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

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A B S T R A C T

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