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Reducing Yearly Variation In Potato Tuber Yield Using Supplemental Irrigation

Yefang Jiang[1] · Tobin Stetson[2] · John Phillips[3] · Ana Kostic[1]

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Abstract
This study investigated the influence of supplemental irrigation (SI) on yearly variation in potato yield and associated economics in a humid climate. On-farm trials were conducted in four to five fields annually in Prince Edward Island, Canada from 2019 to 2022. The research involved four different treatments: rainfed production as the control group, irrigation following conventional practices, irrigation guided by soil moisture monitoring, and irrigation guided by soil moisture monitoring coupled with a 20% reduction in fertilizer input. While six commonly-grown russet potato cultivars were used, local standard cultural practices were followed at all sites. In 2019 SI significantly increased marketable yields (MY), which was primarily attributed to a drought period that extended from July to early August. Similarly, in 2020 SI led to a substantial rise in MY due to growing season rainfall being significantly lower than the optimal water demand for the potato plant. Conversely, in 2021 and 2022, when rainfall was relatively sufficient and evenly distributed, farmers either refrained from irrigating or employed minimal irrigation rates, resulting in negligible MY responses. Tuber yield increase as a result of SI varied with rainfall and thus fluctuated yearly. Cross-year comparisons revealed that SI can effectively mitigate annual fluctuations in tuber yield. A cost–benefit analysis indicated that employing SI to minimize yearly variation in tuber yield can be either profitable or unprofitable in the long term, and is contingent on the costs linked to irrigation equipment, the water supply system, operational aspects, field scale, and rainfall distribution. These findings hold significance for guiding decisions in water management for potato production in humid environments.

✉ Yefang Jiang
Yefang.jiang@agr.gc.ca

[1] Agriculture and Agri-Food Canada, Charlottetown Research and Development Centre, 440 University Ave., Charlottetown, PE C1A 4N6, Canada

[2] Prince Edward Island Department of Agriculture and Land, 11 Kent St., Charlottetown, PE C1A 7N8, Canada

[3] East Prince Agri-Environment Association, 1441 Water View Rd., Summerside, PE C1N 4J8, Canada

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Introduction

Potatoes, consumed by over one billion people worldwide, rank as the third most important food crop globally after wheat and rice (Devaux et al. 2020). The sensitivity of potato plants to moisture fluctuations in the root zone (van Loon 1981; Opena and Porter 1999; Unlu et al. 2006; Obidiegwu et al. 2015) underscores the significance of optimizing water supply in preserving tuber yield and quality (Shock et al. 1998; Cantore et al. 2014; King et al. 2020). Inadequate water provision can compromise potato tuber yield and quality (Epstein and Grant 1973), reducing the financial viability of potato cultivation. Potato cultivation in humid climates has traditionally relied primarily on water supplied by rainfall. However, the increasing variability of growing season (GS) rainfall in these regions, which can range from considerably lower to substantially higher than the optimal requirements for potato growth, presents a significant challenge for maintaining consistent potato yields (Benoit and Grand 1985; Porter et al. 1999; Sexton et al. 2008; Silver et al. 2011). In Prince Edward Island (PEI), which has a humid climate and produces 23% of Canadian potato crops primarily under rainfed conditions (AAFC 2022), the GS (June–September) rainfall ranged from 155 to 479 mm, with an average of 338 mm and a standard deviation of 84 mm, between 2000 and 2020 Environment and Climate Change Canada (ECCC n.d.). In contrast, the optimal water supply for the potato plant or crop evapotranspiration (ET_c) was estimated to be 353–421 mm (Belanger et al. 2000; Xing et al. 2008; Sexton et al. 2008; Silver et al. 2011; Parent and Antil 2012; Jiang et al. 2022a). While rainfall fed cultivation proved economically viable in certain years, the 222 mm deficit between water demand and rainfall during the driest year (2001) resulted in a rainfed marketable yield that was 26% to 45% lower (depending on the cultivar) than in an average year, posing a significant financial challenge for potato growers. This uncertainty becomes even more concerning as production costs rise, profit margins shrink, and market competition intensifies. The coefficient of variation of provincial rainfed tuber yield between 2000 and 2020 varied from 8 to 15%, with GS rainfall accounting for 29% to 69% of the annual fluctuation in tuber yield (Jiang et al. 2022a). This demonstrates the importance of improving water management to reduce variation in tuber yield in a humid climate. Climate change has further compounded the issue of inconsistent potato production, due to more frequent extreme weather events such as droughts and excessive rainfall (Bush et al. 2019; Caretta et al. 2022). Improved water management is critical for ensuring sustainable potato production in this historically rainfed region.

Several studies have investigated the impacts of supplemental irrigation (SI) on potato production in the humid regions of the Northeastern United States and Atlantic Canada. Some studies have indicated that SI has the potential to significantly enhance total tuber yields (Porter et al. 1999; Belanger et al. 2000; Sexton et al. 2008), while others have had mixed results. For instance, in a study conducted by Xing et al. (2012) in New Brunswick, Canada, drip irrigation did not have a notable effect on tuber yield for Shepody potatoes. In PEI the use of SI resulted in a significant increase in marketable tuber yield for Russet Burbank potatoes in some years, while in others, the impact was not evident (Afzaal et al. 2020; Khakbazan et al. 2023). These studies highlight a continuing interest in SI in these areas and demonstrate varied increases in marketable yields resulting from SI, ranging from minimal levels to as high as 11.6 Mg/ha. The large variation in yield benefit raises the question of whether SI is economically viable in this climate. Further investigations by Jiang et al. (2021; 2022a) showed that SI increases tuber yield with decreasing rainfall following a second-order polynomial equation. This suggests that tuber yield response to SI fluctuates annually with rainfall. This variability may explain the annual differences in yield response to SI observed in prior studies. Jiang et al. (2021; 2022a) provided a cost–benefit analysis of SI using provincial average tuber yield data from PEI and cost data from Maine, US. However, these analyses did not comprehensively consider field variation, the impact of drought periods occurring on a weekly or monthly basis or site-specific SI costs. Khakbazan et al. (2023) found that the costs of SI outweighed the benefits based on 2017 and 2018 tuber yield data from a research trial in PEI. Because rainfall and the associated benefit of SI vary yearly, an assessment based on yield data from only two years cannot provide insights on the economic performance of SI for seasons with rainfall outside the experimental ranges (Jiang et al. 2022a).

This study investigated the effects of SI on potato tuber yield and specific gravity in PEI. The hypothesis posits that SI will significantly reduce yearly variation in tuber yield and increase specific gravity compared to conventional rainfed production. A cost–benefit analysis was performed to determine whether SI is economically beneficial for potato production in a humid environment.

Material and Methods

On-farm Experiments

The trials were conducted annually from 2019 to 2022 across four to five fields in PEI, primarily focusing on potato production for processing French fries. Each field was between 20 and 40 ha large and belonged to a distinct commercial farm (Table 1). The fields were located within an area bordered by Victoria (46°12′45.05″N, 63°29′21.81"W), Lower Bedeque (46°20′15.46″N, 63°46′38.6"W), Summerside (46°26′28"N, 63°50′17"W), and north Kensington (46°26′42.11″N, 63°38′38.39"W). This geographic area produces a large percentage of the Province's potatoes. Each field was equipped with a center pivot system for irrigation, except for BC21, which used a hose reel and sprinkler, and KM19, which used a hose reel and boom cart. Irrigation water was sourced either from an on-farm pond fed by groundwater wells or surface water from the nearby Dunk River. Note that trials were also conducted in GM19 in 2019 and CG21 in 2021, but the data are only reported in the Supplemental Material for reference. Potato seed production in GM19 was not comparable with processing potato production, and the yield data from CG21 were confounded by topsoil being mixed with poor-quality deep soil during the construction of a water holding pond near the experimental area in previous years. In adherence with the Province's mandated Agriculture Crop

Table 1 Potato cultivar, fertilizer input, preceding crops, pre-planting soil nitrate content and irrigation rates

Field ID	Potato cultivar	Fertilizer mix ($N–P_2O_5–K_2O$)	Fertilizer rate (kg/ha)	N rate for Y100N (kg N/ha)	N rate for Y80N (kg N/ha)	Preceding crops	Pre-planting soil nitrate content (kg N/ha)	Irrigation rate (mm)
RG19	Russet Burbank	14.91–13.85–14.91	1054	157	126	Winter wheat	24.4	FA = 163 Y100N = 193
KM19	Prospect	14.76–14.72–19.64	1177	173	139	Forages	27	FA = 65 Y100N = 80
AT19	Clearwater Russet	Pre-planting 7–0–16; planting 13–17–15	496; 1289	202	162	Sorghum Sudan Forage	37.8	FA = 128 Y100N = 103
CB20	Mountain Gem Russet			201	161	Sorghum Sudan Forage	61.5	FA = 356 Y100N = 356
JW20	Dakota Russet	Pre-planting 46–0–0; planting 14–22–10	151; 1121	226	181	Forages	45.4	FA = 167 Y100N = 222
JV20	Clearwater Russet	13–20–10; 23–0–22	1121; 383	234	187	Calienti Mustard	57.7	FA = 225 Y100N = 440
AS20	Clearwater Russet	Pre-planting 1: 9–0–47; pre-planting 2: 15.5–0–0; planting 11.9–14.6–9.1	200.7; 290; 981.4	180	143		53.6	FA = 263 Y100N = 281
BC21	Alverstone Russet	Pre-planting 31–0–18; planting 10–18–19	190.5; 1120	171	137	Forages	16.7	FA = 0 Y100N = 0
AL21	Clearwater Russet	Pre-planting 15–16–11; planting 46–0–0	1121; 112	220	176	Forages	14.1	FA = 40 Y100N = 40
KS21	Alverstone Russet	Pre-planting 0–0–60; planting 14–20–10	246; 1121	157	125	Forages	15.3	FA = 40 Y100N = 40
CB22	Mountain Gem Russet			213	170	Grain corn	20.4	FA = 88 Y100N = 88

Table 1 (continued)

Field ID	Potato cultivar	Fertilizer mix ($N–P_2O_5–K_2O$)	Fertilizer rate (kg/ha)	N rate for Y100N (kg N/ha)	N rate for Y80N (kg N/ha)	Preceding crops	Pre-planting soil nitrate content (kg N/ha)	Irrigation rate (mm)
HL22	Mountain Gem Russet	14–18–19	1121	157	125	Forages	50.3	FA = 40 Y100N = 40
BC22	Mountain Gem Russet	Pre-planting 31–0–18; planting 10–18–19	190.5; 1121	171	137	Forages	25.8	FA = 20 Y100N = 20
RG22	Dakota Russet	14.91–13.85–14.91	1054	157	126	Barley	20.3	FA = 21 Y100N = 21
AL22	Clearwater Russet	Pre-planting 15–16–11; planting 46–0–0	1121; 112	220	176	Winter wheat	N/A	FA = 40 Y100N = 40

Each field was identified with an ID instead of owner's name for privacy reasons. The second part of the ID refers to the experimental year. Forages typically consist of a mix of 60% red clover, 20% timothy and 20% rye grass. Spring soil nitrate content represents field average of treatment zone-based composite soil sampling at depths of 0–0.3 m. Soil ammonium concentrations were found at negligible levels and are not reported. Irrigation rates for Y100N and Y80N were identical

Rotation Act, growers typically employed a standard 3-year rotation of potatoes, grains, and forage crops. Most forage mixes consisted of 60% red clover and 40% one or two perennial grass species, such as timothy and rye grass. Standard practices for weed, pest, and disease control were followed (Parent and Antil 1967; PEI-AIC 2022). Potatoes were typically planted in mid-May, with harvest taking place in October, depending on the maturation requirements of the specific cultivars. The potato cultivar, fertilizer input, proceeding crops used in each field, pre-planting soil nitrate content, and irrigation rates are listed in Table 1. Potato cultivar information can be found in the Supplemental Material.

The soil in the experimental fields is derived from local glacial till originating from a sandstone formation consisting of a sequence of Permo-Carboniferous terrestrial red beds (van de Poll 1989). As a result of relatively consistent geology across the island, the soil in each field was relatively uniform, characterized as sandy loam (MacDougall et al. 1988). Prior to planting potatoes, a small number of soil samples were collected in each field using a handheld Dutch auger (0.05 m diameter). These samples were tested for soil organic matter (SOM) using the Broadbent (1965) method, pH using a Lignin pH robot, cation exchange capacity (CEC) based on soil cation values (Munroe 2018), and soil nitrate and ammonium content following the method outlined by Maynard et al. (2008). The results, along with soil texture information, are included in Table 2.

The experiment comprised four treatments: rainfed production (DA) as the control, supplemental irrigation (SI) following the growers' standard practices (FA), SI

Table 2 Soil parameters

Field ID	pH	Soil organic matter (%)	CEC (cmol/kg)	Sand (%)	Clay (%)
RG19	6.6	2.8	8.8	65	9–11
KM19	5.7	2.2	10.3	62–67	9–11
AT19	5.9	2.1	9.0	60	10
CB20	6.3	3.1	11.6	63–67	9–11
JW20	6.0	2.8	11.8	66	9–11
JV20	5.8	2.7	11.5	60–65	10–13
AS20	6.3	3.1	11.2	62–66	9–11
BC21	6.0	2.0	9.9	65	11
AL21	5.8	2.7	12.7	65–67	9–11
KS21	5.8	2.6	11.1	60	11–13
CB22	6.4	1.6	8.1	60	11–13
HL22	6.1	2.4	12.0	67	9–11
AL22	5.5	3.0	11.5	65–67	9–11
BC22	5.3	2.5	10.5	65	11
RG22	6.3	2.1	10.5	65	9–11

The second part of field ID refers to the experimental year. Soil texture information was extracted from the draft of digital soil map of PEI (personal communications with Dr. Xiaoyuan Geng). Other soil properties represented field averages of treatment zone-based soil sampling at depths of 0–0.3 m informed by soil moisture monitoring (Y100N), and SI informed by soil moisture monitoring combined with a 20% reduction in fertilizer input (Y80N). Each of the Y100N and Y80N treatments was implemented on a different section approximately 30 by 30 m in size within a large field, while the FA treatment was employed in the remaining area. Due to the practical challenges of implementing randomization using a single large irrigation system, the treatments were not randomized. Potato growers usually refrain from irrigating in June and September, as rainfall during these months tends to be sufficient for potato plant growth (Jiang et al. 2021; 2022a). Irrigation is more commonly used in July and August when tubers are initiating and bulking (Sexton et al. 2008). Overall, SI takes place on less than 6% of annual potato producing land in PEI (Jiang et al. 2022a).

Irrigation was scheduled on a weekly basis, as a prolonged lack of water can adversely impact potato plants (Jiang et al. 2021; 2022a). For the FA treatment growers empirically aimed for 20–30 mm of water per week with irrigation, by accounting for the forecasted rainfall in July and August (Jiang et al. 2022a). For the Y100N and Y80N treatments irrigation was applied when the volumetric soil moisture in the top 0.3 m of soil (measured from the top of the potato hill) dropped to 16%, which is equivalent to 50% of the water holding capacity (WHC) for sandy loam. This strategy aimed to maintain soil moisture within the 50–85% WHC range recommended by King et al. (2020), Sexton et al. (2008), and Steele (2013). In 2019 and 2020 soil moisture measurements were conducted using a handheld HydroSense II meter (Campbell Scientific, Edmonton, Canada) at multiple points on a weekly basis and the average was calculated for irrigation scheduling purposes. When the average soil moisture approached or fell below 16%, irrigation was applied equally in the Y100N and Y80N treatments at a rate that would rewet the top 0.3 m of soil to a 22% moisture level (i.e., 85% of WHC), taking into account the weekly forecasted rainfall. In 2021 and 2022 automatic sensors were installed for soil moisture monitoring. However, the sensors did not produce reliable readings. In these two years growers empirically aimed for 20–30 mm of water supply per week with irrigation by accounting for the forecasted rainfall.

Sampling and Monitoring

Four representative 3.05 m rows of potatoes were harvested each year from each treatment field section for tuber yield analysis, with the exception of 2019, when six rows were harvested per treatment. The harvested tubers were cleaned, weighed, and converted into total potato yield in Mg per hectare (i.e., ton/ha) using a density factor based on the spacing between the potato rows and plants. Tuber grading to estimate marketable yield was conducted at the Agriculture and Agri-Food Canada (AAFC) facility in Charlottetown for the 2019 samples, while the 2020–2022 samples were graded at the central grading facility at Cavendish Farms. Specific gravity was calculated using representative tubers based on their weight in air and water, following the methodology outlined by Gould (1995).

Rainfall was monitored on-site using rain gauge stations, typically starting in mid- to late June or July. Because on-site data were not complete or/and not comparable as a result of differences in the start of rainfall monitoring, data from Environment and Climate Change Canada's (ECCC n.d.) weather stations at Summerside (46°26′28"N, 63°50′17"W), New Glasgow (46°24′32.08"N, 63°21′01.04"W), and Harrington (46°20′37"N, 63°10′11"W) were used instead. Missing data points were supplemented using available data from nearby ECCC stations.

Statistical Analysis

The SAS MIXED procedure (SAS Studio 3.81, 2012–2020, SAS Institute Inc., Cary, NC, USA) was used to analyze total and marketable tuber yields and specific gravity for each year. Specifically, treatment averages of these variables were used as independent variables with each experimental field location as a replication. The treatment was considered as a fixed factor and field location as a random factor. Although cultivar is confounded with field location, this exercise was still able to determine whether SI was beneficial for potato production. The SAS MIXED procedure was also used to examine annual variation in yield under conditions of sufficient water supply (i.e., adequate rainfall or insufficient rainfall supplemented with irrigation) and insufficient water supply (i.e., inadequate rainfall without irrigation), with the year considered as a fixed effect and random effects omitted. This analysis tested whether SI could effectively mitigate yearly variation in tuber yield. In both cases, multiple comparisons among the fixed factors were performed using the DIFF option in SAS.

Cost–benefit Estimation

A cost–benefit estimation was undertaken to assess the economic performance of SI. The net benefit of SI was determined by deducting the SI cost from the gross benefit. The gross benefit was calculated as the rise in marketable yield resulting from SI, multiplied by the sale price of potatoes. The increase in marketable yield from SI was estimated from the experimental results. Potato tuber yield typically increases with initial increments in water supply (i.e., rainfall + irrigation), becomes relatively insensitive to further increments over a wide range (A–B), and then decreases at very high water supply levels by following the potato water production function (Fig. 1) (Shaykewich et al. 2002; Yuan et al. 2003; Ross 2006; Sexton 2008; Karam et al. 2014; Jiang et al. 2022a). This tuber yield response aligns with typical crop water production functions (English 1990; Varzi 2016; Foster and Brzovic 2018). The potato water production functions indicate that the increase in tuber yield from SI decreases with increasing rainfall, diminishing as rainfall approaches the ET_c level (Jiang et al. 2022a). The temporal distribution of water supply also plays a role in shaping the water production function, as different potato growth stages necessitate varied water supply rates (Shock et al. 1998; King et al. 2020). Since rainfall varies annually in a humid environment, causing fluctuations in irrigation requirements, tuber yield response, and thus the gross benefit of SI, a short-term assessment cannot accurately capture the impact of yearly rainfall variability on the economic performance of SI (Jiang et al. 2022a). Therefore, a per-hectare cost–benefit analysis

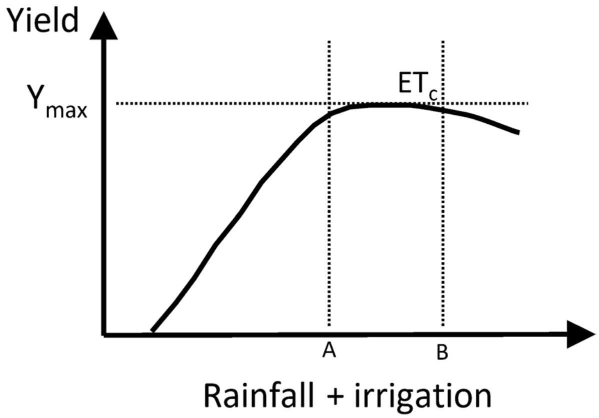

Fig. 1 Potato water production function

was conducted over a 23-year period, roughly corresponding to the typical lifespan of current irrigation systems. The rainfall in this 23-year period was assumed to be the same as observed at New Glasgow from 2000 to 2022. In the absence of a local crop water production function for predicting tuber yield increase, the annual marketable yield increase from SI was extrapolated from the observed values in the experiment or previous studies by matching historical rainfall rates from 2000 to 2022 with those observed during the experimental period. This matching process approximately reflected the relationship governed by the potato water production function. Potato sale prices and the purchase prices for establishing and maintaining the irrigation systems were all scaled to 2018 prices for comparative purposes.

An estimate of the costs associated with typical irrigation systems in PEI was made with the assistance of four growers. These growers owned the RG19, JW20, CG21, and BC21 fields, although the cost data were not necessarily from the experimental fields. Two of the growers provided irrigation cost data for center pivots (pivot I and pivot II), one supplied cost data for irrigation using a hose reel and sprinkler, and another shared the cost information for a hose reel and boom cart. Pivot I was used to irrigate a 38.5-ha field annually with a dedicated water supply system, while the smaller pivot II was moved back and forth to irrigate two adjacent 20-ha fields per year with a shared water supply system. The reel sprinkler was used to serve two 20-ha fields annually, each with a separate water supply system. Similarly, the reel boom cart was moved back and forth to cover two 20-ha fields per year with separate water supply systems.

The overall cost of each irrigation system comprised annual ownership and operation costs (Silver et al. 2011). Annual ownership costs included capital depreciation and interest payments. Capital costs covered equipment purchase, piping installation, water reservoir (or pond) construction and accessories (e.g., float and in-pond pump), power access (power line, electrical panel, and wiring), well drilling, and pump installation. Operation costs included services (setting/wrapping up, system operation/mobilization, and app subscription) and fuel/electricity. The total capital cost over the capital asset lifespan was annualized to provide a uniform annual capital cost per hectare, including interest. In this process, the capital asset was assumed to have a 25-year lifespan with an annual depreciation rate of 8.1% (i.e., the salvage value was 12% of the total capital cost) (Manitoba Agriculture Farm Management 2020). Most growers agreed that a bank loan for 85% of the capital investment was usually obtained, and the total interest over 25 years was calculated using an annual rate of 5% over a five-year term amortized over 25 years. The annual interest payment was calculated on a per-hectare basis as the total interest paid divided by 25 years.

Results

Weather

The mean annual precipitation rates from 2000 to 2022 at Summerside, New Glasgow, and Harrington were 961 mm, 1107 mm, and 1106 mm, respectively, with the mean GS (June–September) rainfall recorded at 334 mm, 389 mm, and 348 mm, respectively (ECCC n.d.). One key reason for the lower annual and GS mean precipitation values in Summerside is that the weather station lost many data points due to equipment malfunction. Consequently, precipitation data from New Glasgow were used to calculate long-term averages, while rainfall data for 2019–2022 from Summerside were used to calculate seasonal rainfall, with missing data points filled using data from nearby weather stations. The monthly water demand of the potato plant (Fig. 2) was computed from potential evapotranspiration estimated using the Linacre equation (Linacre 1977) multiplied by the crop coefficient (Jiang et al. 2022a). Rainfall in June and September typically exceeded the water demand of the potato plant, leading to infrequent SI during these months in PEI. However, July and

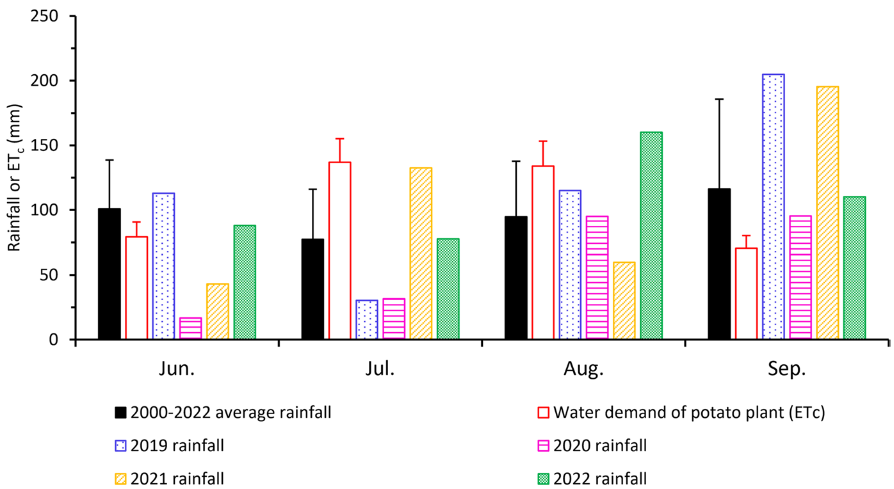

Fig. 2 Growing season rainfall and ET_c of the potato plant (long-term data from New Glasgow and 2019–2022 data from Summerside)

August usually saw lower rainfall levels than the plant water demand (Fig. 2), making SI necessary in dry years.

In 2019 the GS rainfall in Summerside reached 463 mm, which is 19% higher than the long-term average (Fig. 2). This rainfall included 289 mm from July 1 to September 18, an amount comparable to the on-site rainfall rates of 228 mm to 329 mm for the same period (Fig. 2). The relatively large differences in on-site rainfall among the sites was not solely the result of spatial variation; it was partially caused by differences in the start of rainfall monitoring. Despite higher total GS rainfall, the 30.4 mm of rain in July was 61% lower than the long-term average of 77 mm (Fig. 2; Supplemental Material, Table 5). This lack of rainfall in July and early August resulted in an extended drought period in 2019. The 2020 season was the second driest one from 2000 to 2020 (Jiang et al. 2022a; Supplemental Material, Table 5). At only 239 mm, the 2020 rainfall in Summerside was 39% lower than the long-term average. The 31.6 mm of July rainfall was 59% lower than the average. Although the 95 mm of rainfall in August aligned with the long-term average, 81% of this rainfall occurred after August 24 (Figs. 3 and 4). June rainfall was 83% lower than the long-term average of 101 mm, leading to significantly lower carried-over soil moisture. This deficit in rainfall, coupled with uneven temporal distribution of rainfall in July and August and a lack of carried-over soil moisture, resulted in an extended period of drought during the tuber initiation and bulking stages.

The 2021 GS received 431 mm of rainfall, marking a 10.5% increase from the long-term average (Fig. 2). During the 2021 season, on-site gauges at BC21 and AL21 recorded 465 mm, while a gauge at KS21 detected 358 mm. The lower value at KS21 was partly due to missing rainfall data for June. The on-site monitoring data were similar to the ECCC Summerside data. Although June (43 mm) and August (60 mm) rainfall was 57% and 37% lower than the respective long-term averages of 101 mm and 95 mm (Fig. 2), July (132 mm) and September (195 mm) rainfall surpassed the averages by 71% and 68% (77 mm and 116 mm, respectively). Overall, the total 2021 GS rainfall exceeded average levels, and any deficiency in rainfall during certain periods was likely partially compensated for by the carried-over soil moisture, providing sufficient water to the potatoes. In 2022 GS rainfall in Summerside (436 mm) was slightly higher than the long-term average and the water demand of the potato plant. The monthly GS rainfall closely corresponded to the monthly water demand of the potato plant (Fig. 2). The lower rainfall at BC22 was likely due to the lack of early June rainfall data from the on-site rainfall monitoring. These data suggest that the GS rainfall rate and temporal distribution in 2022 were favorable for potato plant growth. SI experiments were conducted in four farms in 2023; however, due to the high GS rainfall (458 mm), growers refrained from irrigating. The data from 2023 are not presented here.

From 2000 to 2022 the frost-free period varied between 100 and 160 days in PEI. Average air temperatures in Summerside in June, July, August, and September during the same period were 15.3℃, 19.8℃, 20.1℃, and 14.6℃, respectively (Fig. 5). Between 2019 and 2022, approximately half of the GS months experienced temperatures similar to the long-term averages. However, the monthly average temperature in September 2019, June 2020, June and July 2021, and September 2022 were 1.3℃ lower, 1.1℃ higher, 2.3℃ higher, 1.9℃ lower, and 0.6℃ higher than the respective long-term monthly averages.

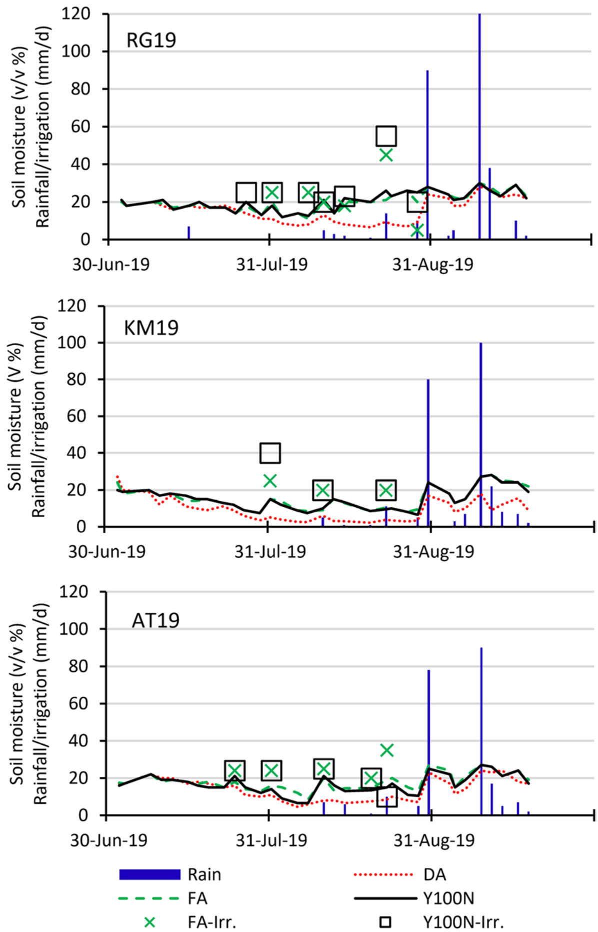

Fig. 3 2019 Growing season rainfall, irrigation rates, and soil moisture

Irrigation and Soil Moisture

In 2019 the three growers used SI from late July to late August. Growers irrigated between three and seven times at approximately 25 mm of water per application (Fig. 3; Table 1). Due to limitations in altering the timing of irrigation for different treatments using a single large irrigation system, the FA and Y100N areas were irrigated simultaneously, albeit at slightly different rates (Fig. 3). Consequently, soil moisture readings under the FA and Y100N treatments were comparable and consistently higher than those observed in the control section (DA) across all four sites during the irrigation period in late July and August. However, soil moisture levels occasionally fell below the lower threshold of 16% for sandy loam in July and August (Fig. 3). This was attributed to several potential factors: delayed irrigation when soil moisture had already dropped below the threshold, insufficient irrigation rates and frequencies, a mismatch between empirical soil retention parameters and soil type, and/or an inadequate

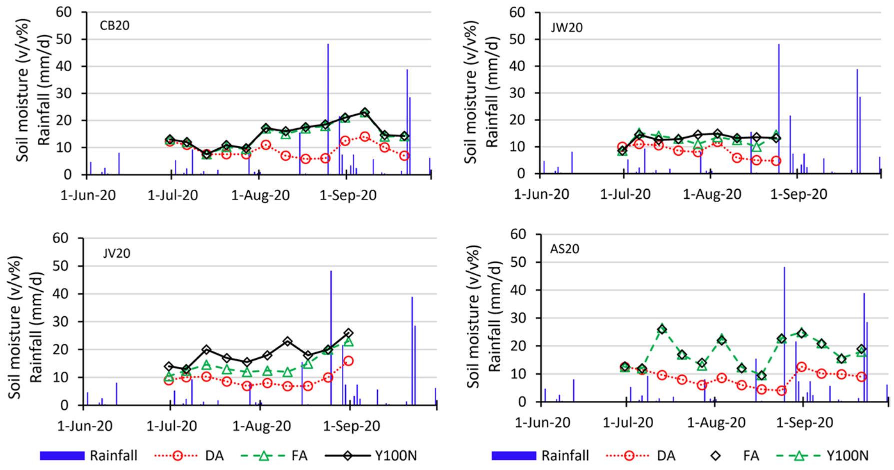

Fig. 4 2020 Growing season rainfall and soil moisture (daily rainfall data from the ECCC Summerside weather station were used for each site as on-site daily data were not available)

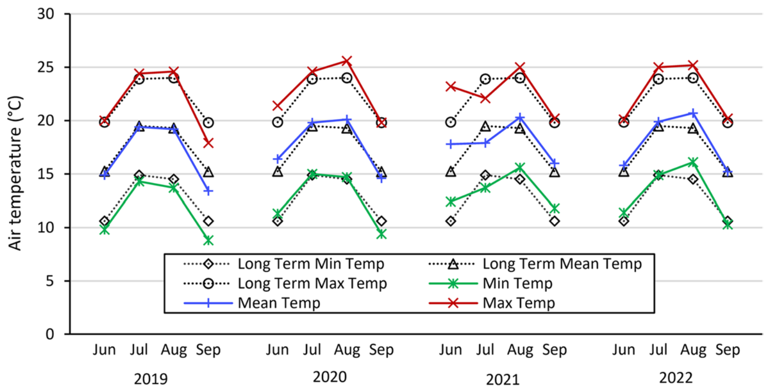

Fig. 5 2019–2022 Growing season air temperature and 2000–2022 air temperature averages at Summerside (ECCC n.d.)

consideration of irrigation equipment efficiency. Soil moisture levels were similar among the treatment zones before irrigation, indicating relative soil moisture uniformity in the absence of irrigation within a field site. Irrigation at RG19 on August 28 in addition to high rainfall occurring around August 30 raised soil moisture to 28%. Even without irrigation at AT19 around August 30, soil moisture was also elevated to 27%. These moisture levels were above the field capacity of 26%, likely resulting in nitrate leaching. Nitrate leaching during the same period was also observed in another field in PEI (Jiang et al. 2022b). These data together reaffirm that rainfall is highly variable in PEI, not only on a yearly basis but also month to month.

In 2020 the four growers administered varying numbers of irrigation applications, ranging from seven to 18 applications of approximately 25 mm each under the FA and Y100N treatments (Fig. 4; Table 1). Overall, the Y100N treatment was irrigated more than the FA treatment, although the timing was similar. As in 2019, soil moisture readings before the initiation of irrigation in early July were uniform under DA, FA, and Y100N, signifying a consistent soil moisture pattern in the absence of irrigation across a field. Soil moisture levels under the Y80N treatment were assumed to be similar to those under the Y100N treatment, as both treatments received identical irrigation and were positioned next to each other in each field. At the AS20, CB20, and JW20 sites, the moisture levels under the FA and Y100N treatments remained comparable, owing to the low variation in irrigation rates employed by the growers for these treatments (Fig. 4; Table 1). Conversely, at JV20 the application of significantly higher irrigation rates for the Y100N treatment compared to the FA treatment resulted in substantially higher moisture readings in the former (Fig. 4; Table 1). As expected, irrigated areas consistently exhibited higher moisture levels than the non-irrigated areas in all fields during the irrigation season, with higher irrigation rates leading to elevated soil moisture levels. For instance, at CB20 the FA and Y100N treatments received the highest irrigation rates and predictably had the highest soil moisture levels among all the sites, sustaining levels above the lower irrigation threshold of 16% for sandy loam from early August to early September. At AS20 the PEI Department of Environment paused water withdrawal from the surface water source in August for the protection of aquatic habitat. This impacted the farm's ability to irrigate and consequently lowered soil moisture. Notably, the soil moisture readings in both 2019 and 2020 did not exhibit a substantial response to SI in the irrigated treatments, despite consistently displaying higher values than the rainfed treatment. This lack of response was attributed to the timing of the moisture readings, taken one or two days post-irrigation, the averaging of readings across a depth of 0–0.3 m, and the relatively low frequency (i.e. weekly) of readings, all contributing to subtle peaks in the data. As in 2019, soil moisture was not consistently maintained above the designated lower threshold of 16% in 2020 due to the challenges mentioned above.

In 2021 BC21 did not utilize any irrigation, while AL21 and KS21 only applied 40 mm, due to high rainfall (Fig. 2; Table 1). Consequently, the DA, FA, and Y100N treatments were identical within BC21, and the FA and Y100N treatments were identical within AL21 and KS21. Similar to 2021, in 2022 all five growers implemented irrigation at low rates, ranging from 20 to 88 mm, due to high rainfall (Fig. 2; Table 1), with no variation in the irrigation rates among FA, Y100N, and Y80N. Soil moisture data for 2021 and 2022 are not presented, as the automatic sensors failed to produce reliable readings, and manual readings were not taken. Because rainfall was sufficient for potato production, and irrigation was infrequently applied in these two years, the failure of the soil moisture sensors did not impact the experiments significantly.

Table 3 Effects of treatment on tuber yield and specific gravity

	Total yield (Mg/ha)	Marketable yield (Mg/ha)	Specific gravity (g/cm^3)
2019			
DA	38.4a	30.4a	
FA	55.4b	49.7b	
Y100N	53.4b	46.2b	
Y80N			
Standard error	3.8	4.1	
p value	0.065	0.057	
2020			
DA	28.8a	19.3a	1.0894
FA	46.0b	33.9b	1.0904
Y100N	47.4b	35.0b	1.0875
Y80N	46.4b	35.5b	1.0900
Standard error	2.6	2.3	0.002
p value	0.0004	0.0012	0.76
2021			
DA	43.7	36.2	1.0854
FA	46.2	37.9	1.0867
Y100N	44.8	36.7	1.0906
Y80N	43.4	35.3	1.0855
Standard error	2.37	2.29	0.006
p value	0.82	0.86	0.38
2022			
DA	50.2	45.3	1.0877
FA	50.7	44.3	1.0907
Y100N	47.8	42.4	1.0929
Y80N	51.2	47.4	1.0922
Standard error	2.3	2.8	0.003
p value	0.579	0.277	0.144

Mean separations were done within each year with field location as replication. Means with the same letter are not significantly different at $p = 0.1$. Multiple comparisons were not conducted unless $p < 0.1$

Tuber Yield and Specific Gravity Response

Year-based comparisons of tuber yield and specific gravity are summarized in Table 3. In 2019 the implementation of SI in FA and Y100N significantly increased both total and marketable tuber yields by 39–44% and 52–63%, respectively, compared to rainfed production (DA) (Table 3). SI also raised the ratio of marketable tuber yield over total tuber yield from 79% to 86–90%. However, tuber yields under FA and Y100N were not significantly different, primarily because their water supplies were only slightly different (Table 1 and 3). In 2020 the application of SI in the FA, Y100N, and Y80N treatments significantly increased total tuber yield by 60–64% and marketable tuber yield by 76–84%, elevating the ratio of marketable yield over total yield from 67% to 74–76%, compared to DA (Table 3). These significant differences were attributed to the severe drought in 2020. In 2021 there was no significant difference in tuber yield between rainfed and SI production, mainly because growers either irrigated as low as 40 mm or refrained from irrigating at all due to high and temporally well-distributed rainfall (Table 1 and 3). Similarly, in 2022 implementing irrigation did not significantly impact total and marketable yields compared to rainfed production (DA), again due to a high and favorably-distributed rainfall rate resulting in low irrigation rates (Table 1 and 3). Consistently across all years, reducing fertilizer input by 20% did not significantly change tuber yield when water supply was sufficient, regardless of whether the water source was only rainfall or a combination of rainfall and irrigation. This suggests that fertilizer input in the experimental fields can be reduced without compromising yield. Treating the field sites as replications, significant differences in specific gravity were not observed among treatments, irrespective of water supply rates, even though a significant influence on specific gravity was evident in some fields/years (see Supplementary Material, Tables 2 to 4).

Cross-year comparisons of tuber yield are presented in Fig. 6. When running the MIXED procedure in SAS for this comparison, tuber yield data for the DA treatment in 2019 and 2020 (which contained extended drought periods) were grouped by year to represent insufficient water supply conditions. Yield data for FA and Y100N in 2019, FA, Y100N, and Y80N in 2020, and DA, FA, Y100N, and Y80N in 2021 and 2022 were combined to represent sufficient water supply conditions. The absence of extended drought periods in 2021 and 2022 precluded the analysis of inadequate water supply in those years. In the absence of SI (i.e., under insufficient water supply), growers experienced a significant loss of 29.4% and 38.2% in total yield, and 36.7% and 44.5% in marketable yield on average in 2019 and 2020 (Fig. 6). The average marketable yield under insufficient water supply was 25.2 Mg/ha, representing a 19.2% decrease compared to the 2000–2018 provincial average of 31.2 Mg/ha (Jiang et al. 2021). With sufficient water supply, the marketable yields still fluctuated yearly from 34.8 to 48 Mg/ha, with the 2019 season having the highest total and marketable yields, followed by 2022, 2021, and 2020. The causes

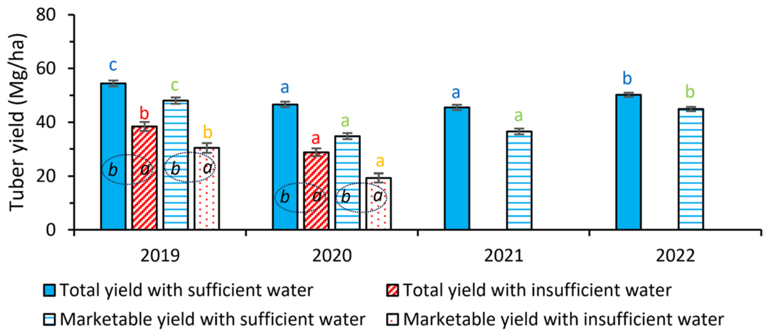

Fig. 6 Cross-year comparisons of tuber yield (LSD α = 5%)

of the exceptionally high yields in 2019 warrant further investigation. The higher yields in 2022 were attributed to favorable rainfall rates and temporal distribution. Additionally, the use of the high-yielding Mountain Gem Russet at three out of the five sites likely contributed to the heigh yields in 2022. The relatively low rainfall in June and August in combination with limited irrigation contributed to the relatively low yields in 2021. The lower yields in 2020 could partly be a result of insufficient irrigation at AS20, caused by the PEI Department of Environment pausing water withdrawal in August for the protection of aquatic habitat. Rainfed yields in 2020 were notably lower than those in 2019 due to the greater severity of the 2020 drought (Fig. 6). With SI, the 2020 yields were comparable to those in the rainfall-sufficient 2021 season, indicating that SI has the potential to effectively mitigate yearly variations in tuber yield under changing climatic conditions. The average marketable tuber yield under sufficient water supply was 41 Mg/ha, which is 31.4% higher than the 2000–2018 provincial average. These results underscore the critical role of SI in ensuring the economic sustainability of potato production during seasons marked by prolonged periods of inadequate rainfall, particularly during the plant's crucial growth stages.

Cost–benefit Analysis

Among the cost items (Table 4), ownership cost accounted for 61%, 84%, 48% and 70% of the total costs for center pivots I and II, the hose reel and sprinkler, and the hose reel and boom cart, respectively. This means that growers had to pay the majority of the total annual irrigation cost to have the irrigation system in place, regardless of whether or not they irrigated or how often. Pivot I was 52% more expensive than pivot II because it is a larger system, with one pass covering about twice as much area as pivot II. Although the two pivots required a similar investment in developing a water supply system and were used to irrigate a similar total area in one year, the total annual cost of using pivot II to irrigate was about 52% lower. This was due to pivot II being moved back and forth to irrigate two 20-ha fields with a shared water supply system, lowering the unit capital cost. Additionally, the service cost for pivot II, which had access to a cheaper power source, was lower. The overall costs for the reel sprinkler was considerably higher than the two pivots and the boom cart systems. The reel sprinkler had higher ownership costs and was powered by diesel, incurring higher operation costs. These cost data suggest that different irrigation systems require varying levels of investment and that operation and water supply system costs are field-dependent. Using site-specific parameters, including the type of irrigation system, financial variables, capital depreciation rates, power/fuel, and service costs, would produce a more accurate estimate.

To estimate the marketable tuber yield increase from SI, each year from 2000 to 2022 was placed into one of three categories based on its rainfall pattern: a very dry (2020-type) category, a 2019-type category, and a wet (2022-type) category. The very dry category included 2 years as observed: 2001 and 2020. 2019 rainfall was characterized by the lowest July rainfall (23.6 mm) from 2000 to 2022 (excluding 2001 and 2020) (Supplemental Material, Table 5). The number of years that fall

Table 4 Cost of supplemental irrigation for potato production

Irrigation equipment and water supply system	Pivot I covers one 38.5-ha field/year with a dedicated water supply system	Pivot II covers two 20-ha fields/year with a shared water supply system	Hose reel & sprinkler covers two 20-ha fields/year with separate water supply systems	Hose reel & boom cart covers two 20-ha fields/year with separate water supply systems
Equipment ($/ha)	140,000/38.5	92,000/40	68,000/40	100,000/40
Piping ($/ha)		28,000/40	56,000/40	130,680/40
Water pond + accessories ($/ha)		45,000/40	83,000/40	45,000/40
Well (s) + pump (s) ($/ha)		30,000/40	90,000/40	75,000/40
Power access ($/ha)		15,000/40	450,00/40	
Total asset ($/ha)	250,000/38.5	210,000/40	342,000/40	350,680/40
Depreciation ($/ha/year)	230	183	297	305
Interest ($/ha/year)	204	131	252	219
Ownership cost ($/ha/year)	**434**	**314**	**549**	**524**
Power/fuel use ($/ha/year)	13		256	124
Services ($/ha/year)	255		333	99
App. subscription ($/ha/year)	7			
Operation cost ($/ha/year)	**275**	**59**	**589**	**223**
Total cost ($/ha/year)	**709**	**373**	**1138**	**747**
Marketable yield increase from irrigation required to break even (Mg/ha/year)	2.8	1.5	4.5	2.9

All costs are in (or approximately equal to) 2018 Canadian Dollars. Operation cost was based on five water applications per year in the 2019-type group was determined by counting all the years with July rainfall lower than 50% of 77 mm – the median July rainfall. The years that met this criterion included 2018, 2012, and 2008. In addition to these three years, one more year was counted toward the 2019-type rainfall pattern category for a conservative estimate. In total, five years (including 2019) from 2000 to 2022 fall in the 2019-type category. The remaining 16 years (including 2021, 2022, and 2023) were placed in the wet category, which had either sufficient rainfall, or rainfall that was so close to the optimal water supply level that SI was either not implemented or implemented at a low rate. The 2019-type rainfall frequency of 5/23 years and the 2022-type frequency of 16/23 years are consistent with the proportion of years that fall into each rainfall category for the 2019–2023 period: 1/5 years were dry and 3/5 years were wet. Assuming that the use of SI in 2001 would have raised the marketable yield to the average 2020 yield (15.5 Mg/ha/year) as shown in Fig. 6, the gross benefit of SI for these two dry years would be $7874/ha, based on the 2018 potato sale price of $254/Mg (AAFC 2022). Assuming that the other four 2019-type years also had a marketable yield increase of 4.4 Mg/ha/year, as observed at AT19 and consistent with previous studies (Belanger et al. 2000; Sexton 2008; Afzaal et al. 2020; Khakbanzan et al. 2023), the gross benefit for the 2019-type five years would be $5588/ha. SI in the remaining 16 years would have resulted in little marketable yield benefit. Summing the gross benefits gives a total of $13462/ha over 23 years, representing a medium-benefit scenario. Considering the two driest years as benefitting from SI and the remaining 21 years as not having any benefit from SI constitutes a low-benefit scenario. Assuming that climate change will result in one more dry year similar to 2020, for a total of 3 dry years, five 2019-type years, and 15 wet years, results in a high-benefit scenario. While total costs vary with irrigation frequency, for simplicity, cost calculations assumed five irrigation applications per year when implemented. This assumption is made because ownership expenses form the predominant portion of the cost, and including or excluding one or two applications does not significantly alter the overall cost. Note that costs only included ownership costs for years without assumed SI occurrence.

The gross benefits for the three benefit scenarios are listed in Table 5. Comparing costs with gross benefits reveals that pivots I and II would gain $68/ha/year and $264/ha/year under the medium-benefit scenario, while the reel sprinkler and boom

Table 5 Comparisons of cost and benefit of supplementary irrigation for potato production

Irrigation system	Total cost for 2000 to 2022 ($/ha)	Total gross benefit for 2000 to 2022 ($/ha)			Annual net benefit ($/ha/year)		
		Low	Medium	High	Low	Medium	High
Pivot I	11907	7874	13462	17399	-175	68	239
Pivot II	7390	7874	13462	17399	21	264	435
Hose reel and sprinkler	16743	7874	13462	17399	-386	-143	28
Hose reel and boom cart	13605	7874	13462	17399	-249	-6	165

All costs and benefits are in (or approximately equal to) 2018 Canadian Dollars cart systems would incur losses of $143/ha/year and $6/ha/year, respectively. Under the low-benefit scenario, three of the four irrigation systems would consistently incur losses while pivot II would gain $21/ha/year. Conversely, all four irrigation systems would become profitable in the long term under the high-benefit scenario.

Discussion

Effects of SI and Fertilizer Rate on Tuber Yield

Potato tuber yield typically reaches the maximum level as water supply (i.e., rainfall + irrigation) approaches the ET_c level (Fig. 1). Using the average ET_c of 353 mm (Belanger et al. 2000; Xing et al. 2008; Sexton et al. 2008; Silver et al. 2011; Parent and Antil 2012; Jiang et al. 2022a) as a reference for optimal water supply, GS rainfall in 2019 (463 mm) exceeded the optimal amount by 31%. However, July rainfall (30 mm) was 78% lower than the average ET_c for July (137 mm) (Fig. 2). The lack of rainfall in July and early August led to an extended drought, adversely affecting rainfed potato yields. The tested russet cultivars typically undergo bulking during these months and are sensitive to moisture deficits (Sexton et al. 2008). This drought partially explains why SI significantly ($p < 0.1$) increased tuber yields for processing potatoes in 2019, aligning with observations from Oregon, USA, and Alberta, Canada, indicating that even brief periods of water stress can considerably reduce tuber yield and quality (Lynch et al. 1995; Shock et al. 1998; King et al. 2020). GS rainfall in 2020 (239 mm) was 32% lower than the average ET_c, representing a significant seasonal deficit. On a monthly basis, rainfall in June (17 mm) was 83% lower than the long-term average of 101 mm (Fig. 2), reducing the amount of moisture that could potentially be carried over into July. Inadequate rainfall continued into July and early August, with July receiving only 32 mm of rainfall, which is 77% below the ET_c. August had 95 mm of rainfall, a 29% deficit compared to the ET_c (134 mm), with 81% of the rainfall occurring after August 24. Below-average GS rainfall, combined with uneven temporal distribution, led to an extended drought period during the tuber initiation and bulking stages. This severe drought explains why SI consistently and significantly increased tuber yields across all sites and cultivars.

GS rainfall in 2021 was 22% higher than the ET_c (Fig. 2). Although June (43 mm) and August (60 mm) rainfall was 45% and 55% lower than the ET_c values, July (132 mm) and September (195 mm) rainfall was close to, and 178% above, the ET_c values, respectively. Because total GS rainfall exceeded the ET_c, deficiencies in rainfall during some periods were likely mitigated by either carried-over soil moisture or subsequent higher rainfall. As a result, rainfed tuber yields were relatively high in 2021. SI had little influence on tuber yield in 2021 because irrigation rates were low and rainfall was relatively high. Reducing fertilizer input by 20% did not significantly affect tuber yield, regardless of irrigation. This is because fertilizing at the Y80N level (e.g., 120 kg N/ha) is adequate for russet-type potatoes in PEI, where potato growth is limited by the relatively short growing season and thus requires relatively low fertilizer input. In addition, pre-planting soil nitrate content was relatively high in many fields (Table 1) and the red clover-dominated forages in the preceding year provided high nitrogen credits (Liang et al. 2019; Azimi et al. 2022; Jiang et al. 2022b). Similar to 2021, GS rainfall in 2022 was 23% higher than the ET_c, with monthly rainfall evenly distributed. The water supply rate was likely situated in the insensitive zone of the water production function for the study fields/cultivars, resulting in a lack of significant yield response to SI in 2022. The 2019 to 2022 tuber yield responses were generally consistent with the potato water production functions reported in literature (Shaykewich et al. 2002; Yuan et al. 2003; Ross 2006; Sexton 2008; Karam et al. 2014; Jiang et al. 2022a).

Although SI resulted in a significant increase in tuber yield in 2019, the magnitude of the increase varied considerably across the three sites (Supplemental Material, Table 1), which may be confounded with other factors. The total water supply at KM19 and AT19 was similar, but the application of 65–80 mm SI at KM19 increased marketable yield by 23 Mg/ha (76–78%), while 103–128 mm of SI at AT19 (approximately 60% higher than at KM19) only increased marketable yield by 3.9–4.1 Mg/ha (11–12%) compared to rainfed production. The visibly sandier soils in the DA section of KM19 may have contributed to the yield response disparity. Differences in cultivars may also have contributed to the varying yield responses. Despite a small difference in irrigation rate (30 mm) and similar soil moisture readings in the FA and Y100N treatments at RG19, the differences in total and marketable yields between the two treatments were substantial, reaching 9.4 and 10 Mg/ha, respectively (Supplemental Material, Table 1). Such a remarkable yield increase resulting from only 30 mm of additional irrigation was not observed for any other sites/cultivars/years. While RG22 and RG19 represented the same site in two different years, the 2022 trial (i.e., RG22 in Supplemental Material, Table 4) did not replicate the high tuber yields observed in the 2019 trial (i.e., RG19), unlike other fields, which had high yields in 2022 due to favorable rainfall. A study conducted at the AAFC Harrington Research Farm in PEI showed that SI using drip irrigation increased the marketable yield of Russet Burbank potatoes from 40.8 Mg/ha with rainfed production to 42.3 Mg/ha with SI when combining yield data from 2017 and 2018, although the increase was not statistically significant (Khakbazan et al. 2023). The GS rainfall in Harrington in 2017 and 2018 was 300 and 362 mm (Jiang et al. 2022a). Afzaal et al. (2020) reported that SI using a sprinkler at a site located in the same area as the present study increased the marketable tuber yield of Russet Burbank potatoes from 35.5 to 38.3 Mg/ha in 2018 and from 30.9 to 34.5 Mg/ha in 2019, although the increase was not statistically significant. The yield increase resulting from SI at AT19 was very similar to the values reported by Belanger et al. (2000), Sexton (2008), Afzaal et al. (2020), and Khakbazan et al. (2023) under comparable rainfall conditions (which were not like the low rainfall levels in 2001 and 2020). This discrepancy suggests that the large yield increases at RG19 and KM19 were not exclusively due to SI. Whether the nitrate leaching events occurring at the end of August (see Irrigation and Moisture section) confounded the yield response remains unclear. Further research is necessary to quantify tuber yield response to SI when extended drought periods coincide with tuber initiation and bulking, particularly when total GS rainfall is adequate and nitrate leaching occurs. The 4.4 Mg/ha marketable yield increase at AT19 was in line with yield data observed in the previous studies. For this reason, yield data from AT19 were used in the cost–benefit analysis, instead of the 2019 cross-site average.

Effects of SI and Fertilizer Rate on Specific Gravity

Specific gravity is influenced by various factors, including cultivar, planting time, seed quality and size, planting density, nutrient and water supply, weeds, disease, insects, and soil type (Hegney 2019). The quantity of water applied and the frequency of application also impact specific gravity. Water stress during the growing season can lead to a reduction in specific gravity (Hegney 2019). Treating field location as replication, analysis of specific gravity data from 2020 to 2022, covering a water supply range of 239 mm to 509 mm for five cultivars, revealed that fluctuations in water supply and fertilizer did not significantly affect specific gravity consistently even though in-field comparisons showed a significant influence in some fields. For example, in 2020, the second driest season between 2000 and 2022, varying water supply from solely rainfed production to as high as 509 mm with SI, and reducing fertilizer input by 20%, did not significantly alter specific gravity in three out of four fields (Supplemental Material, Table 2), but SI with fertilizer reduction (Y80N) led to significantly higher specific gravity at JV20 compared to Y100N, suggesting complex interactions between fertilizer and irrigation. In 2022 reducing fertilizer did not impact specific gravity in any of the fields, but increasing water supply through SI significantly influenced specific gravity in three out of five fields (Supplemental Material, Table 4). A notable trend was observed in 2022 where the increase in water supply from 400–438 mm to 478–488 mm increased the specific gravity of the Mountain Gem Russet at CB22 and HL22 to a level comparable to BC22, where the total water supply was only 393 mm (Supplemental Material, Table 4). This trend contradicts the idea that the specific gravity of potatoes decreases with increasing water supply (Porter et al. 1999; Hegney 2019). Although total water supply was similar in 2021 and 2022, and 2022 had more even and thus more favorable temporal distribution of rainfall, specific gravity in 2022 was more sensitive to irrigation compared to 2021, even though the values in 2021 were not necessarily superior. It is uncertain whether this annual discrepancy in specific gravity was a result of cultivar differences.

Factors Influencing Cost–benefit Analysis

The cost–benefit analysis shows that the profitability of SI varies case by case because it is influenced by many site-specific factors. Where feasible, moving a smaller pivot around to cover two larger fields within a year using a shared water supply system and having a low-cost power source (e.g., pivot II), can significantly reduce costs, making SI profitable. In comparison, although the reel sprinkler was also moved back and forth to serve two 20-ha fields per year, the higher investment in equipment and water supply system, along with high labor and fuel costs, made it unprofitable. Field size also influences costs; if the field size is smaller than 20 ha, the cost of SI increases drastically because most cost items do not proportionally vary with field size (Silver et al. 2011). For instance, if pivot II is used to irrigate only one 20-ha field instead of two in a year, the annual cost would increase to $815/ha, inclusive of $629/ha ownership cost. With this 50% reduction of irrigation service area, the total cost for pivot II under the medium-benefit scenario would increase to $15772, leading to a $100/ha/year loss instead of a $264/ha/year gain in the long term. Adjusting assumptions and financial parameters, such as potato sale price, interest rate, and asset depreciation rate in the cost–benefit analysis can generate additional scenarios, which is beyond the scope of this study. New potato cultivars and irrigation technologies may alter the cost–benefit balance. The value that SI provides by allowing potato farms to financially withstand very dry years, when some might otherwise go bankrupt, was not explicitly factored into the cost–benefit analysis.

The variability of rainfall significantly influences irrigation requirements, yield increases, and associated economic benefits (Fig. 1). Because future rainfall cannot be accurately predicted, a long-term cost–benefit analysis must make an assumption or prediction of rainfall and the associated yield benefits in the absence of long-term data. In this study, it was assumed that the 2000–2022 rainfall is relevant for the 23-year cost–benefit analysis period, following engineering hydrology principles (Eslamian 2014), and the yield benefits were extrapolated from the observed values in this study or/and previous studies. Adjusting this assumption will produce different cost–benefit results. Finally, the use of a long- or short-term approach for the cost–benefit analysis can significantly influence the results. For example, a short-term analysis using 2019 and 2020 data would show that using pivot II and the reel sprinkler would generate average net benefits of $2154/ha/year and $1389/ha/year, respectively, but the same analysis using 2021 and 2022 data would show losses of $373/ha/year and $1138/ha/year, primarily due to the ownership costs. Conversely, a long-term assessment, such as the one presented in this study, demonstrates whether the economic gain of SI in dry years can offset the losses incurred in wet years, and thus better reflects the profitability of SI. The medium-benefit scenario was based on realistic marketable yield increases for the tested russet cultivars as observed in this study and previous studies, along with current irrigation technology. The low- and high-benefit scenarios provide additional perspectives, taking into account the impacts of climate change. Given that current technology cannot accurately predict seasonal rainfall, SI is analogous to an insurance policy for mitigating the impact of climate change on potato production. The cost–benefit information is intended to serve as a reference for growers to determine whether they should invest in SI as an insurance policy.

Limitations and Future Studies

When applying the findings of this study, it is important to consider its limitations. Firstly, the use of empirical soil retention parameters for establishing soil moisture thresholds to initiate irrigation might warrant a reevaluation. Incorporating site-specific retention parameters has the potential to alter the defined soil moisture thresholds. The difficulty of maintaining soil moisture within the specified irrigation thresholds should be addressed, and an exploration of the impact of sustained soil moisture within these thresholds on tuber yield and quality is needed. Secondly, considering the short-term nature of the experiment, further investigation is necessary to quantify the responses of tuber yield and quality to SI, particularly when extended drought periods coincide with tuber initiation and bulking despite adequate total GS rainfall. Third, although the study encompassed six different cultivars, all of which were russet types, cultivar was not considered as an independent variable. Therefore, more research is required to elucidate the impact of SI on different cultivars. Fourth, potato quality parameters, such as scab, hollow heart and specific gravity, were not factored in the cost–benefit analysis. Finally, fertilizer input rate and format varied with field site and thus a 20% reduction in fertilizer does not result in equal fertilizer reduction at each site. This limits a strict comparison of the impact of fertilizer input on tuber yield and quality among field sites.

Conclusions

Supplemental irrigation (SI) resulted in a significant increase in tuber yield in 2019, a season where the total rainfall was adequate but temporally unevenly distributed. During 2020, when GS rainfall was much lower than potato water demand, SI and SI combined with a 20% reduction in fertilizer led to substantial increases in tuber yield. In contrast, SI had minimal impact in seasons with sufficient and evenly distributed rainfall, such as 2021 and 2022. Implementing SI in years with insufficient rainfall (e.g., 2020), or sufficient but unevenly distributed rainfall (e.g., 2019) resulted in tuber yields comparable to rainfed yields in years with sufficient and evenly distributed rainfall, such as 2021 and 2022. Tuber yield increase as a result of SI varied with GS rainfall, and thus, varied year to year. Cross-year comparisons show that SI can effectively reduce yearly fluctuation in tuber yield. The cost–benefit analysis indicates that using SI to reduce yearly variations in tuber yield can be either profitable or unprofitable, depending on the costs associated with irrigation equipment, the water supply system, operational aspects, field scale, and rainfall distribution. With sufficient water supply, reducing fertilizer input by 20% did not significantly alter tuber yields, regardless of the water source. SI, and SI combined with a 20% reduction in fertilizer, did not significantly influence specific gravity regardless of usage of SI. These findings provide important insights for making decisions regarding water and fertilizer management for potato production in humid environments.

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Data Availability Data will be made available on request.

Declarations

Competing Interests The authors declare no competing interests.

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