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Simulation of potato yield, nitrate leaching, and profit margins as influenced by irrigation and nitrogen management in different soils and production regions

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ABSTRACT

The Columbia Basin in the Pacific Northwest is a highly productive area for potatoes in the United States. Here, nitrate is the most frequently documented groundwater contaminant, and the challenge of maximizing crop productivity while minimizing the nitrate pollution still remains. This study assessed the responses of tuber yield, nitrate leaching, and profit margin to irrigation water amount, irrigation interval, nitrogen application rate, and soil type using 30 years of historical weather data and two representative soils in three locations of this region. A potato model was used to simulate the response variables for a total of 7500 scenarios (5 irrigation intervals × 5 irrigation amounts × 5 nitrogen rates × 2 soil types × 30 years) for each location. The results showed that nitrate leaching was greater with a larger irrigation—, a longer irrigation interval, a higher nitrogen rate, and a lighter soil. Tuber yield was larger with a smaller irrigation, a higher nitrogen rate, and a heavier soil. Profit margin was larger with a smaller irrigation and a heavier soil. The optimum amount of irrigation water for the study region was 400 mm, at which both tuber yields and profit margins were the largest with the nitrogen application rate of 336 kg ha^{-1}. The increase in leaching with a larger irrigation was smaller for a longer irrigation interval and a lighter soil but larger for a higher nitrogen rate. These findings might be helpful to potato growers in this region in identifying irrigation and nitrogen application rates aimed toward maximizing yields and profits while minimizing the nitrate contamination of groundwater.

1. Introduction

Potato (*Solanum tuberosum* L.) is an important crop in the Pacific Northwest region of the United States. The state of Washington ranks first and second in the United States in terms of yield per unit area and total potato production, respectively, and has comparative advantage over other potato growing areas in the United States due to the excellent environmental conditions, economical inputs, and close proximity to foreign markets (Beleiciks, 2005; WSPC, 2007). The Columbia Basin in eastern Washington is a highly productive area for high-quality processing potatoes (Alva et al., 2012) and has the highest potato yield across the globe (WSPC, 2015), predominantly under irrigation due to low precipitation. This region comprises rich volcanic soil, a long growing season, and a semi-arid climate characterized by long, hot, dry days followed by cool nights (WSPC, 2007). These ideal growing conditions allow for large-scale production of potatoes in this region in rotation with other high yielding crops such as maize, wheat, and vegetables.

Water and nitrogen (N) comprise the largest inputs to potato production in this region. Because the cost of these inputs relative to the potential income from the crop is small (Hodges, 1999), farmers use high rates of these inputs (Peralta and Sotckle, 2001) which can transport below the root zone and pollute groundwater. Groundwater in this region has high nitrate-N (Cook et al., 1996; WSDE, 2011).

The magnitude of nitrate leaching is influenced by soil type and several crop management factors such as irrigation and N fertilization (Alva et al., 2012; Cambouris et al., 2008). Optimal management of water and N is important to maintain high yields and profits while minimizing the N losses into the environment (Alva, 2004a; Zebarth and Rosen, 2007). Both excess and deficiency of these factors can have detrimental effects on yields, profits, and the environment (Goffart et al., 2011). Increasing public concerns about environmental quality and the sustainability of agro-ecosystems

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have emphasized the need to develop management strategies that can improve N and water use efficiencies and minimize leaching losses (Badr et al., 2012). Potato plants have relatively sparse and shallow root systems (Jabro et al., 2012; Shock et al., 2007), so the water retention capacity of a soil plays a key role in nitrate leaching. Because different soils have different water retention capacities, nitrate leaching is expected to vary by soil type (Alva, 2004a; Cambouris et al., 2008). The amounts of irrigation water and fertilizer to be applied to a crop may be defined by the type of soil and the potential for leaching, so irrigation and fertilization guidelines need to be site specific due to local variability in soil and weather.

Although considerable progress is made in improving our understanding of the effects of N and water management on tuber yield, quality, and N losses, the challenge regarding developing best management practices to maximize crop productivity and minimize environmental impacts still remains (Shrestha et al., 2010; Zebarth and Rosen, 2007). In spite of the reports of nitrate contamination of groundwater and decades of research, selecting the appropriate rates of irrigation and N fertilization still remains a challenging task (Peralta and Stöckle, 2001; Shrestha et al., 2010). Various studies have examined potato yield and N leaching under different irrigation and N fertilization regimes. For instance, Alva et al. (2012) evaluated four scenarios comprising two N and two irrigation (I) levels and found that a 20% reduction in irrigation from the full irrigation that would meet crop water requirement could reduce tuber yield by 28% and that a reduction in N rate from 224 to 112 kg ha^{-1} could reduce the yield significantly. King et al. (2011) evaluated 24 scenarios of 6I × 4N and observed significant interactions between irrigation and N rates for tuber yield, water use efficiency, and gross returns. Peralta and Stöckle (2001) evaluated nine scenarios of 3I × 3N and came up with the finding that the only effective approach to reducing N leaching was reducing fertilization rates. Arora et al. (2013) studied the 3I × 4N scenarios in north India and found that tuber yield, water use, and N uptake were significantly influenced by irrigation and N rates and that the irrigation influence was greater in the presence of Errebhi et al. (1998) investigated the early-season N management effects on yield and N leaching in Minnesota, USA using four N rate scenarios and observed that the amount of nitrate leached increased linearly with an increase in N applied at planting. Jégo et al. (2008) studied the irrigation rate effect on leaching in north Spain with five rates and observed that excessive irrigation could cause significant nitrate leaching. Jiang et al. (2011) studied the leaching response to N rate with five rates and found that increased N input increased leaching. Montoya et al. (2016) after studying five irrigation scenarios found that irrigations meeting 60–80% of crop water requirement had the most efficient water use. Verhagen (1997) studied seven irrigation scenarios and found that larger yields and higher leaching losses were associated with higher rates of fertilization. Although the effects of various combinations of N and irrigation levels on yield or leaching have been examined by many studies, the studies involving the influences of soil type and irrigation frequency are few. Information regarding the comparison of various irrigation frequencies in terms of their impacts on crop water use and productivity is limited (Jabro et al., 2012). No study so far has assessed the effects of irrigation interval and soil type on tuber yield, nitrate leaching, and profit in this region. Literature is lacking on the effects of interactions among irrigation water amount, irrigation interval, N fertilization rate, and soil type on tuber yield, nitrate leaching, and profits. A greater understanding of the interactions among crop management and environmental factors may provide better answers to the old question of 'how much N and irrigation do I apply for my crop'. Production practices involving water and N management not only need to reflect differences among weather conditions, cropping systems, and soil properties but also must be sound from both economic and environmental perspectives in order to help growers realize cost effective crop performance and protect resources (Shock et al., 2007). A truly sustainable cropping system must be balanced from both agronomic and economic viewpoints (Hopkins et al., 2015). Agro-economic-environmental studies on potato production in this region are very limited although it is the highest yielding area in the world.

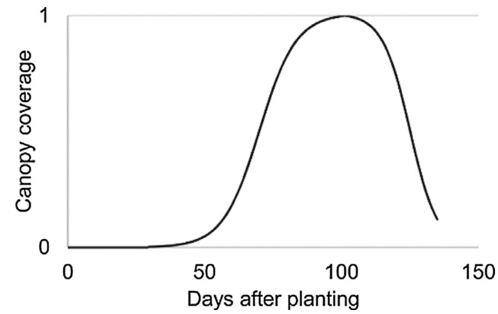

Fig. 1. Potato crop canopy coverage during the growing season (0 = no coverage; 1 = full coverage). Adapted from King and Stark (2014).

This study was carried out to examine how changes in irrigation water amount, irrigation interval, nitrogen application rate, and soil type would affect potato tuber yield, nitrate leaching, and profit margin in the Columbia Basin of United States Pacific Northwest.

2. Materials and methods

This is a modeling study. Simulation modeling is a valuable technique to analyze the behavior of agricultural systems under a wide range of climatic, geographical, and management conditions (Tsuji et al., 1998; Wallach et al., 2014). Potato yields and the associated nitrate leaching were simulated under various scenarios of irrigation, N rate, and soil using the potato model *Simulation of Underground Bulking Storage Organs* (SUBSTOR: IBSNAT, 1993; Singh et al., 1998), which is coupled 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 crop models. The SUBSTOR-Potato model simulates the effects of environment, genotype, management, and soil on potato growth and development and N and water dynamics. Crop growth and development are simulated based on the accumulation and partitioning of biomass in relation to intercepted radiation, photoperiodicity, and temperature. The model has been widely tested and used for predicting tuber yields, yield-N-water relationships, and climate change impacts on potato production (Arora et al., 2013; Prasad et al., 2015; Stastna et al., 2010).

2.1. Sites and scenarios

Based on major potato growing area in the Columbia Basin and the availability of long-term historical weather data, three locations in the basin – Hermiston (45.83°N,119.26°W) in Oregon State and Richland (46.31°N, 119.26°W) and Quincy (47.22°N, 119.85°W) in Washington State – were chosen. Then, the responses of tuber yield, N leaching, and profit margin to irrigation water amount, irrigation interval, N rate, and soil type were examined using five levels of the first three factors and two levels of soil type. The five levels of irrigation interval were 1–5, with 1 meaning irrigation given every day, 2 meaning irrigation given once in every two days, and so on. The five levels of irrigation water amount (seasonal) were 400, 500, 600, 700, and 800 mm. With a given interval, a given amount of irrigation water was applied over the crop season following an assumed crop water demand curve (Fig. 1; King and Stark, 2014). For instance, if **x** mm of irrigation were to be applied with a **y**-day frequency, irri-

Table 1
Values of the measures used to evaluate the performance of the SUBSTOR-Potato model.

Process	Year	Tuber yield			Total biomass		
		RMSE[a]	PE	d-Stat	RMSE	PE	d-Stat
Calibration	1992	573	9	0.99	704	9	0.99
	1993	1419	14	0.99	1493	13	0.99
Evaluation	1994	828	9	0.99	716	6	0.99
	1995	1885	20	0.96	1945	19	0.97

[a] RMSE = root mean squared error, PE = percent error, and d-Stat = the Willmott index.

gation would be given every **y** day(s) in such a way that the amount given per irrigation would follow the demand curve, and the total seasonal amount would equal **x**. The five N rates ($kg\,ha^{-1}$) considered were 0.5R, 0.75R, R, 1.25R, and 1.5R, where R = 336 $kg\,ha^{-1}$ is the recommended N rate for this area (Lauer, 1985; Roberts et al., 1991). To improve uptake efficiency and minimize losses, one-third of the N rate was applied at planting and the remaining as in-season (Alva, 2004a, 2004b; Errebhi et al., 1998) in six equal, split rates. The first in-season rate was applied after 10 days of tuber initiation, which was assumed to occur at 50 days after planting (Zebarth and Rosen, 2007), and the remaining rates were applied at 10 days intervals. Based on suitability to growing potatoes and the proportion of availability in the basin (Hipple, 2011), two soils were considered: (i) Quincy fine sand (mixed, mesic Xeric Torriorthent, an excessively drained soil) and (ii) Taunton sandy loam (mixed, mesic Xeric Haplodurid, a well-drained soil). The effects of the above factors were studied with 30 years of historical weather data, the climate normal period of 1981–2010.

2.2. Model simulations

The SUBSTOR-Potato model has five cultivar coefficients which need to be estimated for every cultivar: G2, leaf area expansion rate after tuber initiation ($cm^2\,m^{-2}\,d^{-1}$); G3, potential tuber growth rate ($g\,m^{-2}\,d^{-1}$); PD, index suppressing tuber growth during the period immediately following tuber induction; P2, tuber initiation sensitivity to long photoperiods; and TC, upper critical temperature for tuber initiation (°C). Values for these coefficients were estimated for Russet Burbank, one of the most popular potato cultivar in this region (Collinge et al., 2010), following the procedures of Boote (1999). All the necessary experimental, management, soil profile, and weather data needed for model calibration and evaluation were obtained from Tom Hodges (unpublished) through Alva et al. (2002a, 2002b). Of the four years' data they had (1992–1995), the 1992–1993 data were used for model calibration and the 1994–1995 data were used for model evaluation. The performance of the model was evaluated using the percent error (PE), the root mean square error (RMSE), and the Willmott index (d-Stat; Willmott, 1981). Values of these measures showed that the potato model performed well in simulating tuber yield as well as total biomass for this cultivar (Table 1). The closer the d-Stat is to 1 and the smaller the RMSE value is, the better the model is. A satisfactory model has $10 \le PE \le 20$ and d-Stat > 0.86, whereas a good model has $PE \le 10$ and d-Stat > 0.94 (Stöckle et al., 1998; Timsina and Humphreys, 2006). The time series values of the estimated tuber yields as well as total biomass were also in good agreement with the observed ones (Fig. 2). The cultivar coefficient values estimated for the Russet Burbank cultivar were as follows: G2 = 1800 $cm^2\,m^{-2}\,d^{-1}$, G3 = 41 $g\,m^{-2}\,d^{-1}$, PD = 0.1, P2 = 0.0, and TC = 19° C. These values were reasonable because Russet Burbank is a high-yielding, indeterminate cultivar with a high leaf area expansion rate after tuber initiation.

The SUBTOR-Potato was then used to simulate tuber yields and nitrate-N leaching for a total of 7500 scenarios for each location (5 irrigation intervals × 5 irrigation water amounts × 5N rates × 2 soil types × 30 years). For simulations, April 1 and September 1 were considered the planting and harvesting dates, respectively (http://www.potatoes.com/our-industry/how-we-grow/). Seed rate and row spacing were specified as 45,600 plants ha^{-1} and 86 cm, 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 residual N was assumed to be 15 $kg\,ha^{-1}$, and the initial soil water content was set to field capacity. The other conditions were assumed to be standard; 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 1981–2010 period were obtained from the National Centers for Environmental Information (http://www.ncdc.noaa.gov/cdo-web/datatools/findstation). The weather data did not include solar radiation, another important weather variable of the model, so the daily values of this variable for the above years were estimated using Weather Generator for Solar Radiation (WGENR), a weather generator developed by Hodges et al. (1985) and later refined by Garcia y Garcia and Hoogenboom (2005). The WGENR is being used as a principal tool to generate solar radiation for crop modeling purposes in the United States.

2.3. Profit margin computation

The economic aspects of potato cultivation and N leaching were studied—based on *profit margin*, calculated as gross profit minus the costs associated with irrigation and N applications:

$$M = YP_Y - (C_I + LP_L + NP_N)$$

where, M is profit margin (US$ ha^{-1}), Y is tuber yield ($kg\,ha^{-1}$), P_Y 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_Y 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).

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

2.4. Significance testing

Significance tests were conducted 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, which is based on the order in which the observations from the two samples fall, was used because the assumption of normality was not met for each test for the classic analysis of variance test. The statistical analyses were performed using R-project (www.r-project.org/).

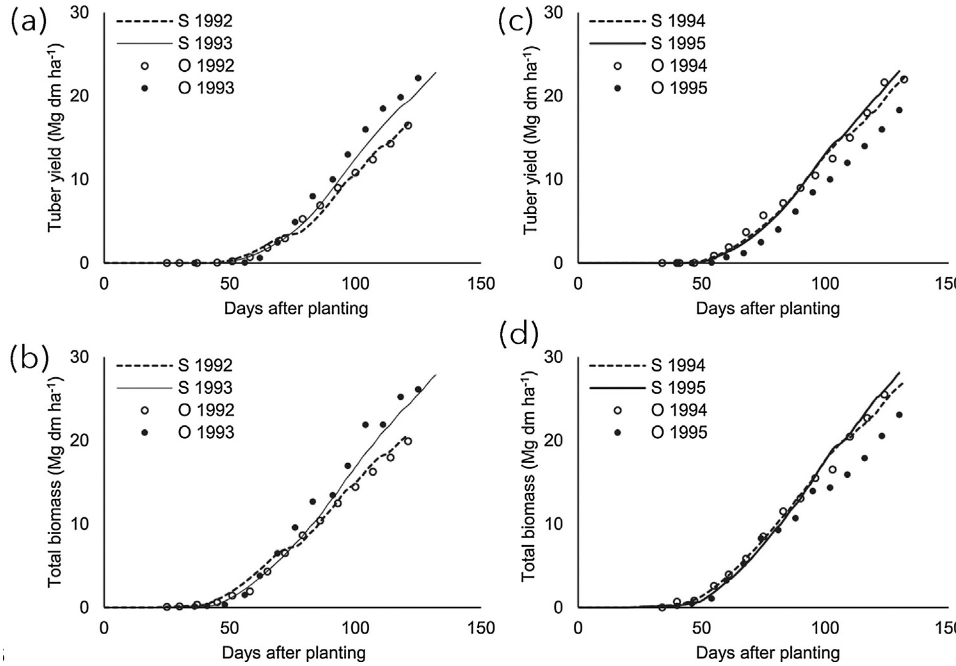

Fig. 2. A comparison between simulated (S) and observed (O) values of: (a) tuber yield and (b) total biomass related to model calibration and (c) tuber yield and (d) total biomass related to model evaluation for the cultivar Russet Burbank.

3. Results and discussion

3.1. Irrigation water amount effects on nitrate leaching

In general, nitrate leaching was more with a larger amount of irrigation water (Table 2). This greater leaching was likely because more amount of water in the soil drained more amount of nitrate dissolved in it. Several previous researchers, such as Giletto and Echeverria (2013), Han et al. (1995), and Poch-Massegú et al. (2014), also found that the amount of nitrate leached was directly proportional to the amount of water irrigated.

The increase in leaching with an increase in irrigation water was smaller with a longer irrigation interval (Fig. 3(a)). With this interval, a larger amount of water per irrigation was applied because the total seasonal amount of water given was the same for all irrigation intervals. Because the amount of water given per irrigation with a longer interval was larger than with a shorter interval, the water given with a smaller irrigation was able to remove most of the nitrate that could be removed through a larger irrigation. Thus, a smaller amount on nitrate was available for leaching for a larger irrigation.

The increase in leaching with an increase in irrigation water was larger with a higher N rate (Fig. 3(b)). The larger increase with a higher N rate was because of the availability of a larger amount of water to drain a larger quantity of N applied into the soil. Shock et al. (2013) found that the higher rates of N fertilizer, combined with heavier irrigations, would allow mobile compounds like nitrate to be readily lost to deep percolation. Arora et al. (2013) also demonstrated that an excessive application of N under excess irrigation would lead it to leaching beyond root zone. Li et al. (2006) observed that an inadequate use of N fertilizers would be associated with low N recovery, high residual N, and high risk of nitrate loss to the environment.

The increase in leaching with an increase in irrigation water beyond 500 mm was smaller in the Quincy soil than in the Taunton soil (Fig. 3(c)). This difference was likely because the former is an extremely-drained soil, whereas the latter is a well-drained soil. Thus, proportionately less amount of N was available in the Quincy soil to be drained by a larger amount of water because a smaller irrigation in this soil was able to remove most of the N that could be removed by a larger irrigation. In the Taunton soil, however, the quantity of N available was larger than that in the Quincy soil due to its higher water holding capacity.

3.2. Irrigation water amount effects on tuber yield

Generally, tuber yield decreased with an increase in the amount of irrigation water (Table 2). Because the highest yield was obtained with 400 mm of water, this amount was indicated as the optimum amount of irrigation water for potatoes in this area. To compare this amount with the potential evapotranspiration (ET_O) of about 800 mm in this area, this optimum amount might seem unrealistic. But, for the amounts of irrigation water larger than 400 mm, the amounts of nitrate leached were significantly larger (Table 2). The yield reductions caused by the decreases in soil N were so large that even the amounts of irrigation water closer to the ET_O were not able to compensate the leaching-induced losses.

The decrease in yield with an increase in irrigation water was smaller with a higher N rate (Fig. 3(e)). The smaller decrease with a higher N rate was likely because the amount of nitrate leached through an increased amount of irrigation water was compensated by a higher rate of N. For the optimum irrigation scenario of 400 mm, however, tuber yield did not increase beyond the N rate of 336 kg ha^{-1}, indicating this rate as the optimum N rate for potatoes in this region. The yield increase with an increase in N rate even beyond 336 kg ha^{-1} for the other irrigation scenarios was because they had little N in the soil due to excessive leaching (Fig. 3(b)), so the larger amounts of N applied contributed to yield increase.

The decrease in yield with an increase in irrigation water beyond 500 mm was larger in the Taunton soil (Fig. 3(f)). The larger decrease in yield in this soil was mainly caused by the larger increase in leaching with an increase in irrigation water.

The decrease in yield with an increase in irrigation water, however, was not influenced by irrigation interval (Fig. 3(d)). Although the leaching response to the amount of irrigation water was influenced by irrigation interval, the differences in the amounts of

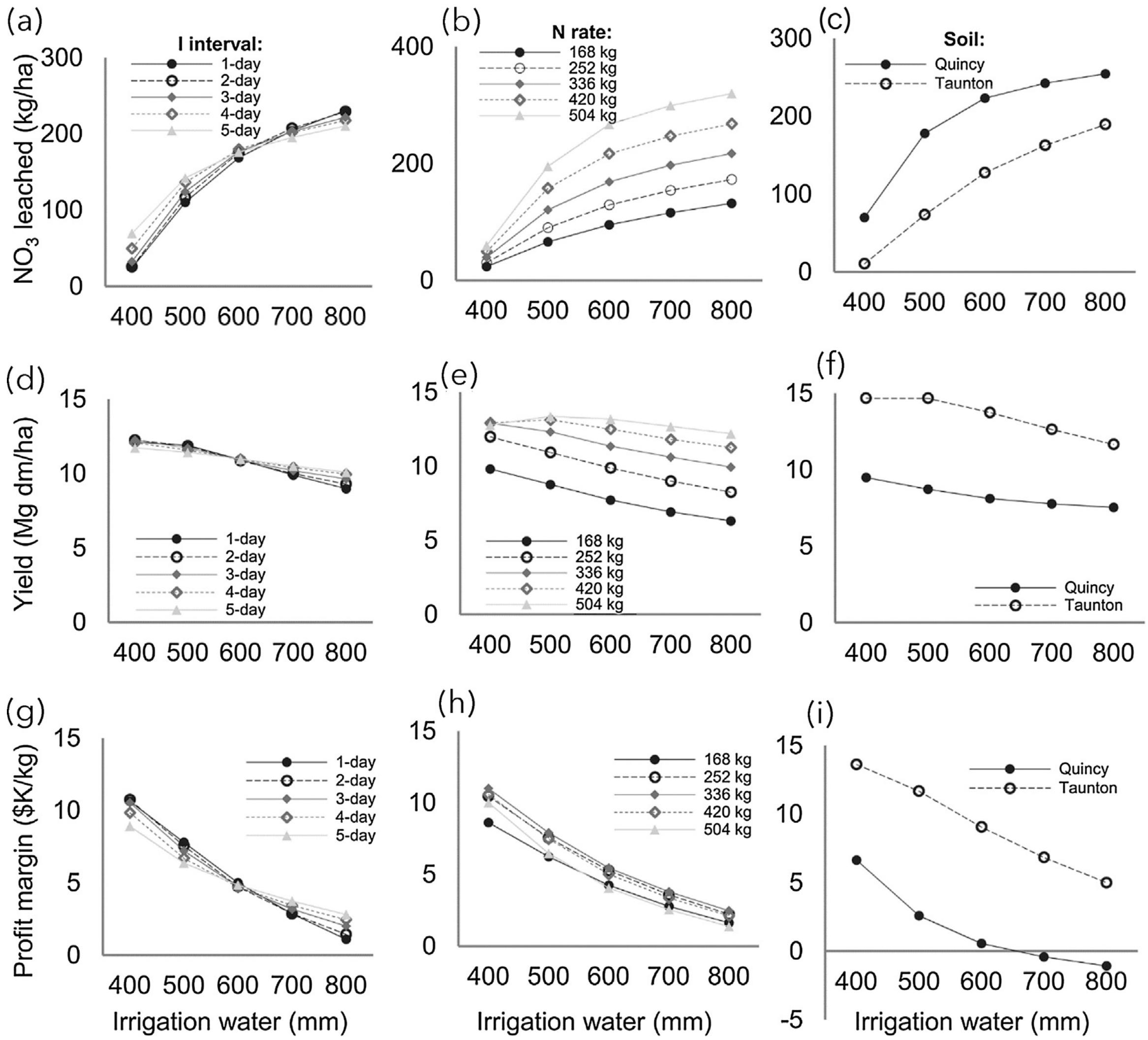

Fig. 3. Responses of nitrate leaching, tuber yield, and profit margin to irrigation water amount as influenced by irrigation (I) interval, nitrogen (N) rate, and soil type at Quincy, Washington.

Table 2
Responses of nitrate leaching, tuber yield, and profit margin to irrigation water (IW) amount, irrigation (I) interval, N rate, and soil type at three locations in the Columbia Basin – Hermiston (H), Richland (R), and Quincy (Q).

		NO_3 leached (kg/ha)			Tuber yield (Mg dm/ha)			Profit margin ($K/ha)		
Factor	Level	H	R	Q	H	R	Q	H	R	Q
IW amount (mm)	400	48^{e*}	37^{e}	40^{e}	11.8^{a}	12.1^{a}	12.0^{a}	9.6^{a}	9.9^{a}	9.9^{a}
	500	131^{d}	119^{d}	126^{d}	11.4^{b}	11.6^{b}	11.7^{b}	6.7^{b}	7.3^{b}	7.1^{b}
	600	179^{c}	168^{c}	175^{c}	10.7^{c}	11.0^{c}	10.9^{c}	4.5^{c}	5.1^{c}	4.8^{c}
	700	205^{b}	195^{b}	203^{b}	10.0^{d}	10.3^{d}	10.2^{d}	2.9^{d}	3.6^{d}	3.2^{d}
	800	225^{a}	215^{a}	222^{a}	9.4^{e}	9.7^{e}	9.6^{e}	1.7^{e}	2.3^{e}	2.0^{e}
I interval (day)	1	150^{b}	142^{b}	148^{b}	10.5^{a}	10.7^{a}	10.7^{a}	5.1^{a}	5.6^{a}	5.5^{a}
	2	150^{b}	142^{b}	148^{b}	10.6^{a}	10.8^{a}	10.9^{a}	5.1^{a}	5.6^{a}	5.5^{a}
	3	156^{ab}	146^{ab}	152^{ab}	10.7^{a}	10.9^{a}	10.9^{a}	5.2^{a}	5.7^{a}	5.5^{a}
	4	162^{a}	151^{a}	158^{a}	10.7^{a}	11.0^{a}	11.0^{a}	5.0^{a}	5.6^{a}	5.4^{a}
	5	162^{a}	151^{a}	159^{a}	10.7^{a}	11.0^{a}	10.9^{a}	5.0^{a}	5.6^{a}	5.3^{a}
N rate (kg/ha)	168	91^{e}	82^{e}	87^{e}	7.7^{e}	8.1^{e}	7.9^{e}	4.4^{b}	5.0^{b}	4.7^{b}
	252	120^{d}	110^{d}	115^{d}	9.8^{d}	10.1^{d}	10.0^{d}	5.4^{a}	6.1^{a}	5.8^{a}
	336	153^{c}	142^{c}	149^{c}	11.2^{c}	11.4^{c}	11.4^{c}	5.7^{a}	6.3^{a}	6.1^{a}
	420	192^{b}	180^{b}	188^{b}	12.1^{b}	12.2^{b}	12.3^{b}	5.3^{a}	5.8^{a}	5.7^{a}
	504	232^{a}	220^{a}	228^{a}	12.6^{a}	12.7^{a}	12.8^{a}	4.5^{b}	4.9^{b}	4.9^{b}
Soil type	Quincy	197^{a}	185^{a}	194^{a}	8.2^{b}	8.5^{b}	8.3^{b}	1.5^{b}	2.1^{b}	1.7^{b}
	Taunton	118^{b}	108^{b}	113^{b}	13.1^{a}	13.3^{a}	13.5^{a}	8.7^{a}	9.2^{a}	9.2^{a}

Means followed by the same letter across a factor in each location-response variable combination are not significantly different at $\alpha = 0.05$.

nitrate leached as influenced by irrigation interval were not large enough to impact the yields.

3.3. Irrigation water amount effects on profit margin

Profit margin, in general, decreased with an increase in the amount of irrigation water (Table 2). This decrease was mainly due to increases in irrigation and leaching costs and decrease in yields. The decrease in profit margin with an increase in irrigation water, however, was smaller with a longer irrigation interval (Fig. 3(g)). The smaller decrease with a longer interval was mainly because the increase in nitrate leaching with an increase in irrigation water was smaller with a longer irrigation interval. The decrease in profit margin with an increase in irrigation water beyond 500 mm was larger in the Taunton soil than in the Quincy soil (Fig. 3(i)). This difference was expected because the increase in leaching and the decrease in yield with an increase in irrigation water were larger in the Taunton soil. The decrease in profit margin with an increase in irrigation water, however, was not significantly influenced by N rate (Fig. 3(h)). With increases in both irrigation water and N rate, the increase in leaching was larger, whereas the decrease in yield was smaller. Thus, the tradeoff between yield benefits and leaching losses made the N rate influence insignificant.

The irrigation water amount of 400 mm was indicated as the best irrigation amount for this region in terms of optimizing yield and profit margin and minimizing nitrate leaching. Under-irrigation might lead to water stress because potato plants have low tolerance to soil moisture stress due to their sparse and shallow root systems (Jabro et al., 2012). Over-irrigation, on the other hand, might reduce yields due to poor soil aeration and leaching of nutrients from the root zone while increasing production costs and nitrate pollution of groundwater (Darwish et al., 2006; Jégo et al., 2008; Shock et al., 2007).

3.4. Irrigation interval effects on nitrate leaching

Nitrate leaching, in general, was more with a longer irrigation interval (Table 2). Because the total amount of water applied in a season under a given irrigation (say, x) was the same (x) for all irrigation intervals, the amount of water applied per irrigation with a longer irrigation interval was larger. Thus, a larger amount of irrigation water led to more deep drainage and thus more nitrate leaching.

The increase in nitrate leaching with a longer irrigation interval was larger with a smaller amount of irrigation water (Fig. 4(a)). With a smaller irrigation, the amount of water applied per irrigation through a longer interval was larger than that applied through a shorter interval, so a longer interval was associated with more leaching. With a larger irrigation, on the other hand, the amount of water applied per irrigation even through a shorter interval was able to drain most of the nitrate that could be drained through a longer interval. With a larger irrigation water, therefore, more diminishing amounts of nitrate were available for leaching for a longer irrigation interval. The effect of irrigation interval on nitrate leaching, however, was not significantly influenced by N rate (Fig. 4(b)) and soil type (Fig. 4(c)).

3.5. Irrigation interval effects on tuber yield

In general, tuber yield was not influenced by irrigation interval (Table 2). Although nitrate leaching was greater with longer irrigation intervals, the differences in the amounts of nitrate leached were not large enough to impact tuber yield. Jabro et al. (2012) found similar results after comparing the effects of two irrigation frequencies – weekly and biweekly – on potato crop water use and productivity in the Great Plains of United States. Kincaid et al. (1993) also found in a study conducted in Idaho that tuber yields were not significantly affected by irrigation frequency. In a study conducted in New Mexico by Curry (1932), the tuber yield per unit of water applied was practically the same for all irrigation frequencies considered.

For larger amounts of irrigation water (>600 mm), however, tuber yields increased with an increase in irrigation interval (Fig. 4(d)). With these amounts (irrigation levels), large quantities of water were applied more frequently through a shorter interval, thus causing more nitrate leaching and smaller yields. Through a longer interval, however, the irrigations with large quantities of water were given less frequently, thus causing less nitrate leaching and larger yields. The yield response to irrigation interval was not influenced by N rate (Fig. 4(e)) and soil type (Fig. 4(f)) because these factors did not impact the leaching response.

3.6. Irrigation interval effects on profit margin

Profit margin, in general, was also not influenced by irrigation interval (Table 2), which was expected because there was no significant influence of irrigation interval on tuber yield. Profit margin, however, increased for larger amounts (>600 mm) of irrigation water and decreased for smaller amounts (<600 mm) with an increase in irrigation interval (Fig. 4(g)). The profit increase for larger water amounts was mainly due to increase in yields, whereas the profit decrease for smaller water amounts was due to increase in nitrate leaching. The profit margin response to irrigation interval was not significantly influenced by N rate (Fig. 4(h)) and soil type (Fig. 4(i)) because these factors did not impact the leaching and yield responses.

3.7. Nitrogen rate effects on nitrate leaching

Generally, nitrate leaching increased with an increase in N rate (Table 2). This increase was expected because more quantity of N was available in the soil for leaching. Several previous researchers, such as Han et al. (1995), Zvomuya et al. (2003), and Cambouris et al. (2008), also observed that nitrate leaching was greater with higher rates of N application.

The increase in leaching with an increase in N rate was larger for a larger amount of irrigation water (Fig. 5(a)). This increase was due the availability of a larger quantity of water for draining a larger quantity of nitrate available through a higher N rate. The leaching response to N rate, however, was not influenced by irrigation interval (Fig. 5(b)) and soil type (Fig. 5(c)).

3.8. Nitrogen rate effects on tuber yield

Tuber yield, in general, also increased with an increase in N rate (Table 2). This increase was due to the availability of a larger quantity of N in the soil for plant uptake. The increase, however, diminished with an increase in N rate because of lower N use efficiencies caused by the increasing rates of leaching and other losses.

The increase in yield with an increase in N rate was smaller with a smaller amount of irrigation water (Fig. 5(d)). With a smaller irrigation, the availability of water relative to the availability of N was less, so plant N uptake was more water-limited. With an increase in the amount of irrigation water, however, the water-limited production condition gradually vanished, so the yield increase with a higher N rate became larger. The yield response to N rate, however, was not influenced by irrigation interval (Fig. 5(e)) and soil type (Fig. 5(f)) because the impacts of these factors on the leaching response to N rate were insignificant.

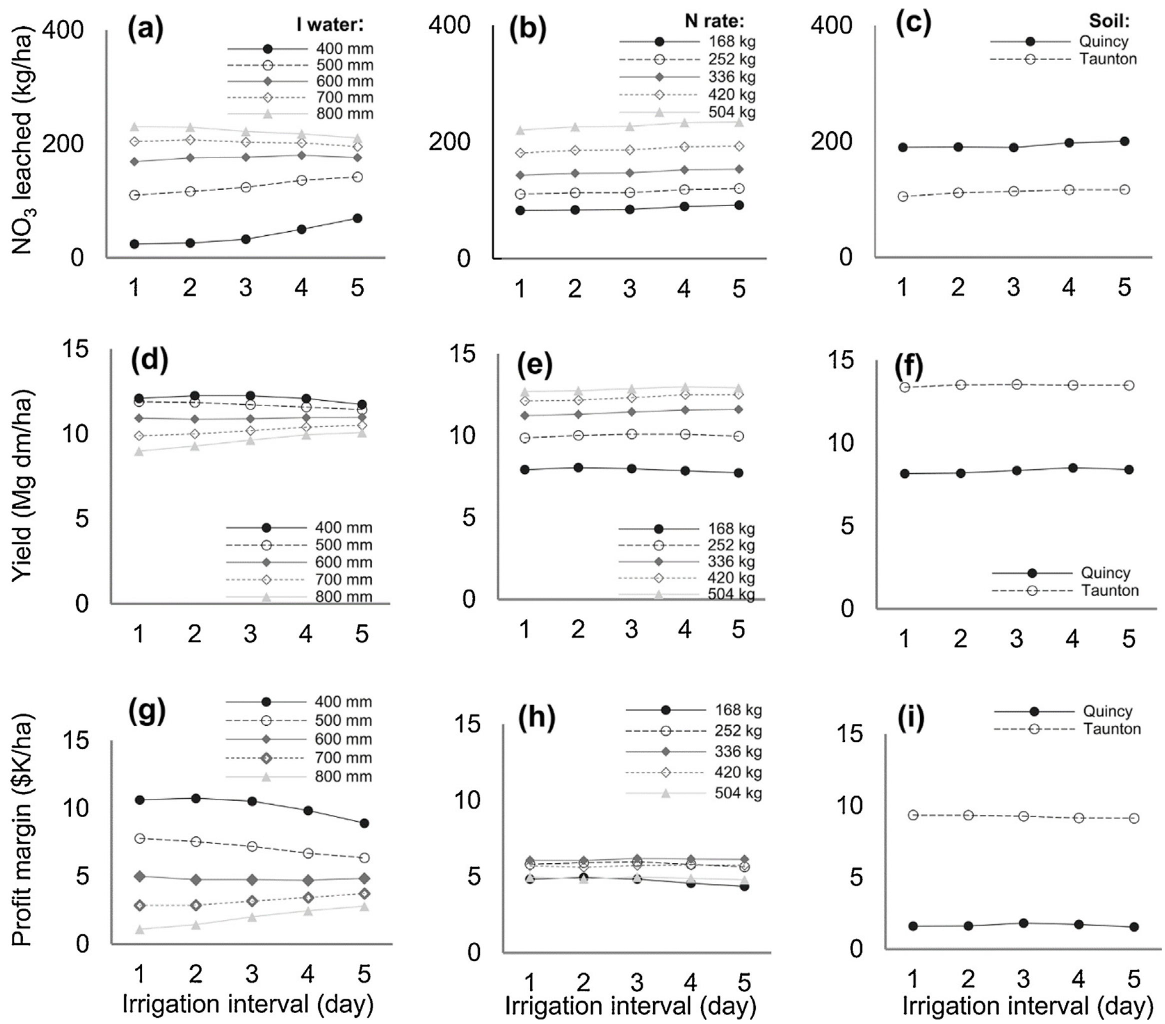

Fig. 4. Responses of nitrate leaching, tuber yield, and profit margin to irrigation interval as influenced by irrigation (I) water amount, nitrogen (N) rate, and soil type at Quincy, Washington.

3.9. *Nitrogen rate effects on profit margin*

Profit margin increased with an increase in N rate, peaked at 336 kg ha^{-1}, and declined thereafter (Table 2). This peak-profit N rate nearly conformed to the recommended rate for this area (Lauer, 1985; Pavek, 2014; Roberts et al., 1991). At this N rate, nitrate leaching was relatively low while tuber yield was relatively high. The response of profit margin to N rate was not impacted by the amount of irrigation water (Fig. 5(g)). The larger increases in both nitrate leaching and tuber yield with an increase in N rate for a larger amount of irrigation water may have masked the influence of irrigation water on the effect of N rate on profit margin. The response of profit margin to N rate was also not impacted by irrigation interval (Fig. 5(h)) and soil type (Fig. 5(i)) because these factors did not influence the responses of both leaching and yield to N rate.

3.10. *Soil type effects on nitrate leaching*

Nitrate leaching was more in the Quincy soil than in the Taunton soil (Table 2). This difference was expected because the former has sandier and lighter texture than has the latter (Hipple, 2011). Soils with lighter texture have lower retention capacity for water and soluble nutrients and thus have higher potential for nitrate leaching, especially in a shallow-rooted crop such as potato (Alva, 2004a; Hodges, 1999; Prasad et al., 2015; Shrestha et al., 2010).

The increase in leaching with a change from the Taunton to the Quincy soil was smaller for a larger amount of irrigation water, especially beyond 400 mm (Fig. 6(a)). This increase was likely because more quantity of water drained more quantity of nitrate in the Taunton soil. In the Quincy soil, however, a significant quantity of nitrate was drained even with the smallest amount of irrigation water. With a larger irrigation, therefore, only a small quantity of additional nitrate was drained. That is, the rate of nitrate leaching was more N-limited for a larger irrigation. The leaching response to soil type, however, was not influenced by irrigation interval (Fig. 6(b)) and N rate (Fig. 6(c)).

3.11. *Soil type effects on tuber yields*

Tuber yields were smaller in the Quincy soil than in the Taunton soil (Table 2). The smaller yields were caused by less availability of soil N for plant uptake due to more leaching. The smaller yields were also likely due to the availability of less amount of water in a lighter soil. Potato plants have low tolerance to water stress because their root systems are relatively sparse and shallow (Jabro et al., 2012; Shock et al., 2007).

The decrease in yield with a change from the Taunton to the Quincy soil was smaller for a larger amount of irrigation water (Fig. 6(d)). This decrease was expected because the Quincy soil drained a significant amount of nitrate even with the smallest

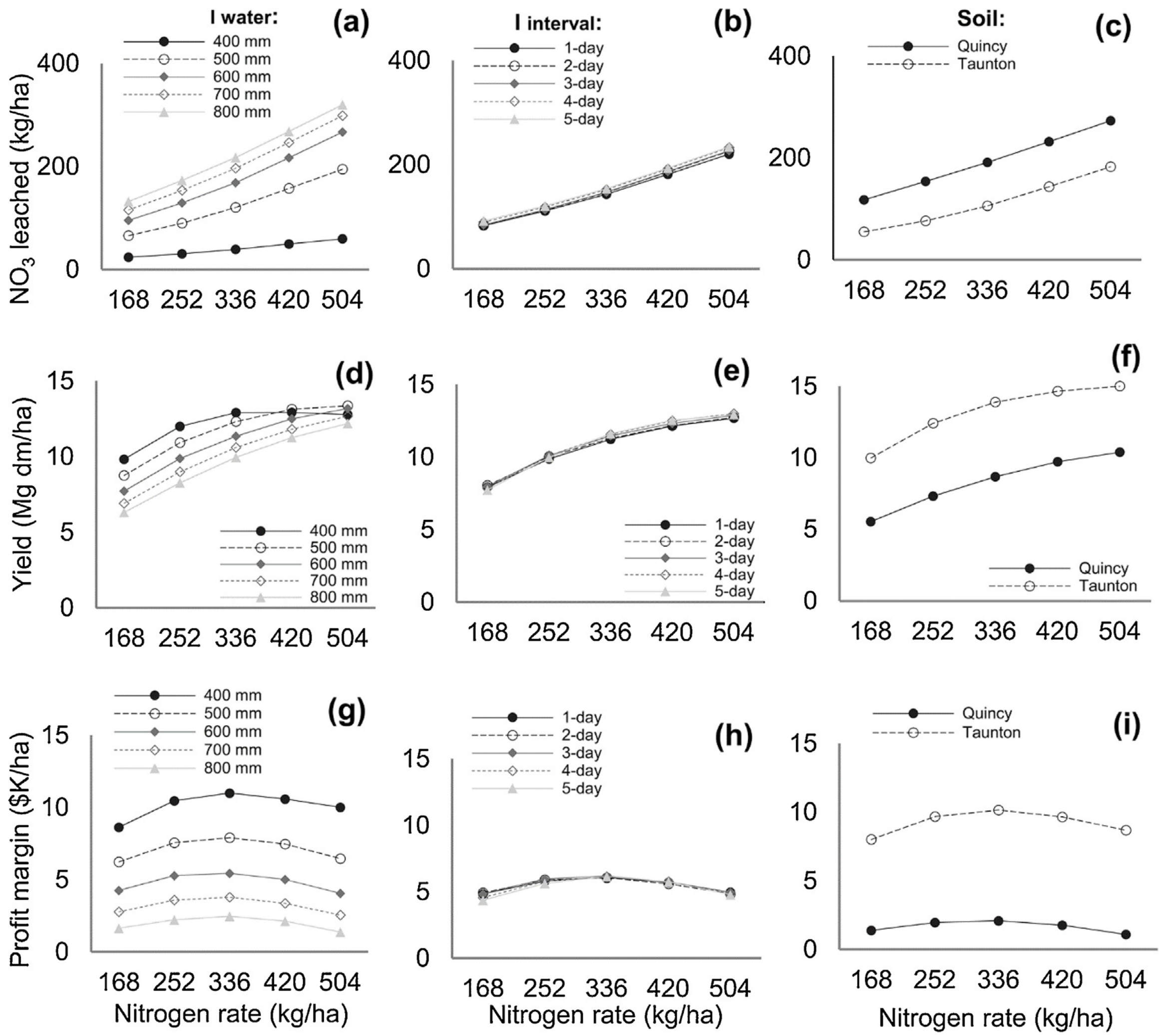

Fig. 5. Responses of nitrate leaching, tuber yield, and profit margin to nitrogen rate as influenced by irrigation (I) water amount, irrigation interval, and soil type at Quincy, Washington.

amount of irrigation water (400 mm). The increase in irrigation water added little to the quantity of nitrate leached because the additional water drained almost the same quantity of nitrate that could be drained by a smaller amount of irrigation water. For the Taunton soil, however, nitrate leaching increased with an increase in irrigation water because the water holding capacity of this soil was higher than that of the Quincy soil. The yield response to soil type, however, was not influenced by irrigation interval (Fig. 6(e)) and N rate (Fig. 6(f)) because these factors did not influence the effect of soil type on tuber yield.

3.12. Soil type effects on profit margin

Profit margin, in general, was smaller with the Quincy soil than with the Taunton soil (Table 2). This difference was due to greater leaching and smaller yields with the Quincy soil. The decrease in profit margin with a change from the Taunton to the Quincy soil was smaller for a larger amount of irrigation water, especially beyond 400 mm (Fig. 6(g)). This smaller decrease in profit margin was mainly caused by the corresponding smaller decrease in yield. The response of profit margin to soil type, however, was not influenced by irrigation interval (Fig. 6(h)) and N rate (Fig. 6(i)) because the responses of leaching and yield to soil type were not influenced by these factors.

Optimal nitrogen and water management is important to improve their uptake efficiencies. The above findings of this study might be helpful to potato growers in this region in identifying the location- and soil-specific rates of irrigation and nitrogen fertilization aimed toward maintaining high tuber yields and net profits while minimizing the nitrate pollution of groundwater. The factors and variables considered in this study represented only simplified conditions. For simplicity, other crop management variables such as plant protection and tillage were assumed to be fixed and in standard conditions. In reality, however, these conditions might vary over time and space. This study considered only a few locations, one cultivar, and two soils due to the lack of sufficient data. For the same reason, it considered the potato crops as continuous. In this area, potatoes are grown in rotations with other crops. Thus, carrying out this kind of study involving several cultivars, soils, and cropping systems or crop rotations can be a potential subject matter for a separate future study. Similarly, conducting a spatial study of potato production in this region from an agro-economic-environmental viewpoint may be another consideration for a future study targeted for a broader audience.

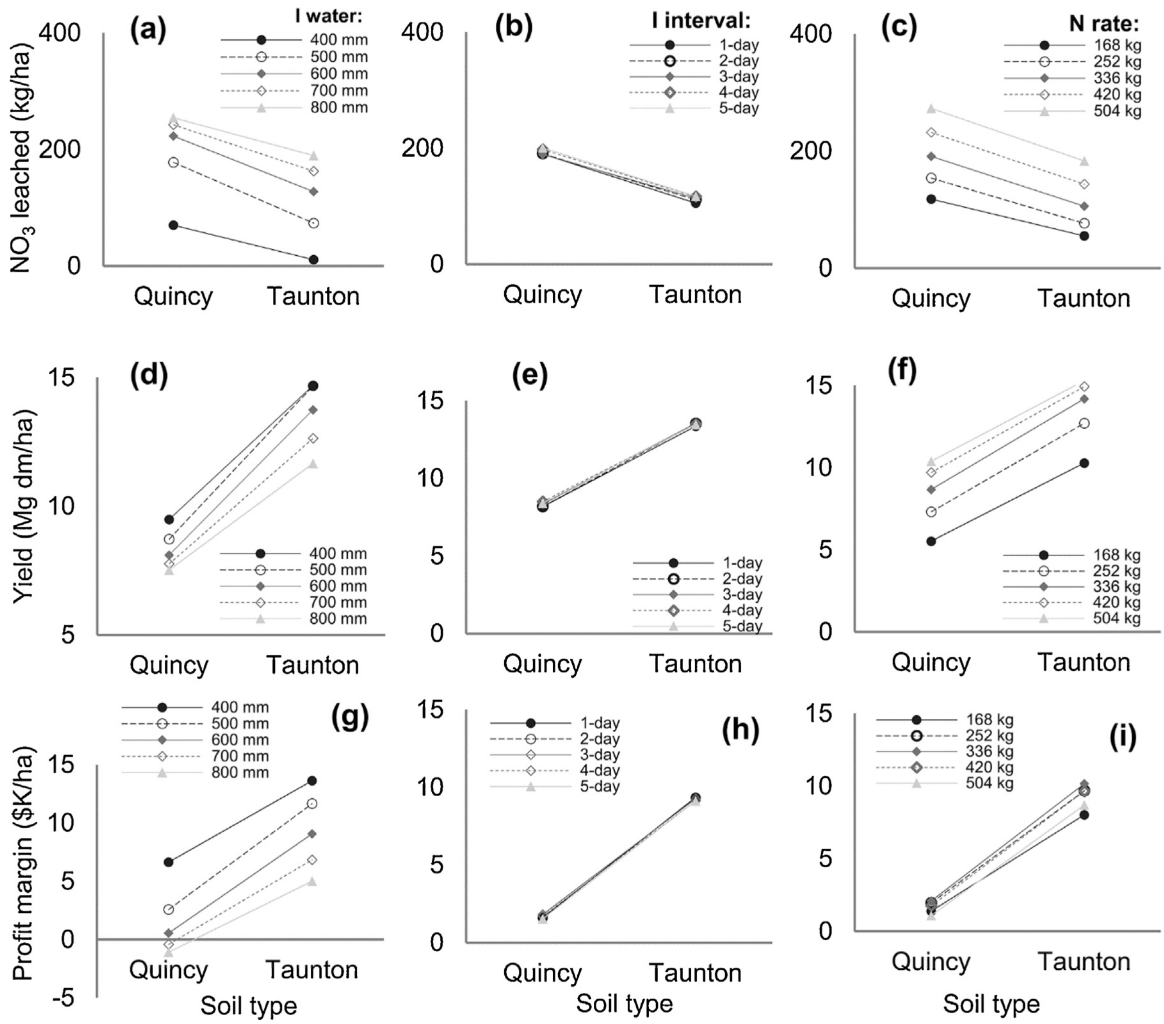

Fig. 6. Responses of nitrate leaching, tuber yield, and profit margin to soil type as influenced by irrigation (I) water amount, irrigation interval, and nitrogen (N) rate at Quincy, Washington.

4. Conclusions

Nitrate leaching was greater with a larger irrigation, a longer irrigation interval, a higher N rate, and a lighter soil. Tuber yields were larger with a smaller irrigation, a higher N rate, and a heavier soil. Profit margin was larger with a smaller irrigation and a heavier soil. The optimum amount of irrigation water for the study region was 400 mm, at which both tuber yields and profit margins were the largest with the N application rate of 336 kg ha^{-1}. The increase in leaching with an increase in irrigation water was larger with a higher N rate, a shorter irrigation interval, and a lighter soil. The decrease in yield with an increase in irrigation water was larger with a lower N rate and a lighter soil. The decrease in profit margin with an increase in irrigation water was larger with a shorter irrigation interval and a lighter soil. The increase in leaching with a longer irrigation interval was larger for a smaller irrigation. The increase in yield with an increase in irrigation interval was larger for a larger irrigation. The increases in leaching and yield with an increase in N rate were larger for a larger irrigation. The increase in leaching and the decreases in yield and profit margin with a change from a heavier to a lighter soil were larger for a smaller irrigation.

These findings indicate that potato growers in this region may obtain higher tuber yields and profit margins with the irrigation water of 400 mm and the N rate of 336 kg ha^{-1} especially in a soil whose water retention capacity is not very low. It is not environment-friendly as well as profitable for them to apply the amounts of irrigation water and N rates greater than these and irrigate heavily with longer intervals, especially in a soil with low water holding capacity. The potato growers should not use high rates of N while using large amounts of irrigation water or vice versa in order to reduce the nitrate contamination of groundwater. They may also not irrigate potatoes more frequently if larger amounts of irrigation water are to be applied especially in a light-textured soil. They need to be aware of the fact that applying lower rates of N especially when large amounts of irrigation water are applied reduces tuber yields. They need to be aware that applying more water more frequently may reduce profit margins. They also need to be cautious that even when they apply a smaller amount of irrigation water, such as 400 mm, leaching is increased if that irrigation water is given less frequently. When potato growers really want to apply larger amounts of irrigation water, irrigating potatoes less frequently may increase yields; but the option of applying smaller irrigations would be far more productive. They need to be careful about applying high rates of N together with larger amounts of irrigation water because, although this combination may produce more yields, it can increase leaching losses exponentially and thus reduce profits. They need to be aware that even with smaller irrigations tuber yields and profits may decrease in a soil with very low water retention capacity through increased leaching.

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