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American Journal of Potato Research
The Official Journal of the Potato Association of America

ISSN 1099-209X

Am. J. Potato Res.
DOI 10.1007/s12230-015-9471-7

Springer

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The Relationship Between Sap Flow and Commercial Soil Water Sensor Readings in Irrigated Potato (*Solanum tuberosum* L.) Production

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Abstract Many irrigation scheduling methods utilized in commercial production settings rely on soil water sensors that are normally purchased as off-the-shelf technology or through contracted services that install and monitor readings throughout the season. These systems often assume a direct relationship between the parameters measured by these soil water sensors (voltage, unitless values, or calibrated soil moisture values) and the water use and deficit stress of the crop. Because of this assumed relationship, these sensors are purported to be useful for triggering irrigation applications by monitoring relative changes in sensor values that represent either a "dry" or "wet" condition in the field. However, there is often little confirmation that these sensors accurately reflect crop water uptake or what soil depths will best represent that relationship. In an attempt to quantify the association between the use of soil water sensors and crop water use in a commercial potato field, measurements of soil water using capacitance probes and plant water use using sap flow sensors were monitored. Measurements were taken in two water application treatments: a normal (full) and partial irrigation schedule because it was hypothesized that the relative strength of the relationship between sensor reading and crop water use may be highly dependent on field soil water status. Relative soil moisture readings and plant water use data were compiled and both linear and quadratic regressions were performed. The correlation between sap flow and soil sensor readings was significant; but the relationship was relatively weak with the strength dependent on the soil depth that was monitored, indicating that care must be taken when utilizing sensor readings for irrigation scheduling.

Resumen Muchos métodos de programación de riego que se utilizan en instalaciones de producción comercial se respaldan en sensores de agua en el suelo que generalmente se compran como tecnología "fuera de la plataforma" o a través de servicios contratados que instalan y le dan seguimiento a las lecturas a lo largo del ciclo. Estos sistemas con frecuencia asumen una relación directa entre los parámetros medidos por estos sensores de agua en el suelo (voltaje, valores sin unidades, o valores calibrados de la humedad del suelo) y el uso del agua y el agobio por déficit del cultivo. Debido a esta asumida relación, estos sensores son formalmente útiles para disparar aplicaciones de riego mediante el monitoreo de los cambios relativos en los valores del sensor que representan ya sea una condición "seca" o "húmeda" en el campo. No obstante, a menudo hay poca confirmación de que estos sensores reflejan con precisión la absorción del agua por el cultivo o a que profundidades del suelo representarán mejor esa relación. En un intento para cuantificar la asociación entre el uso de los sensores del agua del suelo y el uso del agua por el cultivo en una siembra comercial de papa, se dio seguimiento a las mediciones del agua en el suelo utilizando sondas de capacitancia y el uso de agua por la planta con sensores de flujo de savia. Se tomaron las mediciones en dos tratamientos de aplicación de agua: una programación normal (completa) y otra parcial de riego, porque se tuvo la hipótesis

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Published online: 15 August 2015

de que la fuerza relativa de la relación entre la lectura del sensor y el uso de agua por el cultivo pudiera ser altamente dependiente de la situación del agua del suelo en el campo. Se recopilaron datos de las lecturas de la humedad relativa del suelo y del uso de agua por la planta y se les hicieron regresiones lineales y cuadráticas. La correlación entre el flujo de savia y las lecturas de los sensores del suelo fue significativa primero bajo condiciones de agua limitada en el suelo; pero la relación fue relativamente débil con la fuerza dependiente de la profundidad del suelo que se monitoreó, indicando que se debe tener cuidado cuando se utilicen lecturas de sensores para la programación del riego.

Keywords Deficit irrigation · Irrigation management · Sap flow · Soil moisture

Introduction

Managing water use efficiently is a challenge faced by commercial agriculture across the U.S., as approximately 80 % of the nation's ground and surface water is used in agricultural operations (USDA ERS 2012). However, the goal of optimizing the efficiency of irrigation is important since it can lead to a more economically and environmentally sustainable operation for producers. For crops such as potato in Florida, this is especially true since the water requirement for different potato genotypes and environments can range from 40 to 80 cm of water per growing season (Scherer et al. 1999; Haverkort 1982). But meeting those water demands can be quite challenging because the normal growing season in the state (January through June) often encompasses long periods of reduced rainfall accompanied by elevated ambient air temperatures (greater than 32 °C). In addition, the majority of soils where potatoes are produced in Florida are composed of deep, well drained, sandy soils with low water holding capacity. These environmental limitations combined with the relatively shallow rooting depth of potato of 60 cm (Munoz-Arboleda et al. 2006; Lesczynski and Tanner 1976) makes proper irrigation scheduling and management pivotal for producing a high yielding and profitable crop in Florida and regions with similar environmental conditions.

Many past studies have focused on the response of potato to various amounts and timing of water stress in an effort to explore more conservative irrigation options. Much of this work has used some type of soil water measurement, either alone or in conjunction with evapotranspiration (ET), to schedule irrigation to meet crop water demand and maintain soil water status at various thresholds (Shahnazari et al. 2007; Onder et al. 2005; Shock et al. 1992; Lynch et al. 1995; Jefferies and MacKerron 1989). This research has been partially translated into commercially available irrigation scheduling tools for potato that utilize measurements of soil water to make irrigation decisions (Shock et al. 2006; King and Stark 1997). In fact, to date, one of the largest commercial potato producers in Florida has soil water probes in place to aid in making irrigation scheduling decisions (John Nordgaard, Black Gold, Inc., personal communication). The common assumption often made in scheduling irrigation utilizing soil water sensors is that sensor readings are indicative of crop water use and can be used to quantify crop stress levels. For example, Lynch et al. (1995) used a soil water tension of −40 kPa to initiate irrigation of a well-watered treatment and −80 kPa to initiate irrigation for a water stress treatment. Continued research further refined these thresholds and determined that there is a negative impact on tuber yields when soil available water drops below 65 to 50 % of soil water holding capacity (Costa et al. 1997; Ojala et al. 1990; van Loon 1981). These results have led to the development of irrigation scheduling recommendations for commercial potato production that typically advocate keeping the available soil water level in the rooting zone between 60 and 70 % of plant available water (Aegerter et al. 2008; Tomasiewicz et al. 2003; Scherer et al. 1999).

There are many different methods and technologies available to determine soil water content, particularly for potato (Zotarelli et al. 2010; Shock et al. 2006; Tomasiewicz et al. 2003; Scherer et al. 1999; Gordon et al. 1999; Costa et al. 1997; Lynch et al. 1995). Capacitance probes are a common choice for commercial irrigation scheduling and determine soil water content by measuring the dielectric constant of the soil surrounding the sensor (Fares and Alva 2000). Capacitance probes have shown promise for irrigation scheduling in several crops, particularly for bell pepper and tomatoes in Florida (Zotarelli et al. 2009). While capacitance soil water sensors are relied on by many producers for scheduling irrigation (including many large commercial operations), very few producers actually calibrate these sensors. In fact, many commercial companies that market these sensors communicate to growers that calibration is not necessary and that the relative sensor readings between rain or irrigation events and dry conditions can be used to evaluate moisture levels and schedule irrigation (Adcon, Inc., personal communication). However, these recommendations have not been researched using commercial soil water sensors in a typical production setting and in a manner that commercial producers would use. Further, because many of these sensors have the capability of measuring soil water at varying soil depths simultaneously, it would also be important to determine which soil depths most accurately reflect crop water use and how the appropriate monitoring depth may change over the season. The relationship of soil water by depth with crop water uptake is a complex parameter to accurately identify and may vary significantly as the crop develops (Sharp and Davies 1985).

Despite the assumption of soil water measurements as accurate surrogates for potato water use and stress, few studies have directly compared measurements of soil water with crop water use (Starr et al. 2008; Gordon et al. 1999), or compared the strength of this relationship at varying soil depths. Sap flow is one method that could effectively quantify crop water use and allow for comparison with soil water. The measurement of sap flow is a direct and continuous quantification of plant transpiration on a fine time scale (usually 15 to 60 min) but results can also be summed over days or seasons to determine total crop water use (Tognetti et al. 2004). The technique has been used successfully in potato (Gordon et al. 1997) and it has been shown that potato plants undergoing water stress have reduced sap flow compared to plants with adequate water availability (Gordon et al. 1999). Directly relating measurements of soil water with sap flow could test how representative soil water readings are of crop water status and overall crop transpiration, as well as determine the limitations of using soil water sensors for aiding in irrigation scheduling for potato. While the sap flow approach could be quite powerful for evaluating the efficacy of using soil water sensors for irrigation scheduling, only two previous studies have attempted these measurements in potato (Starr et al. 2008; Gordon et al. 1999). These studies however, were aimed primarily at determining the variation between irrigated and drought stressed potatoes and did not directly examine the relationship between sap flow and soil water for irrigation scheduling purposes. Also, the soil water sensor and the manner in which the data were collected in the aforementioned studies were not reflective of those that would be commonly used by commercial producers.

The current practices for scheduling irrigation in commercial potato production in Florida are often observational and based on the "touch and feel" method of physically examining the soil. However, increasing numbers of producers are utilizing commercially available soil water sensors to aid in their irrigation scheduling decisions. The potato crop in Florida is considered by producers to have a shallow rooting depth and is managed as such. Thus, soil water at depths greater than 30 cm are typically ignored. Further, once the plants reach the flowering stage, it is typical for irrigation applications to occur continuously unless a significant rain event occurs (1.3 cm or greater).

To evaluate the efficacy of scheduling irrigation using commercial soil water sensors, the current study aimed to quantify sap flow across the critical water use period for potato (tuber bulking) and relate total crop daily water use with average soil water data collected from sensors commonly utilized by commercial producers in Florida. By conducting this research in a commercial potato field, including utilizing data from producer installed, and uncalibrated soil water equipment, it was possible to evaluate the feasibility of this system for irrigation scheduling and to determine the relationship between soil water and crop water use directly. While this method does not provide absolute readings of soil water, it does provide the opportunity to determine the relative relationship between sensor readings utilized in this fashion with crop water use. Further, since the producer's sensors monitored moisture at six depths simultaneously, the soil depth at which soil water and sap flow were most closely related could be determined across this critical time period of the season. To determine if the strength of this relationship was impacted by reduced irrigation levels, a mild water reduction was imposed and the relationship between sap flow and soil water was compared in full and partial irrigation treatments. A mild reduction was used to reflect a possible water conservation strategy for growers, a policy that is being recommended by water management districts in the area. The specific objectives of the study were to: 1) determine if there was a significant relationship between 24 h daily sap flow totals and average daily soil water levels; and 2) evaluate how the strength of this relationship was affected by moisture measurements at differing soil depths.

Materials and Methods

The research was conducted in 2011 and 2012 in commercial potato fields under the operation of Black Gold Potato, Inc. and were located in O'Brien, FL (30°04′58.82″N, 82°58′29.58″W, elev. Twenty-one meters in 2011; and 30°06′42.84″N, 83°04′02.79″W, elev. 16.5 m in 2012). The soil in these fields was an Alpin fine sand (Thermic, coated Lamellic Quartzipsammets) which is classified as being excessively drained, having moderately rapid permeability, and very low available water holding capacity (USDA NRCS 2006). Texture analysis in both years of the study showed an average of 95 % sand in the upper 61 cm. The potato cultivar 'Frito Lay 1867' (FL-1867), a widely grown cultivar processed for chip products in the U.S., was planted on 18 and 16 February in 2011 and 2012 respectively. For both years, the inter-row spacing was 86 cm while the intra-row spacing between tuber seed pieces was 25 cm. Other location and crop management details are described in Byrd et al. (2014).

Most Florida potato production fields grown under overhead irrigation receive about 1 cm of water applied to the crop on a 24–32 h basis once the crop reaches the flowering stage. In the production fields utilized in this study, which were approximately 54 ha in each year, this was accomplished with a single pass of a Valley (Valmont Irrigation, Valley, NE) center pivot irrigation system equipped with Nelson R3000 (Nelson Irrigation Corporation, Walla Walla, WA) sprinkler nozzles. The center pivot system in 2011 took 30 h to apply 10 mm over the entire field; while in 2012 it took approximately 26 h. Once this irrigation regime was started (roughly 40–45 days after planting, DAP), the irrigation system was run continuously for a 2 month period up to harvest, unless a rainfall event in excess of 1.3 cm was received; at which time, irrigation was delayed for approximately 24 h depending on the amount of precipitation received. The irrigation treatments in this project consisted of: 1) **full treatment**: the normal irrigation schedule as just described; and 2) **partial treatment**: an irrigation skip (or a dry pass) of the center pivot where the partial treatment section was not irrigated while the full treatment section was, followed by full irrigation for two passes of the system in both treatments. When a skip was performed, the pump was manually turned off so that no water was applied as the pivot passed over the partial treatment section completely. In both years, the location of the study within the field was between the fifth and sixth towers from the pivot point, two towers from the edge of the field to prevent any type of border effects. The partial irrigation treatments were designed to be initiated after primary tuber initiation was complete. Based on the number of tubers per plant quantified at harvest in 2011, the first skip likely occurred just prior to the end of tuber initiation in that year; therefore, the irrigation treatment in 2012 was delayed to avoid applying reduced irrigation during the latter part of tuber initiation (Byrd et al. 2014). In 2011, treatments began on 7 April (48 DAP), which resulted in 14 irrigation skips and a difference of 13.5 cm of water applied between the full and partial irrigation treatments; while in 2012, treatments began on 16 April (60 DAP) and resulted in nine irrigation skips and a difference of 9.3 cm of water applied between the full and partial irrigation treatments (Table 1). In order to conform to design and measurement equipment limitations presented by working in a commercial production field, irrigation plots were laid out with two sectors of approximately 5° of the pivot circle; one sector served as the full treatment and one sector as the partial treatment as described above (Fig. 1). Within each sector, four sampling and measurement plots of approximately 18×24 m were arranged randomly across an approximately 3716 m^2 area.

Potatoes were harvested and measurements of soil water and sap flow were ceased on 10 June (110 DAP) and on 23 May (97 DAP) in 2011 and 2012, respectively. The 2011 season was longer in duration compared to 2012 due to slow market demand and processor orders in this year for the FL 1867 variety, which caused the company to delay the commercial harvest of these fields.

Utilization of Soil Water Sensors

For soil water measurements, this study utilized the existing soil water equipment employed by Black Gold Farms for monitoring soil conditions in their commercial fields. Eight Adcon SM1 soil water capacitance sensors (Adcon Telemetry, Klosterneuburg, Austria) were located in the field (four in the full and four in the partial irrigation treatments), and readings were logged every 15 min for the duration of the growing season. Soil moisture sensors were installed on 14 March (24 DAP) and 3 April (47 DAP) in 2011 and 2012, respectively. The sensors measured relative soil water at six depths in the soil profile (10, 20, 30, 40, 50, and 60 cm). Black Gold Farms utilized these Adcon sensors to indicate soil water status in their production fields by monitoring the raw voltage values from the sensors which were not calibrated for actual volumetric water content (VWC). Therefore, individual sensors may have variable absolute values even within the same irrigation treatment. Though these sensors can be calibrated, the current study aimed to accurately reflect what is being utilized by commercial growers who employ this technology for irrigation scheduling; therefore, the raw voltage values were collected to determine relative soil water across treatments. To standardize readings across sensors, a maximum value was found for each individual sensor across all six depths measured during the entire season. This maximum reading for each sensor was considered to be a value of 100 % for that individual sensor, and all other readings from that sensor were expressed as percent of maximum value (PMV). This was done for each of the eight sensors in both years and all relative soil water values were calculated and expressed as PMV readings. The PMV values are presented as daily averages by depth and by treatment so that values could be compared across sensors even though raw values could be variable. These PMV values represent a simple method that growers could use to standardize data if a grower was using more than one sensor in a field or had sensors installed in multiple fields. This method also allowed the evaluation of the utility of the Adcon data managed in this way for irrigation scheduling.

Table 1 Meteorological data from 2011 and 2012 growing seasons including average daily temperature, average minimum and maximum daily temperatures, average relative humidity, irrigation applied, and precipitation totals

Year	Avg. Temp. (C)	Min. Temp. (C)	Max. Temp. (C)	Relative Humidity	Irrigation Applied (cm)		Precipitation (cm)
					Full	Partial	
2011	20.6	12.7	28.8	73 %	57.4	43.9	20.5
2012	20.6	14	28	75 %	58.3	49.1	7.9

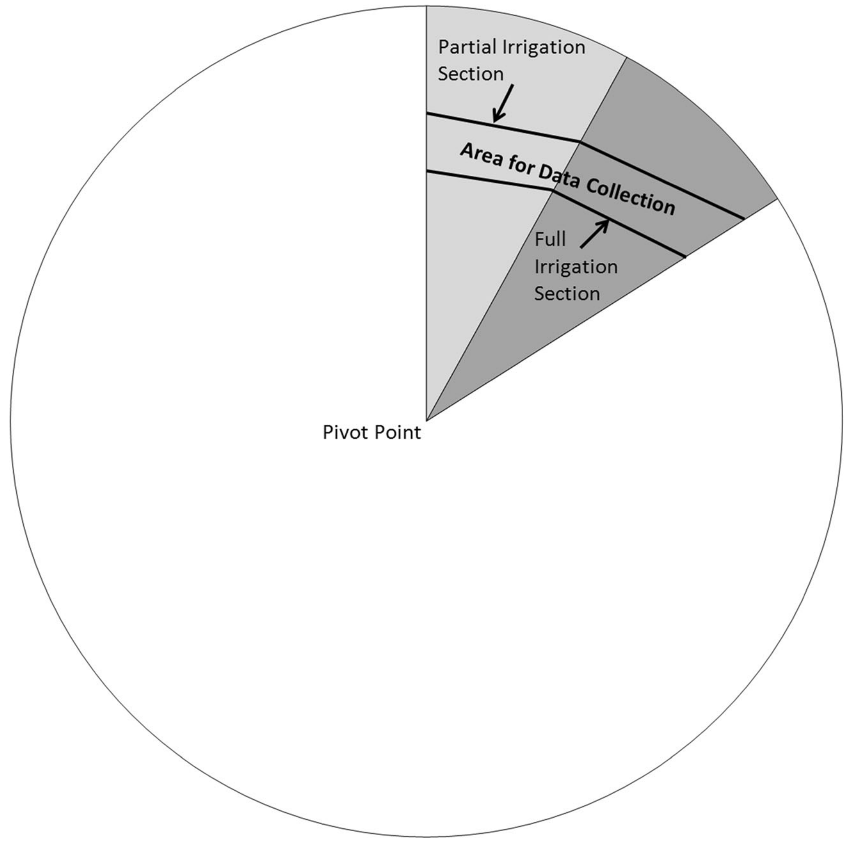

Fig. 1 Diagram of field layout of the study site located within the production field and alignment of treatment sections and data collection areas within each treatment section

Sap Flow Measurements

Sap flow collars (Dynamax Inc., Houston, TX) were installed 1 April (42 DAP) in 2011 and 21 April (65 DAP) in 2012 on four plants in both the full and partial irrigation treatments, in close proximity (approximately 1–2 m) to the soil water sensors. Collars were installed on the main stem of the plants, just above the soil surface and below any lateral stems coming off the main stem. Similarly to the soil water sensors, the sap flow collars logged a reading every 15 min in grams of water flow per hour (g/h). The initial stem size required size SGA-10 sap flow sensors (accommodating stem sizes of approximately 8 to 11 mm) which were later changed in the season to SGA-13 sensors (accommodating stem sizes between 12 and 14 mm) as plants grew. This resulted in SGA-10 sensors being installed for approximately 30 days and the SGA-13 sensors installed for approximately 40 days. After the SGA-13 sensors were installed, stem diameter did not increase for the remainder of the season to an extent that would require larger sensors. Plants were collected just after collars were changed from SGA-10 to SGA-13 sensors (21 and 28 April in 2011 and 2012, respectively) and again when collars were removed just prior to the final crop harvest (2 June and 21 May in 2011 and 2012, respectively). Once collected, the leaves were removed from the stem of each plant and scanned using a LI-COR model 3100 leaf area meter (LI-COR Environmental, Lincoln, NE) in units of cm^2. This value was then used to express normalized sap flow rate (NSFR) in grams per hour per cm^2 of leaf area ($g/h/cm^2$). Data quality was maintained by examining individual 15 min sap flow readings and removing erroneous data points that represented flow rates exceeding actual values (overflow). These overflow values were determined by assessing the threshold maximum value for sap flow; in most cases flow did not exceed 200 g/h; therefore, the individual 15 min values that exceeded 200 g/h were removed in both years (representing approximately 0.02 and 0.03 % of sap flow values in 2011 and 2012, respectively). To calculate total daily water use (TDWU in g/cm^2), NSFR values were summed over each 24 h period (midnight to midnight) for the duration of the collar installation period (57 and 29 days in 2011 and 2012, respectively). The average TDWU values were expressed as an average over the four sensors within each of the irrigation treatments.

Statistical Analysis

Differences in average TDWU between full and partial treatments were compared using ANOVA. To examine the direct relationship between relative average daily soil water readings (PMV) and crop water use on a 24 h basis (TDWU), data were analyzed using both linear and non-linear regression (JMP Pro 9 software, SAS Institute Inc., Cary, NC). For each regression, TDWU across both irrigation treatments and again within treatments (full and partial) was regressed with daily averages of PMV by depth (10, 20, 30, 40, 50, and 60 cm). Performing separate regressions by soil depth for PMV and TDWU allowed the identification of the depth(s) at which soil water and crop water use were strongly related.

Results and Discussion

Rainfall totals during the growing season (19 February to 10 June in 2011; 16 February to 25 May in 2012) were 20.5 and 7.9 cm for 2011 and 2012, respectively (Table 1). In 2011, 57.4 and 43.9 cm of irrigation were applied to the full and partial irrigation treatments, respectively; while in 2012 these totals were 58.3 and 49.1 cm for the full and partial plots, respectively. The full irrigation treatment had significantly higher yields than the partially irrigated treatment in 2011, while in 2012 there was no difference in yield (Byrd et al. 2014). The negative impact on yield due to the reduced irrigation in 2011 likely occurred because tuber initiation was incomplete at the time of imposition of the reduced irrigation rates.

In 2011, average daily NSFR measured in the full treatment ranged from 0.000106 to 0.066564 g/h/cm^2, while in the partial treatment, NSFR values ranged from 0.000110 to 0.106076 g/h/cm^2 (Fig. 2). Average daily NSFR in 2012 in the full treatment ranged from 0.0002 to 0.0549 g/h/cm^2 while in the partial treatment NSFR ranged from 0.0001 g/h/cm^2 0.0733 to g/h/cm^2. Maximum NSFR values were 0.05 to 0.07 g/h/cm^2 and were close to the flow range determined by Gordon et al. (1999) for potato of 600–900 g/h/m^2 (noting the difference in units) in a study performed in Canada. Average NSFR in both years typically peaked for all plants between 13:15 and 17:45 h and gradually declined after 19:00 h to eventual zero flows overnight (Fig. 2). This pattern of sap flow follows other studies in potato which generally show a midday peak (Gordon et al. 1999). However, Gordon et al. (1999) found that sap flow peaked in stressed plants before noon, while in irrigated plants, flow peaked in mid-afternoon. The irrigated plots in that study had an available water deficit (compared to field capacity) of 16 % compared to 81 % in the stressed crop (Gordon et al. 1999). This variable time of day response between full and partial irrigated plants was not found in the current study, most likely due to the fact that the difference in water deficit between full and partial treatments was not as severe as in Gordon et al. (1999). Over the season, sap flow rates in the current study began to decline at approximately 10 days before harvest (89–90 DAP). This decline in late season sap flow observed in this study has not been documented in previous studies on potato and may be related to overall crop senescence. The summation of NSFR

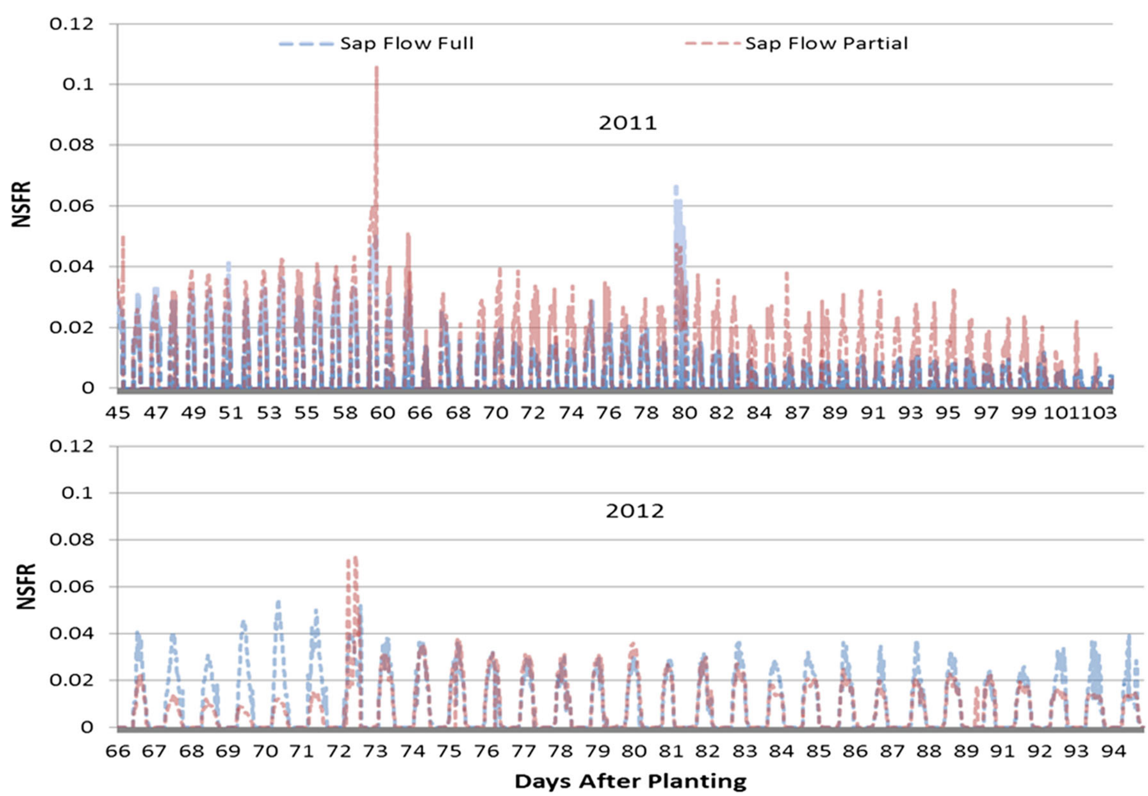

Fig. 2 Seasonal normalized sap flow rates (NSFR) from full and partial treatments in 2011 and 2012. The partial treatment started on 49 DAP in 2011 and 60 DAP in 2012

values over a 24 h period (TDWU) revealed no impact in either year of the irrigation treatment on average TDWU over the sampling period (for 2011 and 2012, respectively: F ratio= 3.3094 and 0.5650; p-value=0.1188 and 0.4807). Average TDWU across both treatments was 0.186 and 0.207 in 2011 and 2012, respectively.

In contrast, irrigation did have an effect on PMV values which varied between irrigation treatments and among soil depths, with an interaction between treatment and depth in both 2011 and 2012 (Table 2). Overall, PMV values were higher in the full than in the partial treatment which agrees with Alva (2008) who found soil water measured by capacitance probes to be decreased under partial irrigation (70 % ET replacement) throughout the soil profile compared to fully irrigated plots. However, because this trend was not true at every depth, there was an interaction between treatment and depth in both 2011 and 2012 (Table 2). Specifically, full plots had higher PMV than the partial irrigated plots at all depths except 50 cm in 2011, and at all depths except 10 and 20 cm in 2012 (Table 3). As an aside, the large difference in basic PMV values in 2011 when compared with PMV values in 2012 is not a factor of more water being applied in 2011, different soil types, or any other environmental factor; it is purely a result of using raw voltage values to obtain PMV and illustrates the wide variability in year to year that can occur when taking measurements of soil water in this manner. This is an important point to make, however, because when growers use these types of sensors in this way to aid in irrigation scheduling, new thresholds would have to be determined each growing season and no carryover of previously obtained thresholds or values could occur.

A key finding and primary focus of this study was the examination of the magnitude of the relationships between TDWU and PMV, because the strength of this relationship is essential for the use of soil water sensors for irrigation scheduling. There was a significant relationship between TDWU and PMV; however, the R^2 values for linear and non-linear regressions between TDWU and PMV across and within both irrigation treatments and across both years were relatively low, ranging from 0.04 to 0.56 (Tables 4 and 5). This relationship between TDWU and PMV across irrigation treatments in this study is somewhat smaller (comparing R^2 values) than for other environmental variables examined in previous studies. For example, Gordon et al. (1999) obtained R^2 values of 0.54 to 0.78 and 0.58 to 0.81 when relating sap flow to solar radiation and vapor pressure deficit, respectively. In another study, Hingley and Harms (2008) found R^2 values of 0.72 and 0.66 when relating sap flow to temperature and net radiation, respectively. These findings are expected since radiation and vapor pressure deficit have a stronger impact on sap flow as these factors directly drive plant transpiration at the leaf level. However, it is important to note that measurements such as solar radiation, vapor pressure deficit, and net radiation are not commonly used in a commercial production setting to aid in irrigation scheduling, unlike soil water, which is commonly used and recommended to serve in this capacity. Within irrigation treatments, the relationship between TDWU and PMV was not significantly correlated when depths were pooled in

Table 2 ANOVA results for soil moisture average daily percent of maximum value (PMV) measurements in 2011 and 2012

Trait factors	df	PMV 2011	PMV 2012
Trt.	1	<.0001	0.0187
Depth	5	<.0001	<.0001
Trt. x depth	5	<.0001	<.0001

Factors include irrigation treatment (full and partial irrigation), soil depth (10, 20, 30, 40, 50, and 60 cm), and the two-way interaction of treatment by depth

Table 3 Average daily percent of maximum value (PMV) from soil moisture capacitance probes in 2011 and 2012 across all collection dates and depths

	Soil depth					
Treatment	10 cm	20 cm	30 cm	40 cm	50 cm	60 cm
2011						
Full treatment	54.9e	52.9f	64.3d	82.1a	71.2c	77.9b
Partial treatment	51.7e	46.4f	56.6d	77.7a	72.4c	75.1b
2012						
Full treatment	31.0d	26.1f	31.8e	45.1a	41.6c	44.0b
Partial treatment	36.1d	26.6f	24.4e	43.6a	40.3c	40.6b

Means within an irrigation followed by the same letter are not significantly different by LSMeans Tukey's

Table 4 Linear and quadratic regressions of total daily water use (TDWU) and percent of maximum value (PMV) from soil moisture sensors across both irrigation treatments in 2011 and 2012; shown are R^2 values for each regression

Soil depths	Linear	Quadratic
2011		
10 cm	0.23 N**	0.29 N**
20 cm	0.15 N**	0.16 P**
30 cm	0.04 N*	0.06 N*
40 cm	NS	NS
50 cm	0.08 P**	0.11 N**
60 cm	NS	NS
2012		
10 cm	0.28 N**	0.29 P**
20 cm	0.24 N**	0.24 P**
30 cm	NS	NS
40 cm	NS	NS
50 cm	NS	NS
60 cm	NS	NS

Direction of regression is indicated as either positive (P) or negative (N) with significance at 0.05 (*) and 0.01 (**)

Table 5 Linear and quadratic regressions of total daily water use (TDWU) and percent of maximum value (PMV) from soil moisture sensors within each irrigation treatment in 2011 and 2012; shown are R^2 values for each regression

Soil depths	Full		Partial	
	Linear	Quadratic	Linear	Quadratic
2011				
10 cm	0.32 N**	0.38 N**	NS	NS
20 cm	0.21 N**	0.28 P**	NS	NS
30 cm	NS	NS	NS	0.18 N**
40 cm	0.22 P**	0.24 N**	0.08 P*	0.25 N**
50 cm	NS	NS	NS	0.17 N**
60 cm	NS	NS	NS	0.14 N*
2012				
10 cm	0.36 N**	0.39 P**	NS	NS
20 cm	0.20 N*	0.28 P*	NS	NS
30 cm	0.20 N*	0.24 P*	0.19 N*	0.30 P*
40 cm	NS	NS	NS	NS
50 cm	NS	NS	NS	NS
60 cm	0.20 N*	0.25 P*	NS	0.56 P**

Direction of regression is indicated as either positive (P) or negative (N) with significance at 0.05 (*) and 0.01 (**)

either year of the study. This illustrates the importance the monitoring the correct depth(s) when attempting to relate soil water levels to plant water use.

Another goal of this study was to examine the specific regression results by soil depth, to determine which soil depths more closely reflect crop water use and could thus be monitored for more accurate irrigation scheduling. Across irrigation treatments, significant relationships between TDWU and PMV were present at all depths except 40 and 60 cm in 2011; while in 2012, only PMV measured at the 10 and 20 cm depths showed a significant relationship with TDWU (Table 4). Overall, the relationship between TDWU and PMV was stronger at shallow depths (10 and 20 cm) with no significance at deep depths (40 and 60 cm). However, these patterns differed somewhat within each irrigation treatment independently, indicating that the relationship between TDWU and PMV depended upon soil water availability. In the partial treatment, sap flow was significantly related to PMV at deep depths (>30 cm); while in the full treatment, relationships were seen at the 10 and 20 cm depths (Table 5). These relationships are also illustrated in Figs. 3 and 4 for 2011 and 2012, respectively. This may indicate a deeper overall rooting depth and water uptake activity in the partial as compared to the full treatment; roots likely responded to the reduced irrigation schedule by expanding

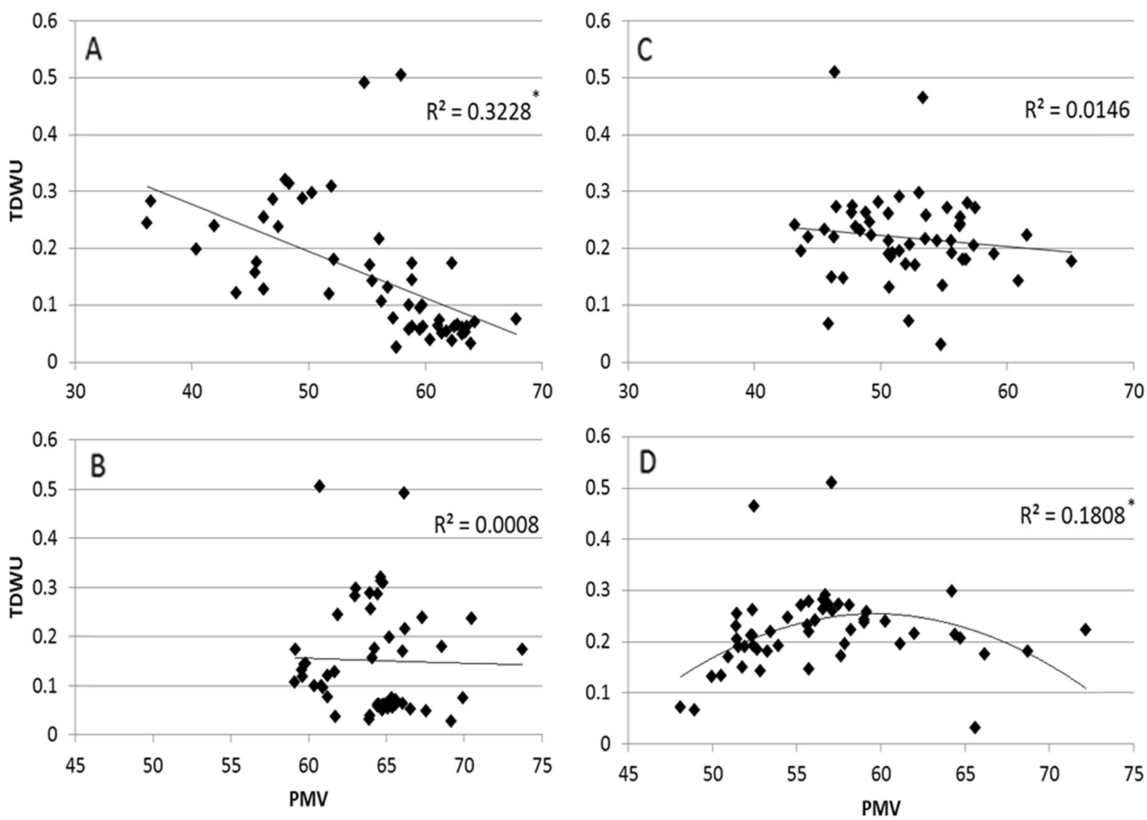

Fig. 3 Linear and quadratic regressions of total daily water use (TDWU) with soil moisture measured as percent of maximum value (PMV) at 10 and 30 cm depth in 2011 from the full and partial irrigation treatments. Treatments and depths of PMV included are: full irrigation at 10 cm (**a**), full irrigation at 30 cm (**b**), partial irrigation at 10 cm (**c**), and partial irrigation at 30 cm (**d**). *Indicates significant regression at α 0.05

deeper into the soil profile than plants under full irrigation. In both 2011 and 2012, the linear relationship in the full treatment at the 10 cm depth was negative which may be indicative of a saturated soil profile such that any additional water added through irrigation caused transpiration to be inhibited leading to declining TDWU (Figs. 3a and 4a). In 2011, this relationship in the full treatment disappeared at deep depths, such as 30 cm and below (with the exception of 40 cm) which could be indicative of little to no root activity at these deeper depths (Fig. 3b). For plants in the partial treatment, there was no relationship between TDWU and PMV at 10 cm, again indicating that root activity was likely negligible at this shallow depth (Fig. 3c). For the deeper 30 cm depth, the relationship was a negative parabolic relationship (Fig. 3d), indicating that TDWU increased with PMV to a threshold value (typically 80 PMV), after which TDWU declined with increasing PMV (Fig. 3c), perhaps due to an inhibition of transpiration beyond this PMV level. However, this pattern was not the same in 2012 – the relationship between TDWU and PMV for the partial treatment was a positive parabolic one (Table 5, Fig. 4). In a study conducted in England on a sandy loam soil, Parker et al. (1989) found that the majority of root water uptake in potatoes occurs in the top 0.4 m of the soil profile, with some smaller amounts of water uptake occurring down to 1.2 m. The majority of the significant relationships in the present study (17 out of 22) occurred at the 40 cm depth or shallower.

While the strength (as reflected by R^2 values) of the relationship between PMV and TDWU appeared to be somewhat low, this is likely related to the lack of large water deficits or associated crop stress levels in either the full or partial treatments. It would be expected that the relationship between soil water and transpiration would strengthen with increasing levels of stress from a physiological standpoint. It is well documented that with decreasing levels of available soil water, transpirational losses in the plant decrease as stomata close, often first mediated by hormonal signals (Jackson 1993; Davies and Zhang 1991). For example, Liu et al. (2005) showed decreasing levels of stomatal conductance and transpiration with progressive soil drying in soybean. However, the fact that the soil water readings were still able to reflect sap flow even under low levels of water deficit demonstrates the efficacy of soil water sensors as a basis for irrigation scheduling. Further, this study shows there is certainly efficacy in using even uncalibrated soil water sensors for this purpose. An additional area of focus that would aid in evaluating the strength of the relationship between PMV and TDWU would be directly measuring the rooting depth of the crop and

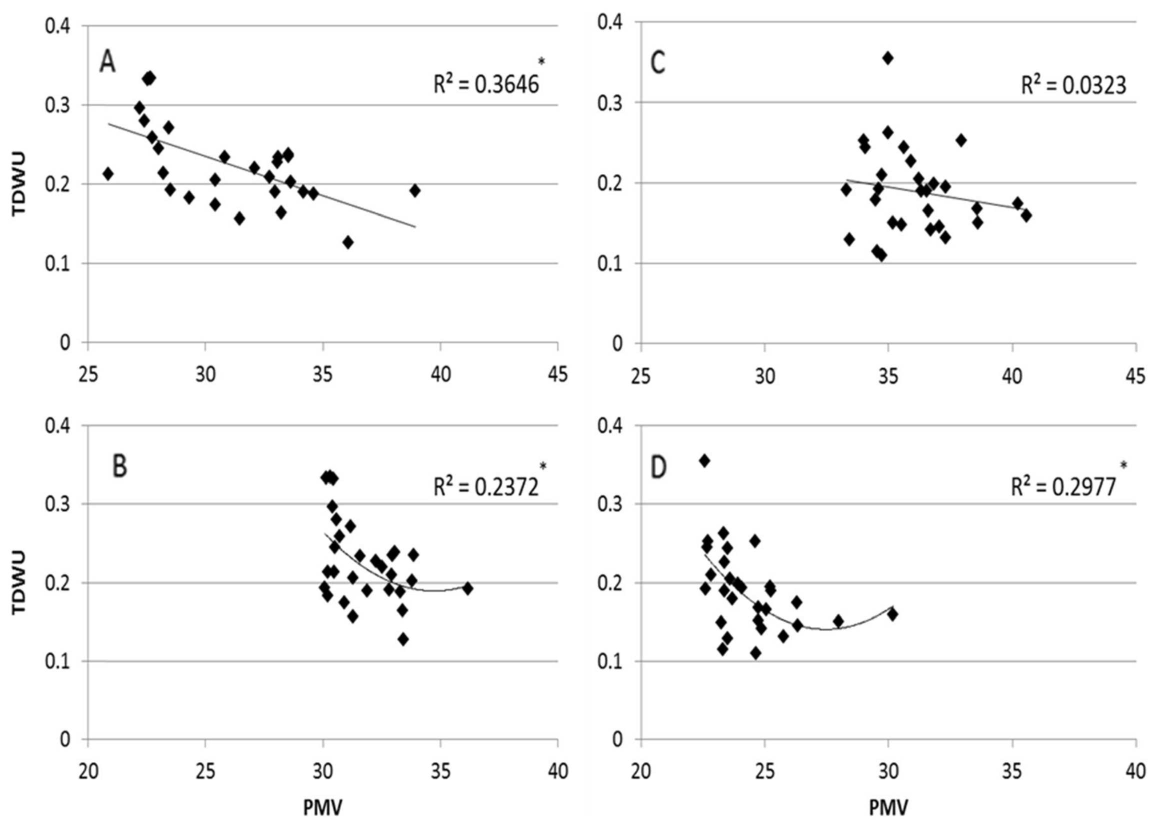

Fig. 4 Linear and quadratic regressions of total daily water use (TDWU) with soil moisture measured as percent of maximum value (PMV) at 10 and 30 cm depth in 2012 from the full and partial irrigation treatments. Treatments and depths of PMV included are: full irrigation at 10 cm (**a**), full irrigation at 30 cm (**b**), partial irrigation at 10 cm (**c**), and partial irrigation at 30 cm (**d**). *Indicates significant regression at α 0.05

determining if direction of the slope as well as the shape and strength of that relationship, when significant, is reflective of plant response or is merely coincidental.

Conclusions

In conclusion, significant relationships were present in the current study between 24 h sap flow totals and soil water levels. This relationship was generally stronger at shallower soil depths across both irrigation treatments and years. This study documented that even uncalibrated soil moisture sensors readings (as is most often utilized in commercial production settings) can be related to crop water use. However, when soil water sensors are used in commercial potato production for irrigation scheduling it would be important to establish the threshold value (calibrated or uncalibrated) that represents optimal soil water conditions. Whether or not this threshold is more effective at triggering irrigation in either a calibrated or uncalibrated probe is not clear. This may best be accomplished by comparing calibrated and uncalibrated sensors within the same location to determine if similar relationships exist between the two. This study also showed that the application of soil moisture sensors for irrigation scheduling in a commercial production system would require monitoring of soil water levels at depths correlated to crop water use, and that more work is needed to identify the specific depths that are relevant to observe. Identifying the critical depths to monitor at particular crop development stages and developing irrigation scheduling recommendations based on a dynamic monitoring program of soil water levels at these depths could greatly improve the benefit gained from the utilization of soil moisture sensors for commercial potato producers.

Even though the soil water sensors in this current study were not calibrated (in an effort to adhere to the commercial protocol in the normal production system), the use of calibrated soil water sensors may assist in relating sap flow rates or crop water use in general to accurate, quantified measures of soil water content and could lead to standard soil water thresholds for triggering irrigation applications in production settings. Of course, sap flow sensors themselves could be used to provide irrigation decisions and they have proven to be successful for irrigation scheduling in grapevines (Patakas et al. 2005), and olive trees (Fernandez et al. 2001). However, triggering irrigation applications based on sap flow alone would also be a difficult concept for commercial producers to adapt, as the installation, data collection, and analysis can be time consuming, especially if multiple fields are involved. Using capacitance soil water sensors for irrigation scheduling is certainly a viable option since commercial producers often have access to the sensors and many already have them in place in their fields. This study documents the direct relationship of soil water sensor readings to daily crop water use for the sensors used in this study, but careful determination of appropriate soil depths and trigger points are essential to their successful adoption.

Acknowledgments We would like to thank UF-IFAS and Black Gold Farms for their support of the research, and specifically Clay Pederson and the rest of Black Gold's staff at the Live Oak, FL farm. We also appreciate the work of the staff of Dr. Rowland's lab group for their help with data collection over the course of the project.

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