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Effects of water table management on least limiting water range and potato root growth

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ABSTRACT

Soil physical quality indicator, Least Limiting Water Range (LLWR) is the range of soil water content, where water, oxygen and mechanical resistance are not limiting factors to root growth. The objective of this study was to evaluate LLWR, soil water availability, potato root growth and tuber yield under different water table management levels. Water table level was managed targeting 0.36 and 0.76 m below the soil surface, denoted as high (HI) and low (LO) level, respectively. Undisturbed soil core samples were obtained in the 0–0.15, 0.15–0.30 and 0.30–0.45 m soil layers to assess the LLWR. Root parameters were assessed using mini-rhizotrons installed into the soil along the potato row. Overall, LLWR decreased in depth due to a decrease in soil organic matter and an increase soil bulk density. The LO resulted in a narrower range for LLWR than HI. In the 0–0.15 m soil layer, the soil water content in the HI treatment fell inside the LLWR limits with high frequency during the growing season, but both water table levels resulted in similar root growth. In contrast, in the 0.15–0.30 and 0.30–0.45 m soil layers, soil water content fell inside LLWR more frequently in the LO than HI treatment. The LO management increased potato root length and surface area in the 0.15–0.30 m soil layer compared to HI; while in the 0.30–0.45 m soil layer, roots were not present in the HI likely due to the soil water content that was above LLWR. Optimal potato root growth was observed when the soil water content fell within the LLWR range at the highest frequency during the season. Despite impacts on the root system, similar tuber yields were achieved between LO and HI treatments. Nevertheless, the treatment HI used three times more water to supply the crop water requirement than LO.

1. Introduction

The production of potato (*Solanum tuberosum* L.) in Florida represents approximately 33% of total U.S. production of spring potatoes, with the northeast region accounting for about 63% of the planted area in the state (USDA-NASS, 2013). This region is characterized by a shallow water table due to an impermeable layer in the subsoil dominated by Flatwood soils (USDA, 1981). This shallow water table, combined with the low costs of maintenance, operation and implementation, justify the use of seepage irrigation for potatoes and other vegetable crops (Dukes et al., 2010). Seepage irrigation consists of meeting crop water demand by manipulating the water table level (Liao et al., 2016; Reyes-Cabrera et al., 2016). However, this irrigation system requires a large volume of water to raise the water table up to the crop root zone, with irrigation water use efficiency ranging from 20 to 70% (Dukes et al., 2010). The water is distributed through furrows spaced every 18 m, which creates a high soil water content in the potato rows closest to the furrows while the potato rows farther from furrows are generally drier, making it more difficult to maintain a uniform soil water content throughout the field (Reyes-Cabrera et al., 2014).

Abbreviations: AFP, air-filled porosity; AW, available water; B_d, bulk density; B_{dc}, critical soil bulk density; CV, coefficient of variation; Dp, soil particle density; ETc, crop evapotranspiration; F, frequency that the soil water content fell inside the LLWR; FC, field capacity; HI, high water table; LLWR, least limiting water range; LO, low water table; PR, penetration resistance; RD, root diameter; RSA, root surface area; RTL, total root length; SOM, soil organic matter; SPRC, soil penetration resistance curve; SWRC, soil water retention curve; WP, wilting point; θ, soil water content; θ_{PR}, soil water content that PR is critical; Ψ, matric potential.

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Potato is extremely sensitive to excess water which reduces the yield and quality of tubers due to increased disease and other physical damage (Ragassi et al., 2009). Excess water also creates hypoxic or anoxic conditions that are detrimental to the crop because potato requires soil oxygen levels between 7 and 12 mL O_2 h^{-1} g^{-1} root dry weight; values that are 5–100 times higher than those required for other annual plants (Bushnell, 1956). Excess soil water also causes reduced root growth leading to limited access of a given soil volume. Further, wet soils may lead to CO_2 toxicity in the root zone due to reduced gas diffusion (Benjamin et al., 2013).

Conversely, in a dry soil, root elongation is impeded through alternative mechanisms often linked to a combination of water stress and mechanical impedance (Bengough et al., 2011). In fact, there is a strong relationship between the soil penetration resistance (PR) and the rate of root growth in potato. Stalham et al. (2007) reported root density and maximum rooting depth of potatoes to be significantly reduced with the increase of PR, leading to reduced leaf area expansion rate, light interception and consequently potato tuber yield. In addition, soil textures ranging from sandy clay loam to medium sand had a potato root penetration rate that was approximately 2 cm day^{-1}, with a 50% reduction in that rate where PR was higher than 1.5 MPa. Similarly, Stone (1988) reported that on a sandy clay loam soil, there was no reduction in potato yield for root penetration resistance between 1.0 and 1.5 MPa; however, PR values greater than 1.5 MPa significantly reduced potato yield. Overall for most agricultural crops, a PR of 2.0 MPa has been used as a threshold delineating a reduction in root penetration (Bengough et al., 2006; da Silva et al., 1994; Safadoust et al., 2014; Smith et al., 1997; Taylor et al., 1966).

The potato root system is often concentrated in the upper 0.30 m of soil, which limits nutrient accessibility and consequently makes the crop more susceptible to water shortages as soils dry (Alva et al., 2012; Liao et al., 2016; Munoz-Arboleda et al., 2006; Ragassi et al., 2009). Limitations in the root architecture of the crop often directly limit potato yield (Onder et al., 2005; Wang et al., 2007). Therefore, it is important to keep soil water content levels in a satisfactory range during the growing season to reduce soil physical and physiological stress on potato plants. Quantification of the impacts of these characteristics on root growth can be expressed through the evaluation of the Least Limiting Water Range (LLWR), which defines the region bounded by the upper and lower soil water content over which water, oxygen, and mechanical resistance become major limiting factors for root growth (da Silva et al., 1994). The LLWR is considered a multifactor index that can be used to describe the soil physical properties that directly affect crop production (Betz et al., 1998; da Silva et al., 1994; Tormena et al., 1999; Wilson et al., 2013) and has been considered an important indicator of soil physical quality. Usually, the critical limits defining the LLWR are soil water content at matric potential (Ψ) = −6 kPa (field capacity) for sandy soil and at Ψ = −1500 kPa (permanent wilting point), air-filled porosity less than 10%, and soil penetration resistance above 2.0 MPa (Taylor et al., 1966). Soil compaction narrows the LLWR due to the increase in soil bulk density (B_d) leading to reduction in soil water availability within the range of the LLWR. Wilson et al. (2013) showed that the maximum LLWR values were found at B_d of 1.1 Mg m^{-3} in a Mollisol, thus, LLWR drastically decreased with increases in B_d. When evaluating a sandy soil, Fidalski et al. (2010) showed a linear and negative relationship between LLWR and B_d. Consequently, small variations in soil water content, PR, or soil aeration may result in soil conditions ranging outside of the LLWR, invariably limiting root development. Therefore, crops cultivated in soils with a narrow range of LLWR values may be more vulnerable to yield losses due to restrictions in root architecture not experienced in soils with a wider range of LLWR values (da Silva and Kay, 1997, 1996).

Clearly, soil water management plays an important role in determining LLWR, thus impacting plant development and potato yield. Management of the water table level influences the temporal and spatial variability of soil water content and, combined with the LLWR model can determine the optimal irrigation management scheme within a particular system. Therefore, irrigation should be managed in a way to provide enough water for crop uptake without limiting soil aeration or resistance to root penetration. Root-limiting soil physical characteristics have not been previously described or quantified for potato growth under seepage irrigation. Thus, the objective of this study was to evaluate the response of LLWR, soil water content variability, potato root growth and yield under different water table levels for the seepage system. It was hypothesized that root growth responds to changes in soil physical properties in conjunction with water availability and that LLWR would be an important parameter that could quantify these processes during a potato growing season.

2. Material and methods

2.1. Experimental site and field experiment

The study was conducted at the University of Florida, Hastings Agricultural Extension Center, Hastings, FL, USA (29°41′50"N, 81°26′48"W, elevation 8 m) in spring 2014. The soil at the experimental field has been classified as hyperthermic Grossarenic Ochraqualf belonging to the Holopaw fine sandy series (USDA, 1981). The parent material consists of sandy and loamy marine deposits. The natural drainage class is poorly drained and the field slope is less than 2% (USDA, 1981). The particle size distribution, the soil organic matter content and the soil bulk density are presented in Table 1.

The experiment was laid out in a randomized complete block design with three replicates. Experimental plots of 21 m long and 18 m wide were planted with the potato cultivar 'Atlantic' using seed pieces of approximately 56 g. Plots were mechanically planted on February 12, 2014, with 0.2 m within-row spacing at a depth of 0.1 m, and ridged immediately after planting. After plant emergence, 9 m plots in three potato rows (2, 4 and 6, Fig. 1A) were marked in the center area of each row and maintained without disturbance to allow for quantification of yield at the end of the season. Tubers were mechanically harvested using a one-row digger following crop senescence and occurred on May 21, 2014. After harvest, tubers were immediately washed and graded into various size classes based on the USDA Standards for Grading of Potatoes (USDA, 1997) as follows: tuber were deemed of marketable size if they had a diameter between 48 and 101.6 mm. Tubers outside this

Table 1
Average and standard deviation of soil particle size distribution, soil organic matter (SOM) and soil bulk density (B_d) for three soil layers under two water table level management, low (LO) level managed at 0.76 m and high (HI) level managed at 0.36 m depth from the soil surface of a sandy soil grown with potatoes in Hastings, FL.

Soil layer (m)		Particle size distribution (g kg^{-1})			SOM	B_d
		Sand	Clay	Silt	(g kg^{-1})	(Mg m^{-3})
0–0.15	LO	915 ± 3	25 ± 1	60 ± 2	19.3 ± 0.3	1.25 ± 0.09
0.15–0.30	LO	900 ± 6	56 ± 6	44 ± 2	15.9 ± 1.7	1.43 ± 0.05
0.30–0.45	LO	938 ± 3	23 ± 3	39 ± 1	7.9 ± 1.3	1.53 ± 0.10
0–0.15	HI	916 ± 4	37 ± 3	47 ± 1	20.7 ± 0.9	1.25 ± 0.09
0.15–0.30	HI	926 ± 2	14 ± 1	60 ± 2	15.3 ± 1.1	1.40 ± 0.09
0.30–0.45	HI	936 ± 2	19 ± 1	45 ± 1	5.7 ± 2.4	1.56 ± 0.07
Coefficient of Variation (%)		3.5	91.7	37.5	8.9	5.8