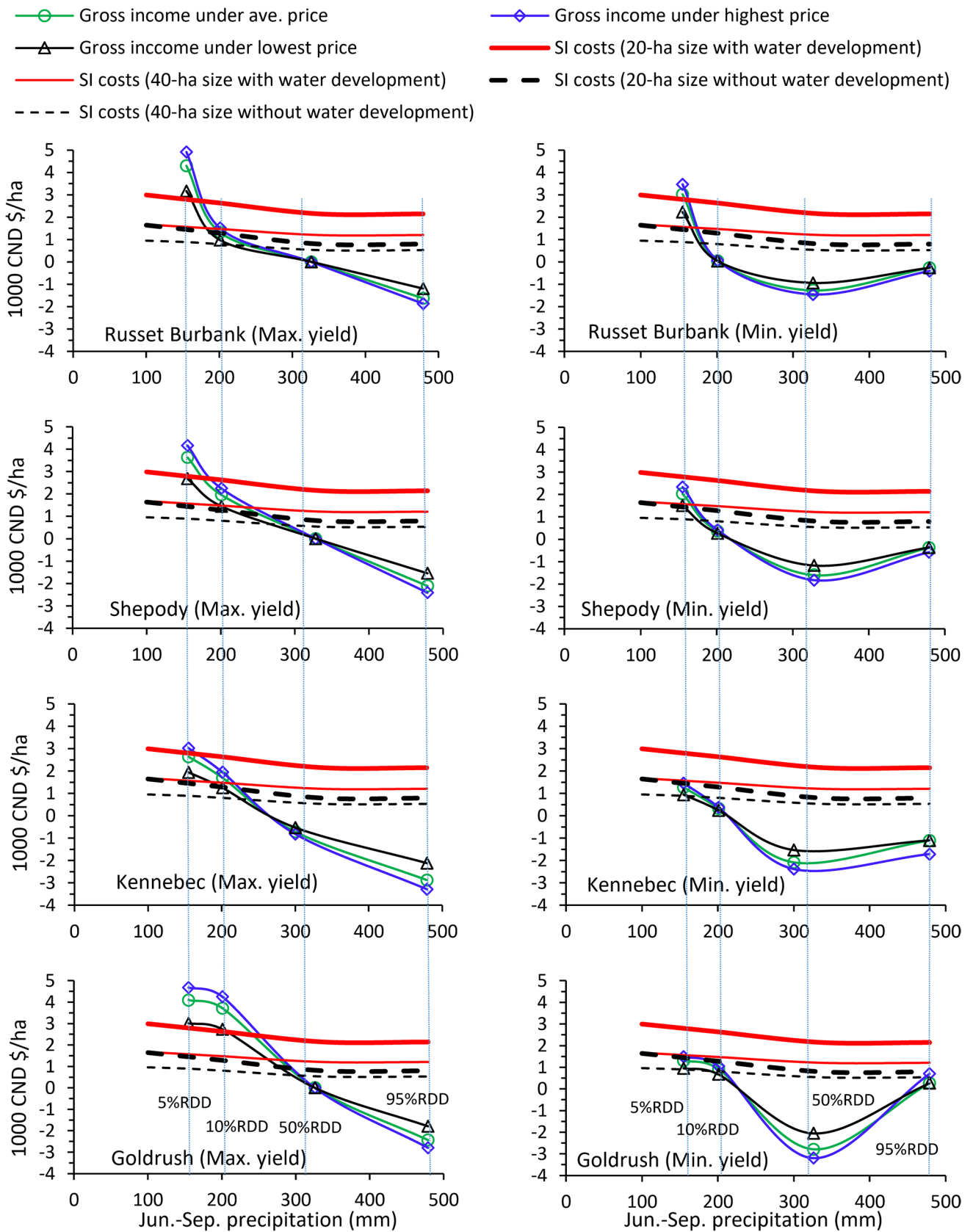


Fig. 7 Comparisons of costs and benefits of SI by assuming yields under SI as the maximum or minimum rain-fed yields observed at normal GS precipitation (All are 2018 prices in Canadian Dollars)

Table 4 Gross income based on yields predicted by the yield-determining equations in Figs. 2–5

Cultivar	GS prec. scenario	Rep. year	GS prec. (mm)	SI/ dewatering (mm)	Yield without SI/dewatering (Mg/ha)	Yield with SI (Mg/ha)	SI gross income (\$/ha, average price = \$254/Mg)	SI gross income (\$/ha, best price = \$291/Mg)	SI gross income (\$/ha, lowest price = \$187/Mg)
Russet Burbank (Optimal water sup- ply = 353 mm)	Lowest (5% RDD)	2001	155	198	19.2	31.0	2982	3417	2196
	Low (10% RDD)	2020	201	152	24.0	31.0	1757	2013	1293
Shepody (Opti- mal water sup- ply = 307 mm)	Normal	2006	326	27	30.7	31.0	55	63	40
	Highest (95% RDD)	2008	479	-126	26.2	N/A	-1212	-1385	-890
	Lowest (5% RDD)	2001	155	152	15.7	22.6	1764	2021	1299
	Low (10% RDD)	2020	201	106	19.2	22.6	859	984	632
Kennebec (Opti- mal water sup- ply = 376 mm)	Normal	2016	328	-21	22.5	22.6	33	38	24
	Highest (95% RDD)	2008	479	-172	13.8	N/A	-2250	-2577	-1656
	Lowest (5% RDD)	2001	155	221	19.4	29.2	2496	2859	1837
	Low (10% RDD)	2020	201	175	23.0	29.2	1568	1796	1154
Goldrush (Opti- mal water sup- ply = 342 mm)	Normal	2017	300	76	28.0	29.2	301	344	221
	Highest (95% RDD)	2008	479	-103	27.1	N/A	-537	-617	-395
	Lowest (5% RDD)	2001	155	187	16.2	23.8	1942	2225	1430
	Low (10% RDD)	2020	201	141	20.0	23.8	967	1108	712
	Normal	2006	326	16	24.0	23.8	-52	-59	-38
	Highest (95% RDD)	2008	479	-137	16.2	N/A	-1942	-2225	-1430

RDD-Rainfall Depth Duration; Rep.-representative; Prec.-precipitation; SI-supplemental irrigation; Negative-income loss; all incomes are in 2018 price of Canadian Dollars

Table 5 Gross income, assuming yields from SI are equal to observed rain-fed maximum or minimum marketable yields

Cultivar and SI yield scenarios	GS precipitation scenario	Obs. yield without SI/dewatering (Mg/ha)	Gross income (\$/ha, S1 & average price = \$254/Mg)	Gross income (\$/ha, S1 & best price = \$291/Mg)	Gross income (\$/ha, S1 & lowest price = \$187/Mg)	Gross income (\$/ha, S2 & average price = \$254/Mg)	Gross income (\$/ha, S2 & best price = \$291/Mg)	Gross income (\$/ha, S2 & lowest price = \$187/Mg)
Russet Burbank	Lowest (5% RDD)	16.3	4293	4918	3160	3023	3463	2225
S1: SI produces obs. max. yield = 33.2 Mg/ha at water supply = 326 mm (e.g. 2006);	Low (10% RDD)	28	1321	1513	972	51	58	37
S2: SI produces obs. min. yield = 28.2 Mg/ha at water supply = 333 mm (e.g. 2012)	Normal	33.2	0	0	0	-1270	-1455	-935
	Highest (95% RDD)	26.8	-1626	-1862	-1197	-262	-407	-262
Shepody:	Lowest (5% RDD)	15.6	3632	4161	2674	2032	2328	1496
S1: SI produces obs. max. yield = 29.9 Mg/ha at water supply = 328 mm (e.g. 2016);	Low (10% RDD)	22.2	1956	2241	1440	356	407	262
S2: SI produces obs. min. yield = 23.6 Mg/ha at water supply = 329 mm (e.g. 2014)	Normal	29.9	0	0	0	-1600	-1833	-1178
	Highest (95% RDD)	21.6	-2108	-2415	-1552	-374	-582	-374
Kennebec:	Lowest (5% RDD)	18.8	2642	3026	1945	1270	1455	935
S1: SI produces obs. max. yield = 32 Mg/ha at water supply = 300 mm (2017); S2: SI produces obs. min. yield = 23.8 Mg/ha at water supply = 358 mm (e.g. 2007)	Low (10% RDD)	22.5	1702	1950	1253	330	378	243
	Normal	32	-711	-815	-524	-2083	-2386	-1533
	Highest (95% RDD)	17.9	-2870	-3288	-2113	-1103	-1717	-1103

Table 5 (continued)

Cultivar and SI yield scenarios	GS precipitation scenario	Obs. yield without SI/dewatering (Mg/ha)	Gross income (\$/ha, S1 & average price = \$254/Mg)	Gross income (\$/ha, S1 & best price = \$291/Mg)	Gross income (\$/ha, S1 & lowest price = \$187/Mg)	Gross income (\$/ha, S2 & average price = \$254/Mg)	Gross income (\$/ha, S2 & best price = \$291/Mg)	Gross income (\$/ha, S2 & lowest price = \$187/Mg)
Goldrush:	Lowest (5% RDD)	17	4089	4685	3011	1295	1484	954
S1: SI produces obs. max.	Low (10% RDD)	18.5	3708	4249	2730	914	1048	673
yield = 33.1 Mg/ha at water supply = 326 mm (e.g. 2006);	Normal	33.1	0	0	0	-2794	-3201	-2057
S2: SI produces obs. min.	Highest (95% RDD)	23.5	-2438	-2794	-1795	262	698	262
yield = 22.1 Mg/ha at water supply = 333 mm (e.g. 2012)								

1) RDD-Rainfall Depth Duration; Rep.-representative; Prec.-precipitation; SI-supplemental irrigation. 2) Under S1 and S2, yields from SI were assumed to reach the maximum or minimum marketable yields as observed when water supply was at a near-optimal level for each cultivar. Yield gains from SI were assumed to be the difference between the maximum or minimum yields and the observed rain-fed yield at a specific rainfall level for each cultivar. 3) The negative numbers represent gross income losses without dewatering under 95% RDD. 4) All gross incomes are in 2018 price of Canadian Dollars

RDD point. If water development is required, the cost of SI increases considerably. Accordingly, the economic returns for all of the above scenarios would worsen (Fig. 6). In this case, SI would only generate marginal net profit in a small number of scenarios, for example, for RB and Kennebec under 5% RDD for a 20-ha field at an above-average sale price and for a 40-ha field at the lowest price, and RB and Kennebec under 10% RDD for 40-ha field size at above the average price.

The cost–benefit scenarios, assuming marketable tuber yields with SI are equal to the observed maximum and minimum rain-fed yields, are presented in Fig. 7 and Table 5. For instance, the maximum and minimum yields with SI for RB were assumed to be 33.2 Mg/ha (represented by the 2006 rain-fed value with GS precipitation = 326 mm, which is very close to the optimum level of 358 mm for RB, Table 1) and 28.2 Mg/ha (represented by the 2012 rain-fed level with GS precipitation = 333 mm, which is also very close to the optimum level of 358 mm, Table 1). If irrigated in 2020, the maximum and minimum yield gains would have been 33.2 – 28 = 5.2 Mg/ha and 28.2 – 28 = 0.2 Mg/ha, respectively. Assuming that SI produces the highest observed rain-fed yields, SI would generate \$1310, \$1868, \$146 and \$2148/ha more gross income for RB, Shepody, Kennebec and Goldrush, respectively, at the average potato price in an extremely dry year (e.g. 2001, 5% RDD), compared to the simulated values shown above. Compared to the annual cost of SI, the increased gross income would make SI profitable for RB, Shepody and Goldrush cultivars, but not Kennebec, regardless of field size and sale price. However, in a dry year (e.g. 2020, 10% RDD), the increased gross income, when using the observed maximum rain-fed yields to represent SI yields, would shrink enough that SI would only make Goldrush consistently profitable regardless of sale price (Fig. 7). The profitability of the other three cultivars would depend on the sale price, field size and requirements of water development (Fig. 7). As GS precipitation increases beyond the 10% RDD level, the net profits of SI gradually diminish. Assuming SI produces yields equal to the lowest observed yields, SI would only create a profit for RB and Shepody in a 20-ha field without water development under 5% RDD regardless of sale price. Under the best case scenario where SI was assumed to produce the maximum observed yields in the two dry years (2001 and 2020) and the best potato sale price was applied, the overall gross income for RB, Shepody, Kennebec and Goldrush would be \$6431/ha, \$6402/ha, \$4979/ha and \$8934/ha in the 20 years. (SI created limited gross income in the other 13 years, as shown in Fig. 7 and Table 5.) These gross incomes are still not enough to make up for the accumulated ownership costs of SI in the 20 years (ranging from \$10,620/ha to \$42,860/ha, depending on field size

and water availability as shown in Table 3) plus the annual operation costs. These large deficits in the simulated yield cases and best case scenarios demonstrate a large financial barrier for growers to widely adopt SI in this region.

Costs and Benefits of Soil Dewatering

The yield-determining equations (Figs. 2–5) predict that the yields for RB, Shepody, Kennebec and Goldrush would have been 4.8, 8.8, 2.1 and 7.9 Mg/ha higher with soil dewatering in a wet year like 2008 (Fig. 1). This corresponds to profit increases of \$1213/ha, \$2250/ha, \$534/ha, and \$2000/ha, based on an average sale price of \$254/Mg. These results suggest that the economic gains from soil dewatering would fully offset the cost of tile drain installation (\$2500/ha) after two extremely wet seasons (GS rainfall > 470 mm) in fields planted with Shepody and Goldrush, after three seasons for RB, and after five seasons for Kennebec. This level of rainfall occurred in three (2008, 2009 and 2010) out of the 20 seasons. In addition, 2002 (426 mm) and 2019 (426 mm) would also have benefited from dewatering because the GS rainfall rates in these two seasons exceeded the optimal level for each cultivar.

Discussion

Yield Response to Water Supply Variation

The yield-determining equations in Figs. 2–5 indicate that GS water supply (as GS precipitation) to the potato plant is the key explanatory variable for year-to-year variation in tuber yield. This provides insight into the inconsistent yield responses to irrigation water supply as observed in short-term irrigation experiments (Porter et al. 1999; Bélanger et al. 2000; Sexton et al. 2008; Xing et al. 2012; Afzaal et al. 2020). In an irrigation experiment, the overall water supply to the potato plant includes SI and GS precipitation. Because GS precipitation varies substantially, applying a similar irrigation rate (SI) in two seasons with very different GS rainfall rates (R1 and R2) can make SI + R1 significantly different than SI + R2, resulting in different yield responses. For example, if R1 + SI is located in the sensitive range of water supply (i.e. Rainfall Zone 1 = 155–257 mm) and R2 + SI in the insensitive range (Rainfall Zone 2 = 258–425 mm) as shown in Figs. 2–5, SI + R1 could create a detectable yield response while SI + R2 may not. This may also plausibly explain why some PEI growers observed a yield benefit in some seasons but not in others by applying a similar SI rate (personal communications). The inconsistent effects of SI on yield illustrate the limitations of short-term irrigation experiments and the importance of long-term data for characterizing tuber yield response to water supply in a humid climate.

Practical Implications

The finding that GS precipitation accounts for 29% to 69% of year-to-year yield variation, depending on the cultivar, highlights the importance of implementing SI for consistent potato production when GS rainfall is insufficient and soil dewatering when GS rainfall is excessive. However, the cost–benefit analysis indicates that SI would only have been profitable in most cases in 5% of the 20 seasons (5% RDD), some cases in 10% of the 20 seasons (10% RDD), and unprofitable in most cases in 85% of the 20 seasons. The financial returns from SI in the few dry seasons would not be enough to offset the costs of SI. The combination of low yield gains and high accumulated annual ownership and operation costs would result in a significant financial loss in the long term. The annual variations in SI requirements and unprofitability of SI in most seasons present a great financial challenge for widely implementing SI for consistent production in this traditionally rain-fed production region. Growers are required to produce consistent yields from year to year in order to satisfy their sale quota agreements and maintain business continuity. Without SI in a dry year, such as 2001 and 2020, growers may fail to produce sufficient potatoes to meet their quotas and consequently lose their buyers. Because of the unpredictable occurrence of drought, SI is equivalent to an insurance policy for economically viable production. In addition, the influence of SI on productivity and profitability as shown above represents average provincial conditions. The productivity and profitability of SI in a specific field may not follow the average trends because field-dependent variables such as soil, field size, farming practices, water availability and weather variables all influence potato productivity. With uncertain precipitation and field-dependent profitability, some growers may invest in SI in fields with promising financial potential to mitigate the risk of drought.

While interest in SI is growing in this region, tile drainage is often overlooked as an important water management tool to enhance potato productivity. This is probably because normal rainfall does not typically create excess moisture in this region owing to its sandy soil. However, the yield-determining equations (Figs. 2–5) indicate that excessive GS rainfall reduced potato yields more frequently than droughts did. Dewatering would have increased yields in five of the 20 years, while SI would only have increased yields in two to three of the 20 years. The cost–benefit analysis for the four cultivars suggests that the one-time cost of tile drain installation can be fully recovered in two to three extremely wet seasons. Additionally, the cost of tile drain per hectare does not vary with field size like SI cost does. All these make dewatering a better investment than SI, especially in fields below 20 ha, which account for 61% of potato production area in PEI and where SI

is not economically viable. “Yield Responses to Monthly Precipitation” section shows that excessive precipitation in May negatively influenced the yield of RB, a long-season cultivar. Excessive moisture in the planting season can reduce productivity by delaying planting and shortening the growing period in this high-latitude region. Tile drainage can extend the growing period by allowing earlier tillage and seedbed preparation in the spring. Tile drains also increase the opportunity for late-season harvesting operations (Evans and Norman 1999). For example, GS rainfall in 2018 was 362 mm, which is close to the optimum level and should theoretically have produced an above-average yield. However, rainfall in October (171 mm) and November (168 mm) exceeded the long-term averages by 46% and 33%. The excessive moisture prevented many growers from harvesting their full crop, resulting in the average harvested yields for RB (19.9 Mg/ha), Shepody (22.8 Mg/ha), Kennebec (20.4 Mg/ha), and Goldrush (22.4 Mg/ha) in 2018 being only 67%, 88%, 81%, and 84% of the long-term averages. Tile drains could have dewatered soil, allowing more potatoes to be harvested in 2018. With tile drains, growers can further lengthen the growing period by delaying harvest, because they do not have to worry about harvest being hindered by excessive moisture later in the season. All of these benefits suggest that tile drainage has the potential to be a useful water management tool for consistent potato production for certain cultivars in a changing climate. Where resources are constrained, growers should prioritize tile drainage over SI in small fields due to its higher economic viability.

This study demonstrates that historical rain-fed potato tuber yield and weather data can be used to characterize yield response to water supply for assessing the economic performance of SI and dewatering in PEI. This approach could work in other jurisdictions with a similar climate where long-term experimental data are lacking, as long as GS precipitation significantly explains annual variation in tuber yield. Many factors other than GS precipitation influence tuber yields, including farming practices, soil, and other weather parameters (Parent et al. 1967; Rosen 2018). If the influence on yield by these other factors outweighs GS precipitation, the yield regression equations will fail to produce reliable predictions for economic assessment. The significant influence of GS precipitation on provincial yield variation in PEI can be attributed to several factors: 1) Growers generally follow the standard local cultural practices as outlined in Bernard et al. (1993) and in the AgriInsurance Agreement (PEIAIC 2022), which remain relatively unchanged since the 1960s (Parent et al. 1967); 2) The soils are relatively uniform across the island (MacDougall et al. 1988); 3) Weather parameters vary spatially but the variation does not dominantly influence variation in tuber yield on the small island; 4) The provincial yield

data are an aggregate of the majority of potato farms in PEI and this aggregation likely smoothed out some of the variation in tuber yield as affected by factors other than GS precipitation.

Limitations and Future Studies

When applying the results of this study, the underlying limitations and assumptions should not be dismissed. First, the yield-determining equations were derived from 20-year provincial yield averages for the four cultivars and weather data from Harrington. Twenty years of historical yield and weather data are relatively limited for this type of exercise. The results should be updated when new data are available. Additionally, yield and profitability responses in one field may differ from the province-wide data depending on the specific conditions of the field. Carefully maintaining soil moisture at levels required for optimum potato plant growth using SI and soil dewatering, coupled with optimizing other potato production management variables, such as planting moisture-sensitive cultivars and optimizing fertilization, may produce very different tuber yield and quality results. These hypotheses require further testing. Second, the costs of SI without water development for a 40-ha field size were \$832/ha in Maine. In Manitoba, Canada, the average annual costs of SI (with 153 mm water application) without water development were estimated to be \$665/ha in 2018 using an irrigation cost calculator from Manitoba (Manitoba Agriculture Farm Management 2020; personal communications with M. Khakbazan, 2022). The difference in cost between Maine and Manitoba makes sense considering Manitoba’s larger field sizes, suggesting that the Maine values are reasonable. However, it is unclear how comparable to costs of SI are between Maine and PEI, given the island’s small, undulating fields and challenging terrain for center-pivot systems. The cost–benefit analysis should be revisited using local SI costs when they become available. Third, SI can influence potato quality parameters such as scab and specific gravity, which can greatly impact potato sale price and associated profitability (Lynch et al. 1995; Potter et al. 1999; King et al. 2020). Considering all these parameters in the cost–benefit analysis is beyond the scope of this work. Fourth, the yield responses were derived from random precipitation as water supply and may not fully reflect real-world SI conditions. Irrigation studies conducted by Shock et al. (1998) and King et al. (2020) in Oregon, US, and Lynch et al. (1995) in Alberta, Canada, suggest that even a short duration of water stress can result in an appreciable reduction in tuber yield and quality. Although GS precipitation in several of the 20 seasons was close to the optimum water demand for the four cultivars (Figs. 2–5), further studies are required to determine whether the yields obtained from optimum

levels of random rainfall (Table 1) are consistent with yields obtained by maintaining soil moisture at optimum levels via SI and soil dewatering. Lastly, the benefits of soil dewatering are based on the assumption that soil dewatering would increase yields from the observed levels to the optimal levels following the yield-determining equations. This assumption needs to be tested by local experiments.

Conclusions

GS precipitation varied from 155 to 479 mm, with an average of 338 mm. Yield increased with GS precipitation in the 155–257 mm range (Rainfall Zone 1; 3/20 seasons), became relatively insensitive to varying water supply with GS precipitation within 258–425 mm (Rainfall Zone 2; 12/20 seasons) and then decreased as GS precipitation increased from 426 to 479 mm (Rainfall Zone 3; 5/20 seasons). Yields responded to GS precipitation following second-order polynomial regressions with GS precipitation explaining 69%, 65%, 29% and 50% of yield variation for RB, Shepody, Kennebec and Goldrush, respectively. The yield-determining equations were similar to the potato water production functions in literature and created optimal water supply rates similar to local empirical evapotranspiration values. The yield-determining equations suggest that consistent potato production requires not only SI but also soil dewatering in this traditionally rain-fed production region. The yield regression equations predict that SI using a center-pivot system would produce positive profit in the first half of Rainfall Zone 1 regardless of field size and in the second half of Rainfall Zone 1 in fields over 40 ha; SI would not produce positive profit in Rainfall Zone 2 regardless of field size because precipitation was high enough that additional water supply would not have resulted in sufficient yield gains to offset the cost of SI; soil dewatering would be beneficial for optimal production in Rainfall Zone 3 in which precipitation was excessive. The annual variation and unpredictability in SI requirements and potential unprofitability in most seasons present a great financial barrier for widely implementing SI in this region. On the other hand, the yield gains for RB, Shepody and Goldrush from soil dewatering in two to three extremely wet seasons would fully offset the one-time cost of tile drain installation, making dewatering an attractive investment for consistent potato production. This study demonstrates that long-term rain-fed yield and weather data can be used to assess the economics of SI and soil dewatering for potato production and provides important economic information for water management decision making.

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Declarations

Conflict of Interest The authors have no conflict of interest.

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