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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

Prem Woli[a,*], Gerrit Hoogenboom[a], Ashok Alva[b]

[a] AgWeatherNet Program, Washington State University, 24106 N. Bunn Rd., Prosser, WA 99350, USA
[b] Agricultural Systems Research Unit, USDA-ARS, 1500 N. Central Ave, Sidney, MT 59270, USA

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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

* Corresponding author.
E-mail address: premwoli@gmail.com (P. Woli).

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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.

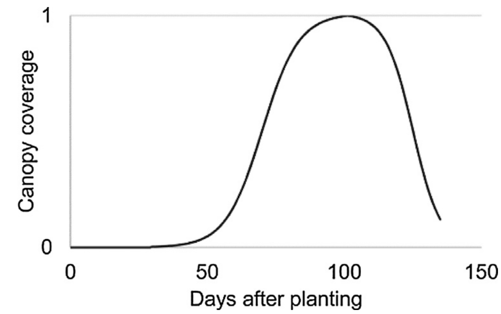

Fig. 1. Potato crop canopy coverage during the growing season (0 = no coverage; 1 = full coverage). Adapted from King and Stark (2014).

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-