Soil Moisture Distribution under Drip Irrigation and Seepage for Potato Production

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Abstract

Keeping soil moisture content at field-capacity in the root zone tends to maximize crop yield. However, this is challenging in sandy soils with a shallow water table and low water holding capacity. Seepage irrigation (SEP) relies on capillarity water movement from a water table to irrigate the crop, creating uneven soil moisture distribution across the field, which could be improved with drip irrigation. The objectives of this study were to evaluate irrigation water use efficiency (IWUE) for potatoes and soil moisture distribution uniformity of two drip tape installation depths (surface at 0.05 m, SUR and subsurface at 0.15 m, SUB) as an alternative method to SEP. The design of the experiment was a randomized complete block with irrigation treatments as main plots, and potato varieties (Atlantic, Fabula, and Red LaSoda) as subplots. The volume of water applied, water table level, and soil volumetric water content were continuously measured for two seasons, 2011 and 2012. Drip irrigation significantly increased the moisture distribution uniformity in the potato ridge. The majority of the plant root system was concentrated in the upper soil layer (~0.3 m), regardless of irrigation treatment. Similar marketable yield between SUR and SEP were achieved for Fabula and Atlantic in the first season, while lower yields were reported for Red LaSoda under drip in both years. The SUB produced lower yield in both years attributed to limited water capillarity. Drip irrigation reduced water use 48% and 88% in 2011 and 2012, respectively. Higher IWUE was obtained with drip compared to SEP for all varieties in 2012. The SEP used more irrigation water to supply the crop than SUR resulting in a difference in IWUE of 5.7 kg m⁻³. The SUR was capable of

adequately irrigating the potato shallow root producing similar yield to SEP for Atlantic and Fabula varieties.

Keywords: Drip irrigation; sandy soils; subirrigation; seepage irrigation; root distribution; irrigation water use efficiency

1. Introduction

Approximately 15,000 ha of land in Florida were cultivated with potatoes under seepage (SEP) in 2013 (USDA-NASS, 2014), which led to an estimated use of 62.7 million cubic meters of water in that year. These figures for 2013 clearly illustrate the need for efficient irrigation management for potatoes for environmental and economic sustainability. For potato, this is largely driven by high production costs and an inherently low tolerance to water stress when compared to other crops (Munoz-Arboleda et al., 2006; Patterson, 2010; Shock et al., 2007).

Seepage or subirrigation is a variation of subsurface irrigation or water table control that uses groundwater. The water table is artificially maintained by water furrows generally spaced every 18 m. (Dukes et al., 2010). It is a low-cost and effective way to irrigate crops in flat locations where a natural impermeable soil layer results in a shallow water table (Haman et al., 1989). However, seepage has relatively low water use efficiency (20-70%), low water distribution uniformity across the field, and high susceptibility to runoff, since the water table level is adjusted by either adding or subtracting water at subsurface layers (Smajstrla et al., 1984; Smajstrla et al., 2000).

The groundwater for seepage irrigation has been both inexpensive and accessible. However in recent years, overpumping has caused the decline of the water levels and upconing of saline water from deeper zones to move into the fresh-water system. This increases chloride concentrations in wells, hence affecting water suitability for agricultural purposes (Spechler, 1994; Lindsey et al., 2009). Excessive irrigation with saline water is particularly problematic for these soils with an impermeable soil layer because of the inability to use mitigation practices like leaching fraction (i.e. irrigation to remove excess salts from saline soils) without a tiling system. In addition, crop establishment and growth may be severely impacted when saline water is used because salt accumulates in the wetting front, impairing the plant's ability to take up nutrients (Hanson et al., 1997). High soil salinity severely reduces potato yield due to its restriction of root water uptake, reduced water infiltration rate, and negative effects on soil aeration (Ayers and Westcot, 1985; Levy and Veilleux, 2007).

It has been demonstrated that by developing irrigation practices that deliver appropriate water quantities that match crop demand, potato production can be optimized (Shock et al., 2003; Yuan et al., 2003). However, soil moisture uniformity at the upper soil layer is difficult to achieve with seepage due to drastic changes of the water table level, especially during rainfall events. Reducing off-site movement of fertilizer and keeping nutrients close to the active root zone is another challenge potato farmers could possibly overcome with more efficient irrigation practices (Alva, 2008). Precise irrigation methods, such as drip, provide the benefit of adequate soil moisture that can be readily extracted by plants. In case of heavy rain, there is also storage capacity in the soil profile for extra water (Onder et al., 2005). The use of drip irrigation can help reduce non-beneficial water consumption while increasing the yield potential of the crop (Howell, 2001).

Drip is an irrigation technology known to increase the control of water application and offers several advantages to growers. It reduces soil evaporation and weed population, increases plant transpiration, and when well-managed, excessive water drainage is unlikely to occur, thus allowing nutrients to be retained in the root zone for prolonged periods (Burt, 1998; Goldberg et al., 1976; Lamm et al., 2011). Moreover, drip offers an opportunity to inject soluble fertilizers combined with irrigation, a process known as fertigation.

Although drip irrigation has the potential to deliver water efficiently, it is necessary to thoroughly evaluate this technology in sandy soil conditions in order to better understand the soil water distribution in the root zone. The installation depth of drip tape is a very important factor to consider in sandy soils due to the high hydraulic conductivity, hence limited capillary rise. The optimal drip tape depth varies among cultural practices and soil physical properties (Burt, 1998). For instance, Patel and Rajput (2007) studied the effects of five different tape installation depths (0, 0.05, 0.10, 0.15, and 0.20 m) on potato yield grown in sandy loam soil and found that tape installation depth significantly affected yield, with maximum yields at 0.10 m installation depth. Deeper drip tape installation has a potential risk of not providing moisture to shallow rooted crops like potato, due to the limited wetting from a point source. Waddell et al. (2000) found that frequent application of a small volume of water using drip irrigation had positive results in maintaining nutrients accessible to plants within the crop root zone. Additionally, the use of drip irrigation for vegetable crop production has been reported to diminish NO_3 losses to water bodies, and increase water and nitrogen fertilizer use efficiency (Lamm et al., 2011; Thompson et al., 2003).

Agricultural water conservation practices are crucial for sustainable production, and drip irrigation may be an efficient strategy to optimize potato production in sandy soils (Ahmadi, 2011). Drip irrigation could reduce the volume of water used to grow potato and minimize the impact of agriculture on salt water intrusion in the Floridan aquifer. Therefore, the objectives of this study were to evaluate irrigation water use efficiency and soil moisture distribution uniformity of two drip tape installation depths as an alternative method to seepage in sandy soils. It was hypothesized that drip irrigation can maintain uniform soil moisture content in the root zone with a reduced water requirement, which will increase irrigation water use efficiency and maintain potato yield.

2. Materials and Methods

Field experiments were carried out at the Hastings Research and Extension Center in Hastings, Florida (29°41' 27.58"N, 81°26'31.37"W). The water table is controlled by the hydrology of a landscape that is only approximately 10 m above sea level (Acharya and Mylavarapu, 2011). The soil has been classified as sandy, siliceous, hyperthermic Arenic Ochraqualf and belongs to the Ellzey series (USDA, 1981). Soil bulk density was 1.37; 1.42; 1.52 and 1.60 g cm⁻³ and saturated hydraulic conductivity was 13.10; 13.41; 15.29 and 10.95 cm h⁻¹; respectively for soil depths at 0.22; 0.45; 0.67 and 0.90 m (Acharya and Mylavarapu, 2011). The soil particle size was 916 g kg⁻¹ of sand, 37 g kg⁻¹ of clay and 47 g kg⁻¹ of silt. Soil organic matter average was 16 g kg⁻¹.

An experimental field of 1.8 ha was used for this study. A typical design of seepage irrigation in the region was used with water furrows spaced every 18 m. The furrows were used for irrigation and drainage during storms. The area in between two water furrows contained 16 raised potato rows, with a length of 80 m each.

The experiment was a randomized complete block design with irrigation and potato cultivar treatments arranged in a split plot with four replicates. Three irrigation treatments were established as main factors, seepage (SEP), subsurface drip tape (SUB) and surface drip tape (SUR). Three potato varieties, Atlantic (chipping), Fabula, and Red LaSoda (both tablestock) were designated as sub-plots.

The SEP and drip plots were separated by a 36 m wide buffer zone. These buffer zones were necessary to eliminate the influence of the water table from SEP plots on the drip plots. The SEP treatment was irrigated through the furrows and the irrigation schedule was similar to farmer practices in the area, which let spigots open and water run through lateral water furrows

to raise the water table to a desired level of 0.55 m below the top of the potato row. The SEP supplied irrigation water continuously throughout the season until plant shoots were desiccated (i.e. vine kill) and suspended during rainfall events.

The drip tape depth for the SUB treatment was placed 0.05 m below the seed piece (0.15 m below the soil surface) before planting and the drip tape for the SUR treatment was installed after planting, at 0.05 m above the seed piece (0.05 m below the soil surface). The SUR and SUB treatments in each block were controlled by the same irrigation valve, therefore there were no differences in volume applied between SUR and SUB. Crop evapotranspiration (ET_c) was calculated from the product of crop coefficient (K_c) and ET_o (Doorenbos and Pruitt 1977). The growing season was divided into four stages and a specific K_c was assigned to each one. The crop stages, approximate DAP intervals and respective K_c were: initial (0–25 DAP, 0.6), development (26–55 DAP, 1.15), midseason (56–92 DAP, 0.75), and late (93–113 DAP, 0.6) (Allen et al. 1998). Between 35 and 55 days after planting (DAP) in 2011, the irrigation depth for drip treatments was 2.9 mm day^{-1} split in three irrigation events. The respective irrigation start times were 900, 1100 and 1400 h. After 56 DAP, the volume applied was increased to 5.1 mm day^{-1} split in four irrigation events with start times at 700, 900, 1100 and 1400 h (Fig. 1). The increase in irrigation volume was required because of the lack of contribution of rainfall and to match the crop evapotranspiration requirement (Table 1). In 2012, between 31 and 56 DAP, four irrigation events were established with a total daily application of 5.1 mm day^{-1} , applied at 700, 900, 1100 and 1400 h. Between 57 and 77 DAP, the irrigation was adjusted to 6.3 mm day^{-1} , with the inclusion of an additional irrigation event starting at 1630 h, and returned to 4 irrigation events a day until 92 DAP. The drip system operated at an average pressure of 55 kPa at the end of the drip tape lines. In the drip irrigated treatments, a single drip line with pressure compensating emitters (RO-DRIP, John Deere Water, Moline, IL, USA), having a flowrate of 1 L h^{-1} , 0.20 m emitter spacing, 16 mm inner diameter, and 0.2 mm thickness was used to deliver irrigation water.

The drip irrigation manifold consisted of 0.05 m T-shaped filters (Amiad filtration systems, Oxnard, CA), pressure gauges, a flowmeter, a single station controller with attached solenoid (SVC-100, Hunter Industries, San Marcos, CA) and pressure regulator (PRFX-20, Senninger Irrigation Inc. Clermont, FL) installed at the inlet of each drip irrigated bed. Water volume applied was manually recorded and quantified from positive displacement flowmeters (DLJ 200 Multi-Jet Water Meter, Daniel L. Jerman Co., Hackensack, NJ) at the inlet of each drip and SEP irrigated block.

Prior to the start of the first season in 2011, the area was laser leveled and raised rows (0.35 m height) were formed. Afterward, the field was fumigated (1, 3-dichloropropene (63.3%) + chloropicrin (34.7%) (Telone® C-35; Dow AgroScience; Indianapolis, IN) at a rate of 103 L ha⁻¹. Potato seed pieces (57-85 g) of Atlantic, Fabula, and Red LaSoda varieties were planted on February 17, 2011 and January 17, 2012. The potato seed pieces were planted at 0.10 m depth, which was used as a point of reference for the installation depth of the drip tape. Total granular fertilizer was banded and incorporated into the soil at rates of 56-112-308 kg ha⁻¹ of N, P₂O₅, and K₂O, respectively. Two additional applications of 84 kg N ha⁻¹ occurred at plant emergence and at tuber initiation as sidedress. Application methods were the same across irrigation methods, i.e. fertigation was not utilized in either drip treatment. Further information about the experimental layout, weather data collection, and crop evapotranspiration can be found in Reyes-Cabrera et al. (2014).

Irrigation events and duration were recorded for each treatment beginning at plant emergence until irrigation was suspended before vine kill. Vine kill was scheduled 20 days prior to harvest, and it is a practice performed to desiccate the aerial part of the plant to induce skin set and increase carbohydrate concentration in the tubers of fresh market varieties. Irrigation water use efficiency (IWUE) was calculated as follows:

$$IWUE = Y / Irr$$

Where Y is marketable tuber yield (kg ha⁻¹) and Irr is seasonal water applied (m³ ha⁻¹) for each irrigation treatment and expressed as kg of tuber yield m⁻³ of water.

2.1 Monitoring soil water content

Volumetric water content (VWC) was recorded using time domain reflectometry (TDR) sensors (CS615 and CS650, Soil Water Content Reflectometer, Campbell Scientific Inc. Logan, UT, USA) installed in the SEP and drip treatments. Three soil pits in each irrigation treatment were opened at different locations in the plots. In each soil pit, ten soil moisture probes were installed horizontally in the soil profile. A single probe installed at 0.05 m at the center of the potato ridge; two probes at 0.15 m depth (one at the center and one probe 0.14 m offset to the right); two probes at 0.30 m depth (one at the center and one probe 0.14 m offset to the left); a single probe at 0.38 m offset to the left; three single probes installed at 0.45; 0.60 and 0.75 m depth aligned with the center of the potato ridge. The soil moisture reading interval was 15 min. Sensors were connected to dataloggers (CR10X and CR1000 datalogger, Campbell Scientific, Logan, UT) via channel relay multiplexers (AM16/32B multiplexer, Campbell Scientific, Logan,

UT) and data downloaded weekly throughout the season. In addition to these sensors, a portable handheld TDR (FieldScout 300, Spectrum Technologies, Aurora, IL) coupled with 0.2 m rods was used to measure weekly soil moisture content in the top of the potato ridge.

2.2 Water table monitoring

Three observation wells containing piezometers (PDCR 1830 Series, General Electric, CT, USA) were installed about 1 m of the soil moisture sensors profile in each experimental block to measure water table depths and monitor the effects of rainfall and irrigation treatments on the groundwater level throughout both potato seasons. Each piezometer was installed in the field using a global positioning system (GPS) receiver (60 CSx handheld GPS Navigator, Garmin International, Inc. Kansas City, KS, USA). Measurements of cable depth from the soil surface to the water table surface were taken during the installation in order to obtain an accurate reading of the water level fluctuations. Piezometers were coupled with wireless dataloggers that uploaded the data every fifteen minutes to a computer receiver. The data was made available to a website provided by the manufacturer. Devices were calibrated at the beginning of each season, updated regularly, and maintained to keep them operating properly.

2.3 Root length density distribution

Root sampling of the Atlantic cultivar was carried out 86 DAP in the 2012 season. Samples were taken at two different surface positions on a transverse line across the potato hill: (1) adjacent to the plant main stem; and (2) 0.15 m away from the plant. Soil cores were sampled in 0.15 m increments (0-0.15, 0.15-0.30, 0.3-0.45, 0.45-0.6, and 0.6-0.75 m). A soil auger (0.10 m diameter) was used to collect samples of the root profile for a representative plant randomly chosen in each plot. Samples were placed in plastic bags and stored at 4 °C until further cleaning. A spray nozzle (Metal Body 584, Gilmour USA, Peoria, IL) was used at a constant low pressure to separate the soil and organic matter particles from the roots. Roots were collected on a round sieve with 1.79 mm mesh screen (Model No. U, Seedburo Company, Chicago, IL). Once the soil and debris were removed, the material left in the mesh was washed into Pyrex glass dishes with enough water to move the material around. Roots were hand-picked using tweezers and placed into petri dishes that were stored at -23 °C until scanned. A commercial software package, WinRHIZO 8.0 (Regent Instruments Inc., Quebec, Canada), and a digital scanner was used to quantify the length and volume of roots in the different soil depths sampled.

2.4 Statistical analysis

The PROC GLIMMIX of SAS (2009), (SAS Institute Inc. Version 9.2, Cary, NC) was used to determine treatments main and interaction effects for the response variables marketable yield, culls, and irrigation water use efficiency. Irrigation and cultivar treatments were treated as fixed effects, while season and replications were treated as random effects. A normality test was performed to check statistical assumptions. When treatment means were significantly different, a Fisher Least Significance Difference (LSD) test was used to determine where the differences occurred.

3. Results and Discussion

3.1 Precipitation, irrigation, and ETc

In 2011 most of the rainfall occurred in the vegetative growth stages, while in 2012 most rainfall was later in the season. In 2011, 85% of the total 116 mm occurred during the initial 55 DAP at vegetative growth and development stages (Table 1). For 2012, total precipitation during the crop season was 62 mm higher than 2011, with 124 mm received during tuber bulking and tuber maturation stages (Fig. 1). Irrigation of the experimental plots was initiated after potato sprouts were fully emerged, which occurred 26 and 30 DAP in 2011 and 2012 seasons, respectively. The crop was irrigated for 67 days in 2011, and 64 days in 2012. Both irrigation systems were shut off three times each season when rainfall was expected.

In 2011, potato was planted 30 days later compared to 2012, thus the crop was exposed to higher temperatures and evapotranspirative demand during tuber bulking and maturation stages. The calculated cumulative ETc from planting to harvest was 380 and 307 mm for 2011 and 2012, respectively (Table 1). The season average daily irrigation volume applied using drip was 3.5 mm, while SEP applied 6.2 mm to maintain the high water table in 2011. In 2012 season, drip applied an average rate of 2.7 mm day⁻¹ while SEP applied 22.0 mm day⁻¹ (Fig. 1). The cumulative irrigation volume applied per irrigation treatment is shown in Figure 1. The difference in the volume of water applied for SEP irrigation between seasons was due to the low precipitation in 2012, more specifically until 75 DAP, which required a large volume of water to raise and maintain the water table levels to irrigate the crop (Fig. 1). The SEP was an inefficient irrigation practice considering crop initial establishment during dry periods, because the water table needed to be increased to wet the upper soil depth layers. In 2012, more water was applied with SEP irrigation during the vegetative growth and tuber initiation stages compared to 2011. Also, two major precipitation events occurred during the tuber bulking stage in 2012, which directly impacted the water table level. There was a cumulative 54.1 mm of rainfall (36 mm in 2 h) between April 21 and 22, 2012. The water retention structures were lowered to drain

excess water and after that particular rainfall event, the area was maintained in a drainage mode until harvest.

3.2 Soil moisture distribution under drip irrigation

Soil moisture distribution under drip irrigation depends on soil hydraulic properties and placement depth of the tape (Badr et al., 2010). Soil moisture measurements at 0.05, 0.15, and 0.45 m depth at the center of the potato ridge had variation in moisture content during irrigation events when SUR and SUB were compared (Fig. 2). Under SUB (Fig. 2C), the soil surface at 0.05 m depth remained dry with soil moisture levels decreasing towards the end of the season due to the low capillarity rise in sandy soil. Patel and Rajput (2007), reported similar dry conditions in the surface of a sandy loam when drip tape was buried at 0.1 m depth, indicating the limited capillary water movement of SUB drip. Similarly, Dukes and Scholberg (2005) found that drip tape placed below 0.23 m soil depth failed to provide enough water to corn grown in sandy soils. Poor upward water movement creates stressful condition for the plant, and in the case of potato, negatively impacted tuber formation causing yield reduction with SUB. At 0.15 m, soil VWC oscillated between 0.12 and 0.22 m³ m⁻³ in response to the irrigation events. Greater moisture content below the soil surface with buried drip tape was reported by Lamm et al. (2011) for grain corn to be advantageous by reducing evaporation, but in our study this practice did not result in yield improvements (Table 2). The SUR treatment had higher soil moisture content at 0.05 m depth ranging from 0.12 to 0.20 m³ m⁻³ with large spikes in soil moisture during irrigation events. In the SUR treatment, soil moisture at the 0.15 m soil depth was maintained at approximately 0.10 to 0.12 m³ m⁻³ (Fig. 2B). A predominant vertical movement of soil moisture was observed from the drip emitter with limited lateral water movement. This vertical water movement is common in soils with high sand content, indicating that shallow drip tape placement could potentially be the most adequate position to irrigate the root zone and overcome poor capillarity (Patel and Rajput, 2007).

The effect of water table management of the SEP treatment on soil moisture in 2011 is shown in Fig. 2D. The soil moisture at 0.40 m depth was maintained near saturation, above 0.40 m³ m⁻³ throughout the crop season. The high water table level in the SEP affected the soil moisture at the 0.05 and 0.15 m soil depth. In both soil layers, there was a slight decrease of soil moisture during day hours, which was attributed to the crop evapotranspiration. During the night, soil moisture increased since the crop evapotranspiration ceased.

On average, the water table was maintained 0.27 and 0.14 m lower in drip irrigated plots than SEP plots in 2011 and 2012, respectively; with the average water table depth for SEP at 0.56

and 0.69 m from the soil surface in 2011 and 2012, respectively (Fig. 2A). However, there was variability in water table level with fluctuations between 0.19 and 0.65 m in 2011 and 0.36 to 0.91 m in 2012. In both seasons, rainfall had an impact on the level of the water table. Rainfall contribution to the water table depended on the water table level prior to precipitation and outlet board management. The potato rows closest to the water furrow showed high impact of rainfall on the soil moisture at 0-0.20 m soil layer compared to the potato rows in the center position between furrows. In the present study, 1 mm of precipitation elevated the water table at 40 mm towards the soil surface (Fig. 2A). Jaber et al. (2006) reported that water table could rise by 15 times the total rainfall in similar soils in southwest Florida.

3.3. Soil moisture distribution under seepage

The SEP had relatively high soil moisture values (>32%) at the 0.3 m depth compared to the drip treatments, which is consistent with raising the water table up to the root zone. Figure 3 shows the soil moisture dynamics before, during, and after a rainfall event and the impacts of the different irrigation methods on drainage. Because of the maintenance of a low water table, an improved capacity for water storage from rain was observed under drip irrigation compared to SEP. The limited capacity for water storage and slower drainage under SEP was previously reported by Campbell et al. (1978), which highlighted the detrimental saturated conditions in the rootzone due to the quick water table response to a rainfall event. During the irrigation (Fig. 3 AFK), the SUR topsoil layer between 0.05 to 0.15 m had increased soil moisture, while SUB had increases at 0.15 to 0.30 m soil depth layer. The dry soil surface on the sides of the hill allowed the rapid infiltration of the incoming rain. The particular rainfall event reported in Fig. 3 was 34 mm in 7.5 hours. As the water entered the soil, there seemed to be preferential water movement in the alleys (and likely runoff), which resulted in greater soil moisture content in that area.

Although the initial soil moisture content was greater in the upper 0.05 m for SUR ($0.17 \text{ m}^3 \text{ m}^{-3}$) and SUB ($0.11 \text{ m}^3 \text{ m}^{-3}$) compared to SEP ($0.08 \text{ m}^3 \text{ m}^{-3}$), the position of the water table at the moment of the rainfall significantly impacted the drainage process and the soil moisture in the root zone. The water table level of the SEP before rainfall was at 0.55 m depth, while for SUR the water table was at 0.92 m and SUB at 0.74 m. The shallow depth of the water table under SEP was quickly raised by the incoming water. This rapid response of the water table likely saturated soil pores at 0.15 m and sharply increased the moisture content in the upper level due to the capillarity effect. After the rainfall, the measured water table levels were 0.32, 0.50, and 0.39 m deep from soil surface for SEP, SUR, and SUB respectively. Different drainage and soil moisture patterns were observed in the soil profile for the treatments after the rainfall. For

example, drainage was slower in the SEP irrigated rows compared to the drip treatments (Fig. 3 E, J, and O). The use of drip tape resulted in a lower water table level in the field, which produced a larger capacity for storage of water during rainfall events. Pandey et al. (2007) has also reported that a high water table reduced the soil's ability to store rainfall and increased runoff after irrigation or rainfall. The maintenance of a high water table increased irrigation water use and possibly increased off-site nutrient discharge due to frequent runoff events.

3.4 Effect of water table level on soil moisture

The diverse effect of the perched water table on the soil VWC varied primarily as a function of the depth at which the soil moisture content was measured, and secondly as a function of the row distance to the water furrow. Fig. 4 shows the impact of the water table level on the soil VWC at different depths during periods when SEP was used to irrigate the crop. For this analysis, the soil moisture data from periods with rainfall was not considered. During the crop season, the water table depth oscillated between 0.32 m at the highest level and 0.90 m at the lowest level.

When examining the soil VWC during this period of fluctuation, the soil moisture at the 0.05 m soil depth was not affected (Fig. 4A). In fact, regardless of the water table level, the moisture at the upper soil layer was predominantly below $0.10 \text{ m}^3 \text{ m}^{-3}$. At the 0.15 m depth (Fig. 4B), a linear response of soil moisture with the increase of water level was reported due to the soil water capillarity; however, soil moisture was generally below field capacity ($0.15 \text{ m}^3 \text{ m}^{-3}$). The low soil moisture at 0-0.15 m under SEP also reflected limited soil water capillarity and the agronomic challenges farmers face to control water table and supply potato water needs in this irrigation system. The soil moisture at 0.3 and 0.45 m depth were directly impacted by the water table level, as it presented the most dynamic interaction between the depth of the water table and soil moisture content (Fig. 4CD). As the water table rose, soil moisture content at 0.30 m increased quadratically, peaking at a water table level of 0.4 m from the soil surface. In that particular soil depth, soil moisture ranged from 0.13 to $0.38 \text{ m}^3 \text{ m}^{-3}$. At the 0.45 m depth, the soil moisture also responded quadratically to the increase of the water table level; however, the soil moisture range (0.34 to $0.43 \text{ m}^3 \text{ m}^{-3}$) was significantly higher than at 0.30 m depth, bringing soil moisture to saturation level. There was a linear response of the soil moisture to the water table increase at the 0.6 and 0.75 m depth; however, at those depths, soil was permanently saturated regardless of the water table level. In general, water table management should target a level that maintains soil moisture in the crop root zone. In the conditions of this experiment, the water

table level between 0.4 and 0.5 m below the surface provided moisture near and above soil field capacity at 0.15 and 0.3 m soil depths.

3.5 Root length density distribution of Atlantic

Root length density (RLD) is often closely related to water and nutrient uptake (Lesczynski and Tanner, 1976). The RLD for Atlantic in this study was not significantly different among irrigation treatments. Depth of sampling was the only factor that significantly influenced RLD ($P < 0.0001$). The RLD decreased rapidly at deeper soil layers, which is consistent with results found in other studies for potato (Munoz-Arboleda et al., 2006; Stalham and Allen, 2001) and tomato (Zotarelli et al., 2009). About 61-77% RLD was found in the 0-0.15 m soil layer. The RLD decreased in subsequent soil layers as follows: 16-33% in the 0.15-0.30 m layer; 4-8% in the 0.30-0.45 m layer; and <2% RLD in the 0.45-0.60 and 0.60-0.75 m soil depths (Fig. 5). The high concentration of roots in the upper 0-0.15 m depth is a function of localized irrigation delivery that could be more easily accomplished with SUR than SEP or SUB. However, larger RLD under SUR did not produce significant yield gain for Atlantic. A high correlation between root development pattern and soil moisture content has been reported and may increase the efficiency of water delivery method (Joyce et al., 1979; Mackerron and Peng, 1990; Tourneux et al., 2003). Atlantic responded to SUB irrigation by lengthening roots deeper and closer to the subsurface water front. While under SEP treatment, RLD at 0.15-0.30 m soil depth layer was double compared to the RLD under drip treatments.

3.6 Potato yield and Irrigation Water Use Efficiency (IWUE)

Tuber yield of each potato variety responded differently to the irrigation treatments. The SUR treatment produced comparable marketable yield with SEP for Fabula in both years and Atlantic in 2011. However, SUB irrigation produced lower yields compared to the other irrigation treatments in 2011. In 2011, SUB reduced the marketable yield of Atlantic by 24% compared to SUR drip. For Red LaSoda, both drip treatments yielded an average 44% lower compared to SEP and there were no differences between irrigation treatments for Fabula (Table 2). In 2012, marketable yield under SEP was 9.5 and 9.3 Mg ha⁻¹ greater for Atlantic and Red LaSoda compared to the average yield under drip treatments, respectively. Fabula response to SUR and SEP treatments was similar in both years, indicating the ability of Fabula to adapt to wetting-drying patterns of drip irrigation. However, low yield performance of Red LaSoda under drip in both years, indicated detrimental effect of changes in soil moisture content with drip, potentially having the greatest impact during tuber bulking stage. The yield of Atlantic was intermediate

with SUR, and relatively low with SUB suggesting the need to further refinement of drip irrigation scheduling for this chipping variety (Reyes-Cabrera et al., 2014).

In order to make an adequate comparison among irrigation systems, an entire area approach was chosen to compare the irrigation methods used in this research. Waddell et al. (1999) compared sprinkler and drip methods and used a similar approach for drip calculations. In that study, authors converted the volume of water applied by drip to a depth using the entire plot area, although half of the area was irrigated. Thus, following this approach drip treatments reduced water use by 48% and 88% compared to the SEP irrigation in 2011 and 2012, respectively.

In both seasons IWUE values were higher for drip treatments, except for Red LaSoda in 2011. The treatment ranking for IWUE was as follow: SUR > SUB > SEP for all tested potato varieties. In 2011, the obtained IWUE values were 7, 6, and 4 kg m⁻³ for SUR, SUB, and SEP treatments, respectively. In 2012, the IWUE values were 10, 6, and 2 kg m⁻³ for SUR, SUB, and SEP, respectively. The SEP treatment had the lowest IWUE values due to the large volume of water applied to raise the water table level. In contrast, the drip treatment consistently achieved higher IWUE levels due to similar marketable yield to those of SEP; however, this treatment utilized less water (Table 2). A 3% increase of IWUE with SUR drip compared to SUB was reported by Onder et al. (2005) when these irrigation methods applied full irrigation requirements.

Although poorly distributed across the field, water delivered by the SEP system was consistently greater, which resulted in low IWUE. Drip irrigation increased the distribution uniformity and water availability in the upper soil layers irrigated with an overall lower water volume compared to SEP. As the SUR treatment had drip tape at a higher position in the soil profile compared to SUB, it resulted in an improved distribution of the soil moisture in the upper part of the soil profile, where 61 to 77% of the roots were located. The low position of the drip tape under the SUB treatment reduced the soil moisture at the upper soil layer causing significant reduction of tuber marketable yield. In addition, granular fertilizer applied at the soil surface may have reduced solubility under drier soil conditions in the upper soil layer.

4. Conclusions

The localized water application of drip irrigation with tape installed above the potato seed piece (SUR) maintained high soil moisture content in the upper soil layers. Similar marketable yield between SUR and SEP were achieved for Fabula and Atlantic in the first season, while lower yields were reported for Red LaSoda under either drip irrigation treatments in both years. Drip

irrigation used 48% to 88% less water compared to SEP, thus higher IWUE was obtained with drip compared to SEP for Atlantic and Fabula in 2011 and for all varieties in 2012. Greater yield for all varieties under seepage, suggests that in order to encourage a wider drip adoption it is necessary to refine management practices for specific varieties and environmental conditions. Drip irrigation could potentially improve potato productivity while reducing non-beneficial water consumption. The RLD of Atlantic was not influenced by irrigation treatment. Across treatments, approximately 90% of the potato roots were located in the upper 0.30 m depth. The SUR drip irrigation showed to be advantageous in irrigating the potato shallow root system, as SEP required $\sim 7000 \text{ m}^3 \text{ ha}^{-1}$ more irrigation water to supply the crop. Overall, SUR irrigation can produce similar marketable yield for Atlantic and Fabula varieties compared to seepage irrigation. The SUR was an effective method for water conservation, considering the fertilizer management adopted in this study. In this system, fertilizer management may be improved with injection of the fertilizer through the drip system. Future research is needed to evaluate the agronomic and economic feasibility of SUR drip irrigation and fertigation.

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REFERENCES

- Acharya, S., Mylavarapu, R.S. 2011. Selected Soil Physical Properties and Implications on Water Management System in Northeast Florida. *Soil Sci.* 176, 1-8.
- Ahmadi, S.H., Plauborg, F., Andersen, M.N., Sepaskhah, A.R., Jensen, C.R., Hansen, S., 2011. Effects of irrigation strategies and soils on field grown potatoes: Root distribution. *Agric. Water Manag.* 98, 1280-1290.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. Rome: Food and Agriculture Organization of the United Nations.
- Alva, A.K., 2008. Water management and water uptake efficiency by potatoes: A review. *Archives of Agron. and Soil Sci.* 54, 53-68.

450 Ayers, R.S., Westcot, D.W., 1985. Water quality for agriculture. FAO Irrigation and Drainage
451 Paper 29. FAO. Rome.

452 Badr, M.A., Abou Hussein, S.D., El-Tohamy, W.A., Gruda, N., 2010. Efficiency of Subsurface
453 Drip Irrigation for Potato Production under Different Dry Stress Conditions. *Gesunde*
454 *Pflanzen*, 62(2): 63-70.

455 Burt, C.M., 1998. Selection of irrigation methods for agriculture: Drip/Micro irrigation.
456 Proceedings of the Water Resources Div., ASCE, Annual Conference. Memphis, Tenn.
457 ITRC Paper 98-004.

458 Campbell, K.L., Rogers, J.S., Hensel, D.R., 1978. Water table control for potatoes in Florida.
459 *Trans ASAE* 21: 701-705.

460 Doorenbos, J., Pruitt, W.O. 1977. Guidelines for predicting crop water requirements. Irrigation
461 and Drainage Paper No. 24. Rome: FAO. Dukes, M.D., Scholberg, J.M., 2005. Soil
462 moisture controlled subsurface drip irrigation on sandy soils. *Appl. Eng. in Agric.* 21: 89-
463 101.

464 Dukes, M.D., Zotarelli, L., Morgan, K.T. 2010. Use of Irrigation technologies for vegetable crops
465 in Florida. *HortTech* 20: 133-142.

466 Dukes, M.D., Zotarelli, L., Liu, G.D., Simonne, E.H., 2012. Principles and practices of irrigation
467 management for vegetables. Florida Cooperative Extension's Electronic Data
468 Information Source (EDIS), Univ. of Florida, Gainesville, FL. <
469 <http://edis.ifas.ufl.edu/pdf/cv/cv10700.pdf>> (accessed 11.25.13.).

470 Goldberg, D., Gornat, B., Rimón, D., 1976. Drip irrigation principles. Design and agricultural
471 practices. Kfar Shmaryahu, Israel: Drip Irrigation Scientific Publications.

472 Haman, D.Z., Smajstrla, A.G., Zazueta, F.S., Hensel, D.R., 1989. Water recycling in seepage
473 irrigation of potatoes. Special Publication SJ89-SP1. Palatka, Florida. St. Johns River
474 Water Management District.

475 Hanson, B.R., L.J. Schwab, K.F. Schulbach, G.S. Pettygrove. 1997. A comparison of furrow,
476 surface drip, and subsurface drip irrigation on lettuce yield and applied water. *Agric.*
477 *Water Manag.* 33: 139-157.

478 Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* 93:281-
479 289.

480 Jaber, F. H., Shukla, S., Srivastava, S., 2006. Recharge, upflux and water table response for
481 shallow water table conditions. *Hydrolog. Process.* 20, 1895–1907.

482 Joyce, R.A., Steckel, J.R., Gray, D., 1979. Drought tolerance in potatoes. *J. Agric. Sci.*,
483 Cambridge 92, 375–381.

484 Lamm, F.R., Bordovsky, J.P., Schwankl, L.J., Grawbow, G.L., Enciso-Medina, J., Peters, R.T.,
485 Colaizzi, P.D., Trooien, T.P., Porter, D.O., 2011. Subsurface drip irrigation: Status of the
486 technology in 2010. *Trans. ASABE* 55, 483-491.

487 Lesczynski, D. B., Tanner, C.B., 1976. Seasonal variation of root distribution of irrigated, field-
488 grown Russet Burbank potato. *Am. Potato J.*: 53, 69-78.

489 Levy, D., Veilleux, R.E., 2007. Adaptation of potato to high temperatures and salinity – a review.
490 *Am. Potato J.* 84, 487-506.

491 Lindsey, B.D., Berndt, M.P., Katz, B.G., Ardis, A.F., Skach, K.A., 2009. Factors affecting water
492 quality in selected carbonate aquifers in the United States, 1993-2005. Report 2008-
493 5240. U.S. Department of the Interior & U.S. Geological Service. Reston, Virginia.

494 Mackerron, D.K.L., Peng, Z.Y., 1990. Relations between root and shoot growth: genotypic
495 differences in response to water-stress. *Potato Res.* 33, 292–293.

496 Munoz-Arboleda, F., Mylavarapu, R.S., Hutchinson, C.M., Portier, K.M., 2006. Root distribution
497 under seepage-irrigated potatoes in northeast Florida. *Amer. J. of Potato Res.* 83, 463-
498 472.

499 Onder, S., Caliskan, M.E., Onder, D., Caliskan, S., 2005. Different irrigation methods and water
500 stress effects on potato yield and yield components. *Agric. Water Manag.* 73, 73-86.

501 Pandey, C., Shukla, S., Obreza, T. A., 2007: Development and evaluation of soil moisture-
502 based seepage irrigation management for water use and quality. *J. Irrig. Drainage Eng.*
503 *ASCE* 133, 435-443.

504 Patel, N., Rajput, T.B., 2007. Effect of drip tape placement depth and irrigation level on yield of
505 potato. *Agric. Water Manag.* 88: 209-223.

506 Patterson, P., 2010. Cost of production, p. 19-20. In: W.H. Bohl and S.B. Johnson (eds.).
507 Commercial potato production in North America. The Potato Association of America,
508 Orono, ME.

509 Reyes-Cabrera, J., Zotarelli, L., Rowland, D.L., Dukes, M.D., Sargent, S.A., 2014. Drip
 510 as alternative irrigation method for potato in Florida sandy soils. Am. J. Potato
 511 Res. 91, 504-516.

512 SAS, 2009. The SAS System for Windows. Release 9.2. SAS Institute. Inc., Cary, NC.

513 Shock, C.C., Feibert, E.B.G., Saunders, L.D., 2003. 'Umatilla Russet' and 'Russet Legend'
 514 potato yield and quality response to irrigation. HortScience. 38, 1117-1121.

515 Shock, C.C., Pereira, A.B., Eldredge, E.P., 2007. Irrigation best management practices for
 516 potato. Amer. J. of Potato Res. 84, 29-37.

517 Smajstrla, A.G., Hensel, D.R., Harrison, D.S., Zazueta, F.S., 1984. Improved seepage irrigation
 518 efficiency by controlled water applications. Proc. Fla. State Hort. Soc. 97, 181-187.

519 Smajstrla, A.G., Locascio, S.J., Weingartner, D.P., Hensel, D.R., 2000. Subsurface drip
 520 irrigation for water table control and potato production. App. Eng. in Agric.16, 225-229.

521 Spechler, R.M., 1994. Saltwater intrusion and quality of water in the Floridan aquifer system,
 522 northeastern Florida. Water-Resources Investigations Report 92-4174. U.S. Geological
 523 Survey. Tallahassee, FL.

524 Stalham, M.A., Allen, E.J., 2001. Effect of variety, irrigation regime and planting date on depth,
 525 rate, duration and density of root growth in the potato (*Solanum tuberosum*) crop. J. of
 526 Agric. Sci. 137, 251-270.

527 Thompson, T.L., White, S.A., Walworth, J., Sower, G.J., 2003. Fertigation frequency for
 528 subsurface drip-irrigated broccoli. Soil Sci. Soc. Am. J. 67, 910-918.

529 Tourneux, C., Devaux, A., Camacho, M.R., Mamani, P., Ledent, J.F., 2003. Effects of water
 530 shortage on six potato genotypes in the highlands of Bolivia (II): water relations,
 531 physiological parameters. Agronomie 32, 181–190.

532 U.S. Department of Agriculture.1981. Soil survey of St. Johns county, Florida. Soil conservation
 533 service. U.S. Dept. Agr., Washington, D.C.

534 U.S. Department of Agriculture. 2014. Potatoes 2013 Summary. USDA, NASS. <
 535 <https://www.census.gov/history/pdf/idahopotatoes2014.pdf>> (accessed 12.11.14.).

536 Waddell, J.T., Gupta, S.C., Moncrief, J.F., Rosen, C.J., Steele, D.D., 1999. Irrigation and
537 nitrogen-management effects on potato yield, tuber quality, and nitrogen uptake. Agron.
538 J. 91, 991-997.

539 Waddell, J.T., Gupta, S.C., Moncrief, J.F., Rosen, C.J., Steele, D.D., 2000. Irrigation and
540 nitrogen-management impacts on nitrate leaching under potato. J. of Environm. Qual.
541 29, 251-261.

542 Yuan, B.Z., Nishiyama, S., Kang, Y., 2003. Effects of different irrigation regimes on the growth
543 and yield of drip irrigated potato. Agric. Water Manag. 63, 153-167.

544 Zotarelli, L., Scholberg, J.M., Dukes, M.D., Munoz-Carpena, R., Icerman J., 2009. Tomato yield,
545 biomass accumulation, root distribution and irrigation water use efficiency on a sandy
546 soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manag. 96, 23-
547 34.

548

Fig. 1. Cumulative irrigation water volume applied for surface drip irrigation (SUR) and subsurface drip irrigation (SUB) and seepage irrigation (SEP), calculated cumulative crop evapotranspiration (ETc), and daily rainfall during potato growing season of 2011 and 2012 in Hastings, FL.

Fig. 2. Irrigation water application, rainfall, volumetric soil water content at 0.05, 0.15, and 0.45 m depth, and water table level between tuber initiation and maturation stages in 2011 season. A corresponds to water table level and rainfall; B corresponds to surface drip irrigation (SUR); C corresponds to subsurface drip irrigation (SUB); D corresponds to seepage irrigation (SEP).

Fig. 3. Soil moisture content in the potato ridge for surface drip irrigation (A to E), subsurface drip irrigation (F to J), and seepage (K to O) before rainfall (A, F and K); during a 34 mm rainfall (B, G and L); 24h, 48h and 72h after rainfall (C, H and M; D, I and N; E, J and O, respectively), during 2012 season in Hastings, FL. White dot denotes location of tape for drip irrigated treatments.

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3 Fig. 4. Relationship between soil volumetric water content and water table level at 0.05 m (A), 0.15 m
 4 (B), 0.30 m (C), 0.45 m (D), 0.60 (E) and 0.75 m (F) soil depth under seepage irrigated during 2011 crop
 5 season.

Fig. 5. Root length density of potato 'Atlantic' at five soil depth intervals (0-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60, and 0.60-0.75 m) in the potato ridge at 86 days after planting in 2012 season. Bars represent standard deviation of the mean.

Table 1. Average daily air temperature (T_{AIR}) at 0.6 m, relative humidity (RH), solar radiation (SR), and wind speed for the 2011 and 2012 potato growing season at Hastings, FL.

Year ^A	Plant stage	T_{AIR} (°C)	RH (%)	SR (MJ m ⁻² d ⁻¹)	Wind speed (m s ⁻¹)	Cumulative rainfall (mm)	ETc (mm)
2011	Sprout development (0-12 DAT)	18.9	83.1	16	2.8	0	19
	Emergence and vegetative growth (13-43 DAT)	17.6	80.3	17	3.1	85	77
	Tuber initiation and bulking (44-72 DAT)	21.4	76.6	23	2.9	16	136
	Tuber bulking (73-92 DAT)	23.4	73.4	24	2.9	15	127
	Tuber maturation (93-109 DAT)	25.3	76.7	21	2.7	0	20
	<i>Average/cumulative</i>	<i>21.3</i>	<i>78.0</i>	<i>20</i>	<i>2.9</i>	<i>116</i>	<i>380</i>
2012	Sprout development (0-12 DAT)	15.1	83.9	12	2.5	7	15
	Emergence and vegetative growth (13-44 DAT)	16.5	82.8	12	2.9	35	58
	Tuber initiation and bulking (44 – 75 DAT)	19.5	81.6	17	2.9	69	104
	Tuber bulking (75-90 DAT)	20.8	76.0	22	2.9	55	103
	Tuber maturation (90-112 DAT)	24.0	82.1	23	2.6	14	27
	<i>Average/cumulative</i>	<i>19.2</i>	<i>81.3</i>	<i>17</i>	<i>2.8</i>	<i>180</i>	<i>307</i>

^A Data presented corresponds to the duration of the experiment. In 2011, field experiment was initiated on February 17th and harvested on June 6th. In 2012, potato was planted on January 17th and harvested on May 8th.

18 Table 2. Potato marketable yield, culls and irrigation water use efficiency (IWUE) across
 19 irrigation treatments for Atlantic, Fabula, and Red LaSoda potato cultivars grown in field
 20 conditions in 2011 and 2012 potato season at Hastings, FL.

Season	Cultivar	Irrigation	Marketable yield (Mg ha ⁻¹)	Culls ^z (Mg ha ⁻¹)	IWUE (kg m ⁻³)
2011	Atlantic	Surface	26.3 a ^y	5.0 a ^y	9.7 a
		Subsurface	19.9 b	3.4 b	7.4 b
		Seepage	23.5 ab	4.4 ab	4.5 c
	Fabula	Surface	16.1 a	6.1 a	6.0 a
		Subsurface	12.0 a	2.8 b	4.5 b
		Seepage	15.8 a	6.0 a	3.0 c
	Red LaSoda	Surface	12.7 b	6.3 ab	4.7 b
		Subsurface	16.4 b	6.1 b	6.1 a
		Seepage	26.1 a	7.5 a	5.0 ab
2012	Atlantic	Surface	26.9 b	1.8 a	14.1 a
		Subsurface	19.7 c	2.0 a	10.3 b
		Seepage	32.8 a	2.4 a	2.3 c
	Fabula	Surface	18.7 a	1.3 b	9.8 a
		Subsurface	7.8 b	1.5 b	4.1 b
		Seepage	17.6 a	3.5 a	1.3 c
	Red LaSoda	Surface	14.1 b	4.0 b	7.4 a
		Subsurface	9.2 c	3.7 b	4.8 b
		Seepage	20.9 a	5.4 a	1.5 c

21 ^z Total culls include the sum of unmarketable tuber presenting one or combination of external disorders:
 22 growth cracks, misshapen, sunburned, and decay.

23 ^y Values within columns followed by the same lowercase letter indicate that means are not significantly
 24 different at p<0.05 significance level according to Fisher's LSD test between irrigation treatment within the
 25 same potato variety and season.

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