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Simulating weather effects on potato yield, nitrate leaching, and profit margin in the US Pacific Northwest

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ABSTRACT

The US Pacific Northwest is one of the most productive potato regions in the world. However, due to the high inputs, nitrate contamination of groundwater is frequently documented, and maximizing crop productivity while minimizing nitrate leaching is still challenging. The goal of this study was to assess how irrigation level, soil type, and weather condition during various phenological phases would affect tuber yield and the associated nitrate leaching and profit margin. The Cropping System Model (CSM)-SUBSTOR-Potato was used to simulate the response variables for various scenarios that comprised two soil types, five irrigation levels, five phenological phases, five weather conditions, and 75 years of historical weather data for 3 locations in this region. The simulation results showed that nitrate leaching was higher with a higher amount of irrigation and for a lighter soil. Tuber yield and profit margins were lowest for a lighter soil and highest for 300 mm of irrigation for an extremely-drained soil and 400 mm of irrigation for a well-drained soil. The increase in profit margins with an increase in total irrigation up to 400 mm was highest for a well-drained soil, whereas the decrease in profit margins with an increase in irrigation beyond a total amount of 300 mm was larger for an extremely-drained soil. For the different types of weather scenarios that were studied, only severe hot weather had an impact on tuber yield and profit margins. The reduction was highest at tuber bulking and significant when hot weather continued from sprout development through tuber bulking or from plant establishment through tuber maturation. However, any change in weather condition from the long-term average for any growth phase did not affect leaching. These findings might be helpful to potato growers in this region to protect their potatoes from adverse weather conditions through appropriate mitigation strategies.

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most valuable field crops in the Pacific Northwest region of the USA. The Columbia River Basin is the most productive area for high-quality processing potatoes (Alva et al., 2012) and has the highest potato yield in the world (Washington State Potato Commission, WSPC, 2015). This area has a comparative advantage over other potato growing areas in the United States due to close proximity to foreign markets, economical production inputs, excellent environmental conditions, and good irrigation facilities (Beleiciks, 2005; WSPC, 2007). The Columbia Basin consists of long growing seasons, rich volcanic soils, and a semi-arid climate characterized by long, hot, dry days and cool nights (WSPC, 2007). Due to these ideal growing conditions potato production in this area can be conducted at a large scale in rotation with other high-yielding crops such as maize, vegetables, and wheat.

The major inputs to potato production in the Columbia Basin are nitrogen (N) and water. Potato growers in this region use high rates of these inputs (Peralta and Stöckle, 2001) since the cost associated with them relative to the expected income from the crop is small (Hodges, 1999). The high rates of N and water are expected to transport nitrate below the root zone and eventually contaminate groundwater. The groundwater in this region contains a high concentration of nitrate (Cook et al., 1996; WSDE, 2011).

Nitrate leaching is influenced by various crop, environmental, and management factors such as growth phase, irrigation, soil type, and weather condition (Alva et al., 2012; Cambouris et al., 2008; Jiang et al., 2011). Potato management practices must reflect differences among climatic conditions, soil properties, and water management, among other things (Zebarth and Rosen, 2007). It is important to optimally manage N and water for maintaining high yield levels and profits, while minimizing nitrate pollution of the groundwater (Alva,

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2004a; Zebarth and Rosen, 2007). The excess or deficiency of water or N can have harmful effects on the environment, profit, and tuber yield (Goffart et al., 2011). Public concern about the sustainability of agro-ecosystems and environmental quality is increasing, thus emphasizing the need for developing management strategies that can improve N and water use efficiencies and minimize losses (Badr et al., 2012). Because the roots of potato plants are comparatively sparse and shallow (Jabro et al., 2012; Shock et al., 2007), the retention capacity of a soil for water and soluble nutrients plays an important role in nitrate leaching in this crop. Because soils differ in retention capacity, nitrate leaching is expected to be different for different soil types (Alva, 2004a; Cambouris et al., 2008). Fertilization and irrigation guidelines are supposed to be location-specific because the amounts of fertilizer and water to be applied may be defined by soil type and weather, both of which vary significantly across space.

Potato production is greatly affected by weather conditions. An unpredictable environment can have profound effects on both tuber yield and quality (Pavek et al., 2015). For the optimal occurrence of each phenological phase, especially sprout development, tuber initiation, and tuber growth, optimum daytime and nighttime temperatures are required (Dwelle et al., 1981; FAO, 2015; Kooman and Haverkort, 1995; Wheeler et al., 1986). Weather conditions at planting impact the length of the growing season through the influence on emergence. For instance, continued cool temperatures may prolong the rest period and thus delay sprout development. Cool nights during tuber bulking, on the other hand, may promote tuber growth (Montoya et al., 2016). Any interruption of ideal weather conditions may result in reduced tuber growth rates and losses in yield and quality (Dean, 1994). Any condition that limits healthy foliage growth, disrupts tuber growth, or shifts dry matter partitioning from the tubers to the foliage decreases yield potential. Temperature is one of the key factors that affect tuber bulking and shift the balance between vine and tuber growth (Dwelle and Love, 2003). Temperature and precipitation are the key meteorological factors that control nitrate leaching (Wick et al., 2012). Temperature influences a number of processes that are involved in nitrate leaching (Hill, 1991) and is the dominating factor for the variability of the nitrate concentration in leachate (Liang et al., 2011). Weather conditions affect the potential for N loss by influencing various processes such as nitrification, denitrification, and volatilization. Nitrate leaching may occur once N is converted into nitrate, a water-soluble product, through the nitrification process. Weather also impacts water uptake and the soil water balance. Because the relative importance of plant available soil moisture varies across plant growth phases (Shock et al., 1993; Wright and Stark 1990), the effects of weather conditions on potato production and associated nitrate leaching are, therefore, affected by the phenological phase of the potato plant.

The challenge of developing best management practices that maximize crop productivity while minimizing harmful environmental impacts still exists in spite of the considerable progress that has been made in improving the understanding of N and water management effects on tuber yield, quality, and N losses (Shrestha et al., 2010; Zebarth and Rosen, 2007). Determining the correct application rates for fertilizer and irrigation is still challenging despite decades of research (Peralta and Stöckle, 2001; Shrestha et al., 2010) as shown by the reports of nitrate contamination of groundwater. Potato tuber yield and the associated nitrate leaching have been assessed in various studies that have evaluated different irrigation and N fertilization regimes. For instance, Alva et al. (2012) evaluated the scenarios comprising two irrigation (I) and two N levels and found that a 20% reduction in full irrigation and 50% reduction in the recommended N application reduced tuber yield considerably. With the evaluation of the interaction of six irrigation and four nitrogen scenarios, King et al. (2011) found significant interactions between irrigation and N rates for tuber yield, water use efficiency, and gross return. Peralta and Stöckle (2001) concluded that reducing fertilization rates would be the only effective approach to reducing nitrate leaching. Arora et al. (2013) discovered that the effect of irrigation on tuber yield, water use, and N uptake was greater when N was sufficient. Montoya et al. (2016), after studying 5I scenarios, came up with the finding that the most efficient use of water would be associated with the irrigations meeting 60–80% of crop water demand. Various researchers, including Errebhi et al. (1998), Jégo et al. (2008), Jiang et al. (2011), Verhagen (1997), and Woli et al. (2016), found that nitrate leaching would be greater with a larger irrigation amount, a longer irrigation interval, a higher N application rate, and a lighter soil, and that the increase in leaching with an increase in irrigation water would be smaller for a longer irrigation interval and a lighter soil but larger for a higher N rate.

So far ample studies have been conducted on the interaction of irrigation and N fertilizer application rates. However, studies that include the effect of soil type and weather conditions are limited. Especially information regarding the impact of different weather conditions during the main phenological phases on potato productivity, nitrate leaching, and economic returns are rare. Literature is lacking on the interactions among crop phenological phase, irrigation amount, soil type, and weather condition on tuber yield, nitrate leaching, and profit margins. An improved understanding of the interactions among management and environmental factors could help adopt better management practices. Production practices involving fertilization and irrigation must be sound from both economic and environmental perspectives, reflecting differences among soil properties and weather conditions (Shock et al., 2007) and balanced from both agronomic and economic perspectives (Hopkins et al., 2015). Although Columbia Basin is the highest potato yielder in the world, agro-economic-environmental studies on potato production for this region are very limited. This study was conducted to assess how changes in irrigation amount, soil type, and weather condition at various phenological phases of potato would affect tuber yield and the associated nitrate leaching and profit margins.

2. Materials and methods

This study was conducted using a systems analysis and modeling approach, which is valuable method for analyzing the response of agricultural systems under different climatic, geographical, and management conditions (Tsuji et al., 1998; Wallach et al., 2014). Potato tuber yields and the associated nitrate leaching were simulated for various irrigation, soil, and weather scenarios using a widely tested and used potato model (Arora et al., 2013; Prasad et al., 2015; Stastna et al., 2010) called Simulation of Underground Bulking Storage Organs (SUBSTOR: Griffin et al., 1993; Singh et al., 1998).

2.1. The SUBSTOR-Potato model

The SUBSTOR-Potato model belongs to Decision Support System for Agrotechnology Transfer (DSSAT: Hoogenboom et al., 2015; Jones et al., 2003), a suite of computer programs that facilitate the application of a family of crop models. Using weather data, soil properties, genotype parameters, and crop management information as inputs, SUBSTOR-Potato simulates the daily dynamics of water, nitrogen, biomass, phenology, and tuber yield accumulation, among other things. The models of soil water and soil N dynamics used in the SUBSTOR-Potato are capacity type. The potato model assumes five phenological stages (pre-planting – sprout elongation – emergence – tuber initiation – maturity); has five genotypic parameters that control plant growth and development processes such as leaf area expansion, tuber initiation, potential tuber growth rate, and tuber growth cessation; and uses various relative temperature functions (with values ranging from 0 to 1 for each cardinal temperature – base, optimum, and maximum) for simulating the temperature effects on leaf, root, and tuber growth, photosynthesis, and tuber initiation. Potato growth and development are simulated based on the accumulation and partitioning of biomass in relation to intercepted radiation, photoperiodicity, and temperature. Tuber growth is controlled by the potential tuber growth rate and soil water and N balances. Soil water balance comprises precipitation/irrigation infiltration, deep drainage, unsaturated flow, soil evaporation, and plant transpiration processes. Plant transpiration is defined by the potential evapotranspiration, plant root distribution, and the plant available water in the soil, computed as the difference between field capacity and wilting point values. Soil nitrogen balance consists of various N processes such as mineralization, immobilization, nitrification, denitrification, ammonification, and plant N uptake, which in turn is defined by crop demand and soil supply. For details, the reader is referred to Griffin et al. (1993) and Singh et al. (1998).

2.2. Sites and scenarios

Three locations, including Hermiston, Oregon (45.83°N,119.26°W), Richland, Washington (46.31°N, 119.26°W), and Quincy, Washington (47.22°N, 119.85°W), were selected for the study because of the geographical distribution, the availability of long-term historical weather data, and major potato growing areas in the Columbia Basin. Then, the effects of irrigation amount, soil type, and weather on tuber yield, nitrate leaching, and profit margin were assessed using five amounts of irrigation, two types of soil, and five types of weather. The effect of each weather type was examined with 12 different growth phases. The five levels of irrigation were a seasonal amount of 200, 300, 400, 500, and 600 mm. A given amount of irrigation was applied during the growing season following an assumed crop canopy coverage curve (Fig. 1; King and Stark, 2014). For instance, if **x** mm of irrigation were to be applied, irrigation would be given once in every three days in such a way that the amount given per irrigation would follow the crop demand (represented by the canopy coverage curve) and that the total seasonal amount would equal **x**. Nitrogen was applied at the rate of 336 kg ha^{-1}, the recommended rate for this area (Lauer, 1985; Roberts et al., 1991; Woli et al., 2016). To minimize losses and improve uptake efficiency, one-third of it was applied at planting and the rest as in-season (Alva, 2004a, 2004b; Errebhi et al., 1998) in six equal parts. The first in-season part was applied 10 days after tuber initiation, which was assumed to occur at 50 days after planting (DAP) (Zebarth and Rosen, 2007), and the other applications were conducted at 10-day intervals.

Soil properties play a major role in soil water dynamics. The property values control various flows in the soil water balance, such as surface runoff, infiltration, deep drainage, water retention, capillary rise, etc. In the Columbia basin, most of the soils used in potato growing are fine sand or sandy loam. Thus, based on the distribution of local soil types in the basin and the suitability for growing potatoes (Hipple, 2011), two soils were considered (as representative soils for the region): Taunton sandy loam (mixed, mesic Xeric Haplodurid) and Quincy fine sand (mixed, mesic Xeric Torriorthent). These soils were distinct in terms of water retention capacity: Taunton sandy loam was moderately-drained, whereas Quincy fine sand was extremely-drained. The relevant properties of the two soils are presented in Table 1. Because including additional soils, basically similar to the above, might not provide new information about the soil effects, no additional soils were considered. Additionally, one of the basic objectives of this study was to compare different locations in the region in terms of climate difference. In order to avoid any confounding effects of local soils on climate comparison, therefore, no location-specific soils were considered.

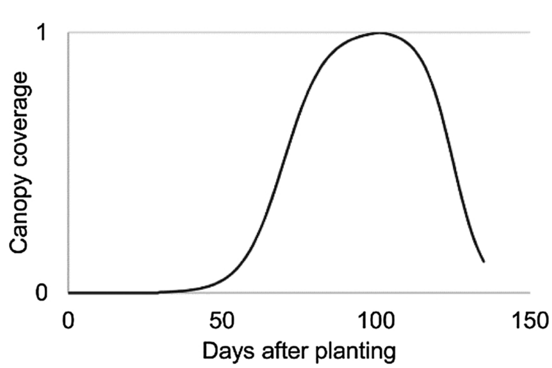

Fig. 1. Potato crop canopy coverage during the growing season (0 = no coverage; 1 = full coverage).

A potato plant has five growth phases (Zebarth and Rosen, 2007): I, sprout development (1–30 DAP); II, plant establishment (31–50 DAP); III, tuber initiation (51–70 DAP); IV, tuber bulking (71–120 DAP); and V, tuber maturation (121–150 DAP). The 12 growth phases considered in this study comprised these five growth phases plus seven different combinations thereof: I, II, III, IV, V, I–II, I–III, I–IV, I–V, II–V, III–V, and IV–V. The five types of weather considered were severe cold, mild cold, average, mild hot, and severe hot as explained in the following paragraph. The effects of the above factors were studied with 75 years of historical weather data (1941–2015).

The potato growing season in each year was divided into five periods, one for each growth phase, using the growth phase windows stated above. Then, average temperature was computed for each period in each year. From the 75 temperature values of each period, the 5th, 23rd, 27th, 48th, 52nd, 73rd, 77th, and 95th percentiles were computed. The years belonging to < 5th, 23rd–27th, 48th–52nd, 73rd–77th, and > 95th percentiles of temperature values were then defined as severe cold, mild cold, average, mild hot, and severe hot years, respectively. Thus, the probability of occurrence of each of these weather scenarios that was considered was 0.05. Such classification was carried out for each growth phase. For each growth phase-year type (referred to hereafter as weather type) combination, the weather data during a given growth phase were pulled from the years belonging to the weather type. For each weather type, these pulled periodical or partial seasonal weather type-specific weather data from all growth phases were then combined to form the full seasonal weather data, which finally were used in model simulations.

2.3. Model simulations

The model simulations were carried out for Russet Burbank, a very popular potato cultivar in this region (Collinge et al., 2010). The SUBSTOR-Potato model was already calibrated and evaluated for Russet Burbank in this region by Woli et al. (2016). Their results showed that the model performance was quite satisfactory. In the current study, therefore, no further evaluation was conducted. The potato model was used to simulate tuber yield and nitrate-N leaching for a number of scenarios comprising 12 growth phases, 5 irrigation amounts, 2 soil types, and 5 weather classes. April 1 and September 1 were considered the planting and harvesting dates, respectively (http://www.potatoes.com/our-industry/how-we-grow/). Row spacing and seed rate were specified as 86 cm and 45,600 plants ha^{-1}, respectively (Alva, 2004a, 2004b). Planting depth was considered to be 20 cm (Pavek and Thornton, 2009), and emergence was assumed to occur at 30 days after planting. At the start of simulation, the initial soil water content was set to field capacity, and the residual N was assumed to be 15 kg ha^{-1}. The other growing conditions were assumed to be standard, and no stresses other than those of N and water were assumed. The soil profile data used in simulations were obtained from the National Cooperative Soil Survey Soil Characterization Database (http://ncsslabdatamart.sc.egov.usda.gov/). The daily weather data comprising minimum and maximum temperatures and precipitation for the 1941–2015 period were obtained from the National Centers for Environmental Information (http://www.ncdc.noaa.gov/cdo-web/datatools/findstation). As the weather data did not include solar radiation, another weather variable of the model, daily values of this variable for the above years were estimated using Weather Generator for Solar Radiation (WGENR), initially developed by Hodges et al. (1985) and later refined by Garcia y Garcia and Hoogenboom (2005). The WGENR is being used as a basic tool to generate solar radiation for crop modeling purposes in the US.

Table 1
The properties of two representative soils located in the Columbia basin of the US Northwest.

Soil	Layer (cm)	Master horizon	Soil properties WP[†] (−)	FC (−)	SA (−)	WH (−)	HC ($cm\,h^{-1}$)	Clay (%)	Silt (%)	TN (%)	OC (%)
Quincy fine sand (drainage coefficient = 0.85; run-off curve number = 61):											
	0–15	A	0.03	0.09	0.35	0.06	21.0	2.8	3.8	0.02	0.17
	15–35	AC	0.03	0.08	0.33	0.05	21.0	2.9	4.9	0.02	0.11
	35–61	C1	0.03	0.06	0.32	0.03	21.0	2.5	4.2	–	0.10
	61–102	C2	0.03	0.06	0.31	0.03	21.0	1.6	4.1	–	0.07
	102–157	C3	0.04	0.08	0.39	0.04	21.0	1.6	4.1	–	0.08
	Weighted avg.		*0.03*	*0.07*	*0.35*	*0.04*	*21.0*	*2.0*	*4.2*	*0.02*	*0.09*
Taunton sandy loam (drainage coefficient = 0.60; run-off curve number = 73):											
	0–10	A	0.06	0.16	0.41	0.10	6.1	2.4	15.9	0.12	1.21
	10–23	Bw1	0.05	0.15	0.39	0.10	2.6	5.2	24.5	0.07	0.63
	23–38	Bw2	0.05	0.15	0.35	0.10	6.1	4.6	17.1	–	0.32
	38–71	Bk	0.07	0.21	0.37	0.14	2.6	4.1	35.3	–	0.42
	71–87	Bkqm	0.05	0.21	0.37	0.16	0.7	4.2	52.8	–	0.18
	Weighted avg.		*0.06*	*0.18*	*0.37*	*0.13*	*3.3*	*4.2*	*31.5*	*0.09*	*0.48*

[†] WP = permanent wilting point, FC = field capacity, SA = saturation, WH = water holding capacity, HC = saturated hydraulic conductivity, TN = total soil N, OC = soil organic carbon.

2.4. Profit margin computation

The economic aspects of potato production and nitrate leaching were assessed based on profit margin, the difference between gross profit and the application costs associated with irrigation and N fertilizer:

$$D = TP_T - (C_I + LP_L + NP_N)$$

where, D is profit margin (US$ ha^{-1}), T is tuber yield ($kg\,ha^{-1}$), P_T is the farm gate price of potatoes (US$ kg^{-1}), C_I is the cost of irrigation, L is the amount of NO_3-N leached ($kg\,ha^{-1}$), P_L is the cost of leaching per kg of NO_3-N, N is the amount of N fertilizer applied ($kg\,ha^{-1}$), and P_N is the farm gate price of N fertilizer (US$ kg^{-1}). In this study, P_T was assumed to be US$ 0.2 kg^{-1} potatoes (Washivore, 2014; WSPC, 2014), C_I to be US$ 0.06 m^{-3} (personal communication with potato growers in the Basin), P_L to be US$ 30 kg^{-1} NO_3-N (Collins and Gillies, 2014), and P_N to be US$ 1.5 kg^{-1} N fertilizer (USDA-ERS, 2013).

The costs of the other inputs and management, such as harvesting, planting, plant protection, seed, tillage, and other fertilizers, were not included in the computation of profit margin. These costs were assumed to be constant for all scenarios because the main idea of this study was to assess the effects of irrigation and N fertilization only.

2.5. Significance testing

Statistical significance tests were performed to examine if the values of a response variable across the levels of a factor were different from each other, using the pairwise Wilcoxon rank sum test (Wilcoxon, 1945), a nonparametric alternative to the two-sample *t*-test, with Bonferroni as the p-value adjustment method (Bonferroni, 1936). The Wilcoxon test was used because the assumption of normality was not met for each test for the analysis of variance test. The statistical analyses were performed using R-project (www.r-project.org/).

3. Results and discussion

3.1. Irrigation and soil effects on leaching

Nitrate leaching increased almost exponentially with an increase in the amount of irrigation water (Table 2). This increase was expected because more amount of water present in the soil caused more drainage and thus more losses of N. This result was in agreement with the findings of several previous researchers, such as Giletto and Echeverria (2013), Han et al. (1995), Jégo et al. (2008), and Poch-Massegú et al. (2014), that the amount of nitrate leached was directly associated with the amount of water irrigated.

Nitrate leaching was greater in the Quincy soil than in the Taunton soil (Table 2). The higher leaching in the Quincy soil was because it was much sandier and lighter than the Taunton soil and extremely-drained (Hipple, 2011). Lighter soils have higher potential for nitrate leaching, especially in a shallow-rooted crop such as potato, because of their lower retention capacity for water and soluble nutrients (Alva, 2004a; Hodges, 1999; Prasad et al., 2015; Shrestha et al., 2010).

The leaching difference between the two soils increased with an increase in the amount of irrigation water (Fig. 2). The rate of nitrate leaching with respect to irrigation water was higher for the Quincy soil. This difference was likely because the Quincy soil, having very low water holding capacity, drained more quantity of water and its solutes than did the Taunton soil, and a larger quantity of water thus drained removed more amount of N it contained.

3.2. Irrigation and soil effects on yield

Tuber yield increased with an increase in the amount of irrigation water until it peaked at 400 mm and declined thereafter (Table 2). These results indicated that 400 mm is the optimum amount of irrigation for potatoes in this area. Woli et al. (2016), who examined the effects of irrigation amount with five levels, 400–800 mm, also came up with the same finding. Although the optimum amount may seem unlikely to compare with the potential evapotranspiration (ET_O) of 800 mm in this area, the amounts of nitrate leached were significantly larger for the irrigation amounts larger than 400 mm (Fig. 2). The decrease in yield because of the decrease in soil N due to leaching was so large that even the larger amounts of irrigation were not able to compensate for the yield losses caused by N leaching.

Compared with the Taunton soil, the Quincy soil was associated with smaller yields (Table 2). The smaller yield was because of the availability of less quantity of N for plant uptake due to more nitrate leaching. The smaller yield was also likely due to the availability of less water in a lighter soil. Potato plants have low tolerance to soil water stress because they have relatively sparse and shallow root systems (Jabro et al., 2012; Shock et al., 2007). Arora et al. (2013) also observed that yield and water productivity would be less on a lighter soil for comparable irrigation and N regime.

The yield difference between the two soils increased with an increase in irrigation amount (Fig. 2). The increase in yield with an

Table 2
Responses of nitrate leaching, tuber yield (dry matter), and profit margin to irrigation amount and soil type at three locations − Quincy (Q), WA; Richland (R), WA; and Hermiston (H), OR.

Factor	Level	NO_3 leached (kg ha^{-1})			Tuber yield (Mg/ha)			Profit margin ($K/ha)		
		Q	R	H	Q	R	H	Q	R	H
Ir. amount (mm)	200	0^{e}	0^{e}	0^{e}	7^{e}	6^{d}	8^{d}	6^{d}	5^{c}	7^{b}
	300	2^{d}	1^{d}	3^{d}	10^{d}	8^{c}	11^{c}	9^{b}	8^{b}	10^{a}
	400	29^{c}	26^{c}	48^{c}	13^{a}	11^{a}	13^{a}	11^{a}	10^{a}	10^{a}
	500	104^{b}	91^{b}	116^{b}	12^{b}	11^{a}	12^{b}	8^{c}	8^{b}	7^{b}
	600	151^{a}	142^{a}	156^{a}	11^{c}	10^{b}	11^{c}	6^{d}	5^{c}	5^{c}
Soil type	Quincy	71^{a}	77^{a}	85^{a}	8^{b}	8^{b}	9^{b}	5^{b}	5^{b}	6^{b}
	Taunton	33^{b}	37^{b}	44^{b}	11^{a}	12^{a}	13^{a}	9^{a}	10^{a}	11^{a}

[*]Means followed by the same letter across a factor in each location-response variable combination are not significantly different at α = 0.05.

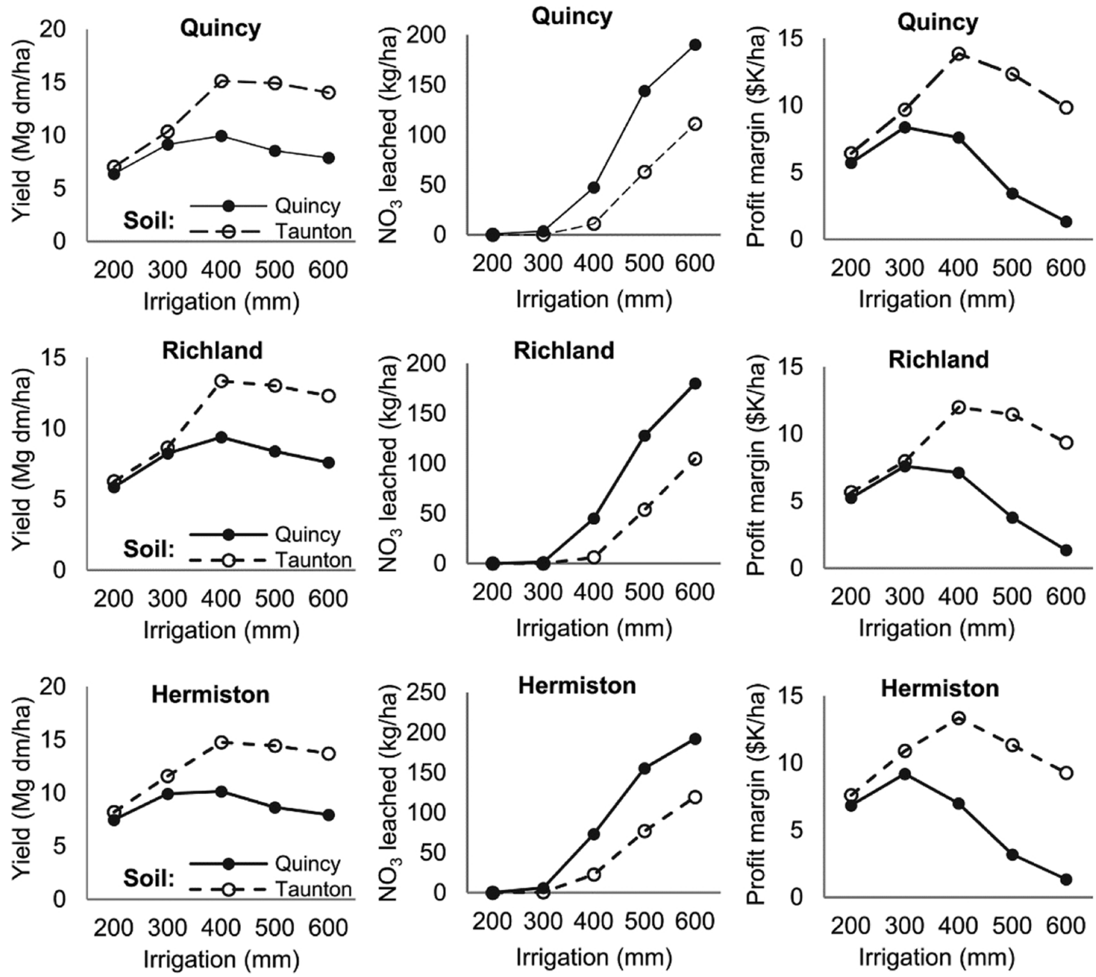

Fig. 2. Responses of tuber yield, nitrate leaching, and profit margin to irrigation amount for two soils – Quincy and Taunton – at three locations in the Columbia Basin: Quincy, Richland, and Hermiston.

increase in irrigation amount up to 400 mm was larger in the Taunton soil, whereas the decrease in yield with an increase in irrigation amount beyond 400 mm was larger in the Quincy soil. The larger yield increase in the Taunton soil was because the amount of nitrate leached up to the irrigation amount of 400 mm was very small, so N uptake was higher. Because the water holding capacity of this soil was higher, its water use efficiency was also higher. The larger yield decrease in the Quincy soil was because the amount of nitrate leached beyond the irrigation amount of 400 mm was very large, so N uptake was lower. The water use efficiency of this soil was also lower because its water retention capacity was far lower than that of the Taunton soil.

3.3. Irrigation and soil effects on profit

The profit margin increased with an increase in irrigation water up to 300 mm for the Quincy soil or 400 mm for the Taunton soil and declined thereafter (Table 2). Thus, the irrigation water of 300 mm and 400 mm were indicated as the optimum amount for the Quincy and Taunton soils in this region, respectively, in terms of maximizing profit margin. The largest profit margin with 300 mm of irrigation for the Quincy soil was because nitrate leaching was negligible, whereas tuber yields were close to the maximum (Fig. 2). On the other hand, the largest profit margin with 400 mm of irrigation for the Taunton soil was because of very low nitrate leaching but the highest tuber yields. With

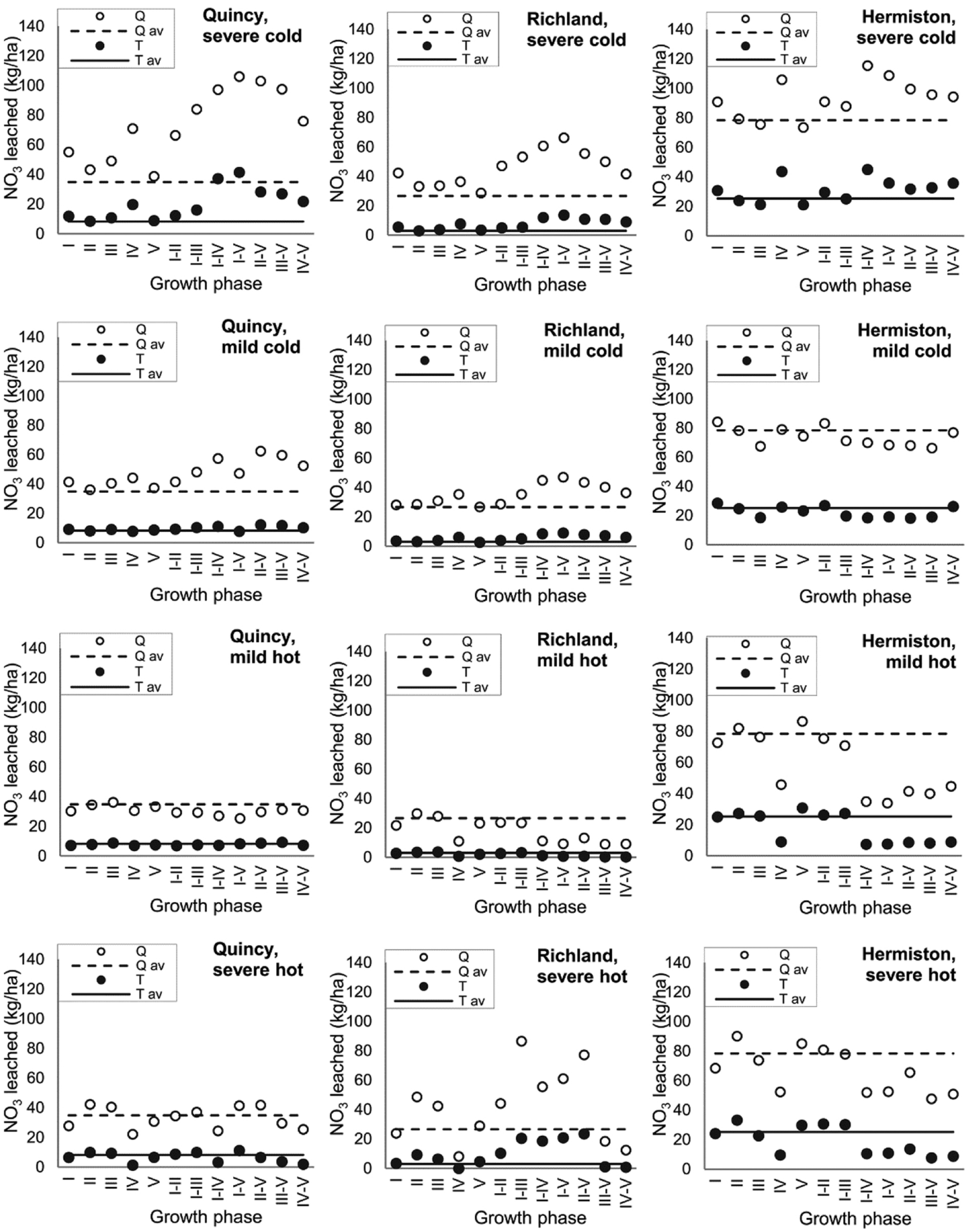

Fig. 3. Response of nitrate leaching to various weather conditions – severe cold, mild cold, mild hot, and severe hot – at various growth phases for two soils – Quincy (Q) and Taunton (T) – at Quincy, Richland, and Hermiston.
Note: The dotted (…) and solid (–) lines represent the N leached under average weather conditions for Quincy (Qav) and Taunton (Tav) soils, respectively.

irrigation water of greater than or equal to 400 mm, the Taunton soil produced more yields than did the Quincy soil compared with the irrigation water of less than 400 mm, which was because leaching in the latter was much greater than that in the former when the irrigation amount was greater than 300 mm. With an increase in irrigation beyond 300 or 400 mm, therefore, leaching increased significantly thus decreasing profit margin.

The profit margin was higher with the Taunton soil than with the Quincy soil (Table 2). This difference was expected because the Taunton soil, having higher water holding capacity, was associated with lower nitrate leaching and higher tuber yields. While lower leaching led to smaller leaching costs, higher yield led to larger gross

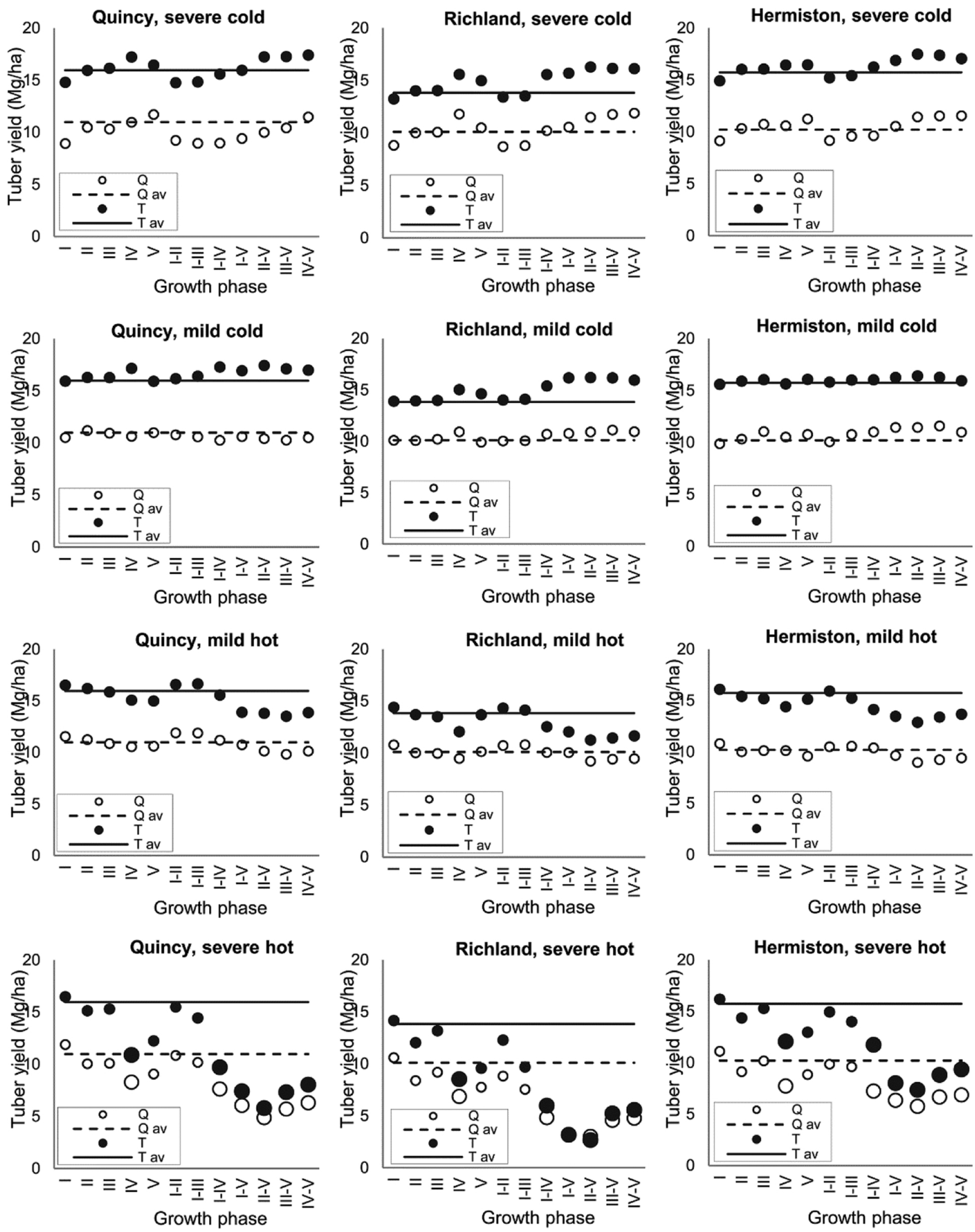

Fig. 4. Response of tuber yield to various weather conditions – severe cold, mild cold, mild hot, and severe hot – at various growth phases for two soils – Quincy (Q) and Taunton (T) – at Quincy, Richland, and Hermiston.

Note: The dotted (…) and solid (–) lines represent yields under average weather conditions for Quincy (Qav) and Taunton (Tav) soils, respectively. The growth phases with larger markers for a given soil indicate that tuber yields under given weather conditions at these phases were significantly different (at α = 0.05) from the ones under average weather conditions.

revenues.

The profit margin difference between the two soils increased with an increase in irrigation amount (Fig. 2). The increase in profit margin with an increase in irrigation amount up to 400 mm was larger in the Taunton soil, whereas the decrease in profit margin with an increase in irrigation amount beyond 400 mm was larger in the Quincy soil. The larger profit margin increase in the Taunton soil was because of the corresponding lower leaching and larger yields. The larger profit margin decrease in the Quincy soil was because of the corresponding higher leaching and smaller yields.

Table 3
Average periodical temperatures (°C) during various potato growth phases under five weather conditions at three locations in the Columbia Basin of the US Pacific Northwest.

Location	Weather	Growth phase*				
		Phase I	Phase II	Phase III	Phase IV	Phase V
Quincy, WA	Severe cold	8	11	14	19	19
	Mild cold	9	13	16	20	21
	Average	10	14	17	21	22
	Mild hot	11	16	18	22	23
	Severe hot	13	18	20	25	26
Richland, WA	Severe cold	9	12	15	20	21
	Mild cold	11	15	17	22	22
	Average	12	16	18	23	24
	Mild hot	13	17	20	23	24
	Severe hot	14	19	22	26	27
Hermiston, OR	Severe cold	9	12	15	19	20
	Mild cold	10	14	16	21	22
	Average	11	15	17	22	23
	Mild hot	12	16	19	23	24
	Severe hot	14	18	21	25	26

* I = sprout dev., II = plant establishment, III = tuberization, IV = tuber bulking, V = tuber maturation.

3.4. Weather effects on leaching

Depending on growth phase and location, the periodical (growth phase duration) average temperature (PAT) of the severe cold weather was 2.2–3.8 °C below the long-term average weather temperature (LAT), the PAT of the mild cold weather was 0.6–1.4 °C below the LAT, the PAT of the mild hot weather was 0.5–1.6 °C above the LAT, and the PAT of the severe hot weather was 2.2–5.4 °C above the LAT. Any change in weather from the long-term average – severe cold, mild cold, mild hot, or severe hot – at any potato phase – sprout development, plant establishment, tuber initiation, tuber bulking, or tuber maturation – did not affect nitrate leaching significantly in any soil or location in the Columbia Basin (Fig. 3). The amount of nitrate leached for a given soil and location under all weather conditions at all plant growth phases were about the same.

These results, however, did not conform to the findings of several other researchers who observed that nitrate leaching would be impacted by temperature. Jabloun et al. (2015) found that N leaching would increase with an increase in temperature due to an increase in mineralization. Similarly, Liang et al. (2011) observed that increasing temperature could increase the rate of soil nitrification and thus the concentration of nitrate in the leachate. Wick et al. (2012), on the other hand, noticed that higher temperature would result in lower nitrate concentration of groundwater possibly due to an increase in evapotranspiration. Schweigert et al. (2004) also observed that high temperatures, often correlating with dryness, would slow the process of mineralization, eventually reducing nitrate leaching. Hill (1991) concluded that an increase in temperature would slow down the rate of leaching by increasing the rate of evapotranspiration and, in the presence of crop cover, by accelerating the rates of N uptake and crop growth, whereas, in the absence of crop cover, would increase the rate of leaching by increasing the rate of nitrification. Turner and Henry (2010) found that increase in nitrate leaching would generally occur when plant roots were largely inactive or plants were not fully established. The disagreement of our results with those of the above researchers could be due to the following reasons. First, the temperature differences between the long-term average weather and the mild cold or mild hot weathers were not significant (0.5–1.6 °C). Second, the soils used in our study had very low organic matter content, so the expected enhanced rate of mineralization through organic matter decomposition was negligible. Third, irrigations of smaller amounts were given frequently (once every three days), so low nitrate leaching and more accumulated soil N due to high evaporation was expected. Fourth, N fertilizer was applied on small, split doses (every 10 days), so the rates of nitrification were possibly low.

3.5. Weather effects on yield

Among the five weather types, only severe hot weather was significantly influential on tuber yield (Fig. 4). For all soils and locations, the influence of this weather was greatest during tuber bulking (phase IV) and the least during the sprout development (phase I) and tuber initiation (phase III) phases. Among the five growth phases, phase IV was associated with the largest yield reduction, whereas phase I did not have any yield reductions. When severe hot weather conditions continued from phase I through phase IV, from phase I through phase V, from phase II through phase V, from phase III through phase V, or from phase IV through phase V, the decrease in tuber yield was significant. For other periods, such as phase I through phase II or phase I through phase III, tuber yield under severe hot conditions was about the same as those under average weather conditions. Of the 12 growth phases studied (five basic plus seven combined), the II–V phase was the most vulnerable to severe hot weather conditions. The same results were found for both soils. That is, the weather type-growth phase interaction effect was not significantly influenced by soil type. The other weather conditions – severe cold, mild cold, and mild hot – during any single or combined growth phase did not significantly influence tuber yield for any soil or location.

The results that nitrate leaching was not impacted by weather type-growth phase interactions showed that the tuber yield responses observed above were not due to the leaching of nitrate from the root zone but to the influence of temperature on plant physiology. Both mild cold and mild hot weather conditions at each of the five growth phases had about the same temperatures as had the long-term average weather (Table 3). Thus, tuber yield under mild cold and mil hot weather conditions was not different from the ones under the average weather conditions. At growth phase I, sprout development, the temperatures under both severe cold weather and severe hot weather were greater than 5 °C, the minimum temperature needed for tuber sprouting, but were less than 18 °C, the upper limit of the optimum range for sprout growth (McGee et al., 1986). These weather types during phase I, therefore, did not have tuber yields significantly smaller than those under the long-term average weather. During phase II, plant establishment, the temperatures under severe cold weather and severe hot weather each were in between 10 °C and 28 °C, the broad optimum range for photosynthesis (Dean, 1994). Above and below this range, the rates of net photosynthesis decrease rapidly. Because the temperatures under these weather conditions at this growth phase did not fall outside of this range, there were no significant yield reductions under these weather conditions. Accordingly, the tuber yields under these weather types did not differ from the ones under the average weather. During phase III, tuberization, the temperatures under severe cold (14–15 °C) and severe hot (20–21 °C) weather conditions were close to 15–20 °C, the optimum range for tuber formation (Rykaczewska, 2013), as were the temperatures of the average weather conditions (17 °C). Thus, there were no significant yield reductions due to these weather conditions at this growth phase. Accordingly, tuber yield under these weathers was not different from the ones under the average weather. During phase IV, tuber bulking, the severe cold weather had temperatures within 15–22 °C, the optimum range for tuber bulking (Dean, 1994). Thus, tuber yield under this weather condition was not significantly lower than the yield for the average weather temperature range of 19–23 °C. Under severe hot weather conditions during growth phase IV, however, temperatures were higher (25–26 °C) than the optimum range. Thus, there were significant yield losses due to severe hot weather conditions at this phase. Accordingly, the tuber yield differences between severe hot and average weather conditions were significant. During growth phase V, tuber maturation, the severe cold weather had temperatures

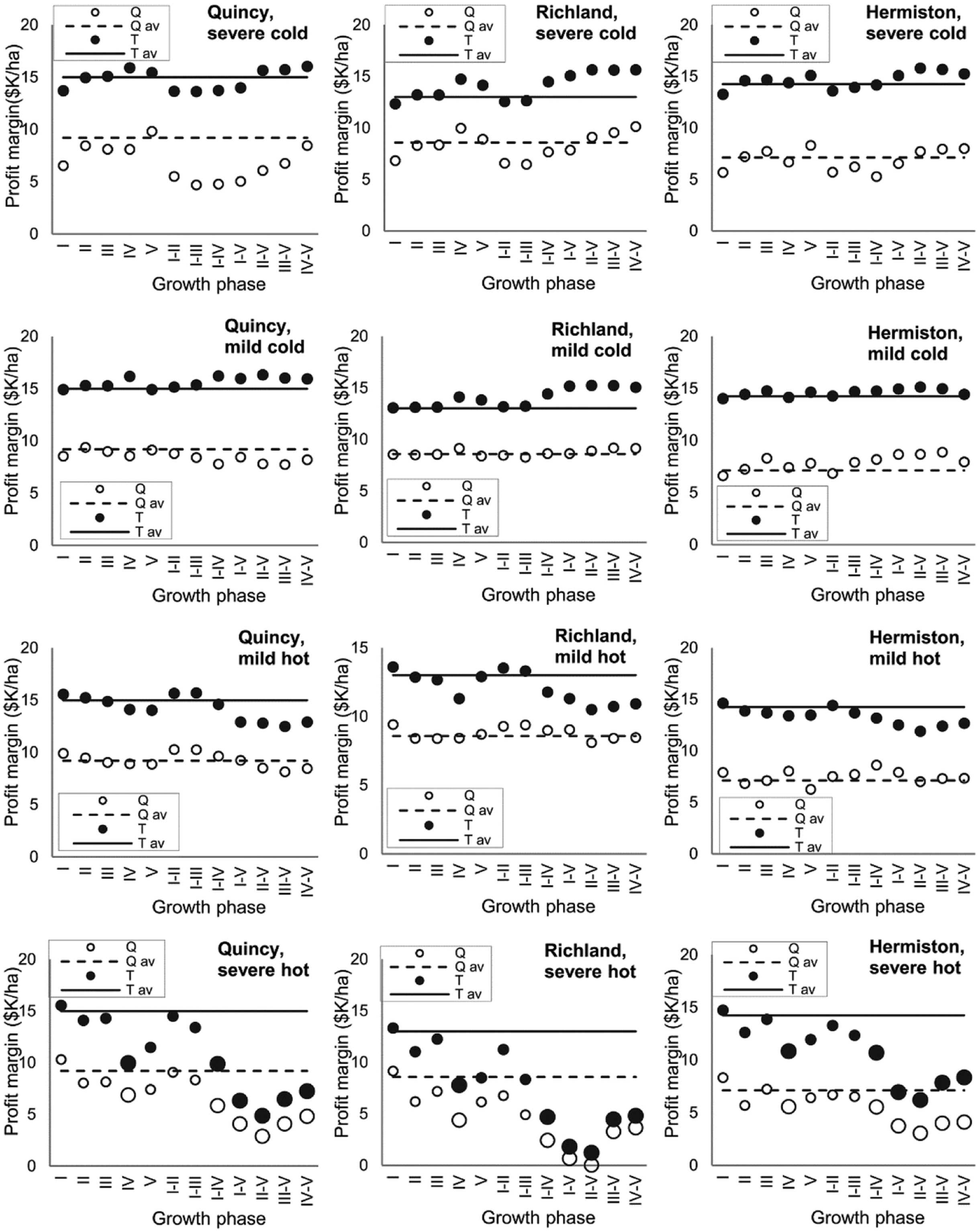

Fig. 5. Response of profit margin to various weather conditions – severe cold, mild cold, mild hot, and severe hot – at various growth phases for two soils – Quincy (Q) and Taunton (T) – at Quincy, Richland, and Hermiston.
Note: The dotted (…) and solid (–) lines represent profit margin under average weather conditions for Quincy (Qav) and Taunton (Tav) soils, respectively. The growth phases with larger markers for a given soil indicate that profit margins under given weather conditions at these phases were significantly different (at α = 0.05) from the ones under average weather conditions.

within the optimum range for tuber bulking, whereas the temperatures were higher than the optimum range under severe hot weather. During tuber maturation, however, temperature is not an important factor in terms of tuber yield although it is a critical factor for tuber quality. Thus, tuber yield under severe hot weather was not significantly different from the ones under the average weather.

3.6. Weather effects on profit

The effects of weather conditions on profit margins were similar to those on tuber yield (Fig. 5). That is, only severe hot weather was influential on profit margins. The profit margin reduction of the five basic growth phases studied was greatest during phase IV, and the greatest profit margin decrease of the seven combined phases was when all growth phases from the second through the fifth were exposed to severe hot weather. The severe hot weather conditions during phase I did not actually reduce profit margins. When severe hot weather continued from the first phase through the fourth or fifth phase; or from the second, third, or fourth phase through the fifth phase; the decrease in profit margin was significant. These responses were mainly due to the effects of weather type-growth phase interaction on tuber yield. A change in yield led to a similar change in gross revenue and thus in profit margin. As on tuber yield, the interaction effects of weather type and growth phase on profit margin were not significant under severe cold, mild cold, or mild hot weather conditions, which were because the corresponding interaction effects on tuber yield were not significant under these weather conditions.

To sum up, nitrate leaching was higher with a larger irrigation and on a lighter soil. The increase in leaching with an increase in irrigation water was higher for a lighter soil. Tuber yields were smaller with a lighter soil and increased with an increase in irrigation water until they peaked at 400 mm and declined thereafter. The increase in yield with an increase in irrigation water of up to 400 mm was larger on a well-drained soil, whereas the decrease in yield with an increase in irrigation water beyond 400 mm was larger on an extremely-drained soil. Profit margin was smaller on a lighter soil and increased with an increase in irrigation water of up to 300 mm for an extremely-drained soil or up to 400 mm for a well-drained soil and declined thereafter, indicating these amounts as the optimum irrigation amounts for these soils in this region in terms of maximizing profit margins. The increase in profit margin with an increase in irrigation up to the optimum amount was larger on a well-drained soil, whereas the decrease in profit margin with an increase in irrigation beyond the optimum amount was larger on an extremely-drained soil. Any change in weather from the long-term average during any potato growth phase was not found to affect leaching for any soil or location. To tuber yield and profit margin, only severe hot weather was influential. The reductions in tuber yield and profit margin due to severe hot weather were highest during tuber bulking (TB) but lowest during sprout development (SD) and tuber initiation (TI). Tuber yield and profit margin reductions were significant when severe hot weather continued from SD through TB or tuber maturation (TM); or from plant establishment (PE), TI, or TB through TM. Of the various growth periods studied, the PE-TM period was the most vulnerable to severe hot weather in terms of reducing both tuber yield and profit margins.

Managing water optimally taking into consideration crop phenological phase, soil type, and weather condition is crucial to improve water uptake efficiency and maximize yield and profits. The findings of this study can be helpful to the people involved in potato production in this region in identifying the growth phase-, location-, soil-, and weather-specific rates of irrigation aimed at maintaining high tuber yields and profits while minimizing the nitrate contamination of groundwater. The findings, however, are based on the study where the factors and variables considered represent only simplified conditions. For simplicity, other crop management variables, such as plant protection and tillage, were assumed to be in standard conditions and fixed. In reality, these conditions might vary over space and time. Furthermore, the finding that any change in weather from the long-term average at any potato growth phase did not affect leaching is based on a specific set of growing conditions: insignificant temperature differences between long-term average weather and mild cold/hot weathers; very low organic matter containing soils; frequent, smaller irrigations; and small, split doses of N fertilizers. The results could be very different if the growing conditions were different from the ones considered. For instance, if temperature differences were large or if irrigations were infrequent and large or if N fertilizer doses were large and undivided, a change in weather from the long-term average could impact leaching at one or more phenological phase. Due to the unavailability of sufficient data, this study considered just one cultivar and a few locations and soils. It also considered potato crops as continuous for the same reason although potatoes in this region are grown in rotations with other crops such as maize or wheat. Based on the availability of necessary data, which is increasing over time, some potential future studies may involve various cropping systems and additional cultivars and soils. Another consideration for a future study may be conducting a spatial analysis of potato production in this region from an agro-economic-environmental perspective.

4. Conclusions

The findings of this study indicated that potato growers in the Columbia basin might obtain highest profit margins with the irrigation of 300 mm on an extremely-drained soil and 400 mm on a moderately-drained soil. It may be less profitable and environment-friendly to apply larger amounts than these, especially on a soil with low water holding capacity. The potato growers need to be cautious while irrigating an extremely-drained soil that profit margin may decrease substantially if irrigation is given beyond the optimum amount. They are further cautioned that although the results showed no effect of weather change at any growth phase on leaching, the results do not apply to heavy, infrequent irrigations; heavy, undivided N fertilizations; and large temperature anomalies. They also need to be aware that tuber bulking is the most susceptible phase to severe hot weather and that tuber yield and profit margin are hit hardest if this weather continues from the vegetative establishment phase through the tuber maturation phase. Although it is not possible to control weather, it is possible to mitigate its effects through the adoption of appropriate strategies such as crop canopy maintenance, cultivar selection, fertilization, and irrigation. For instance, the potential impact of severe hot weather at tuber bulking, the most vulnerable phase, could be skipped by shifting the time of planting (preponing or postponing). A drier/hotter year in this region may be anticipated from the El Niño-Southern Oscillation (ENSO) phenomenon. If a certain year is forecast to be an El Niño year, this year is generally drier and hotter in the US Pacific Northwest. Another way for reducing the impact of severe hot weather could be using a heat-tolerant cultivar. The application of light, frequent irrigations might also be an effective mitigation measure for minimizing the impact of severe hot weather. Using one or more of such strategies or measures, potato growers in this region might protect their potatoes from severe hot weather.

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