DRIP IRRIGATION AS ALTERNATIVE TO SEEPAGE TO INCREASE WATER USE EFFICIENCY IN POTATO PRODUCTION

By

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To Jesus

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Seepage is the traditional irrigation method for potato production in Florida. Although inexpensive, it has low water use efficiency (20-70%). Drip irrigation is >90% efficient and has the potential to produce potatoes in Florida. The objective of this study was to assess the feasibility of drip irrigation as alternative for potato production in Florida sandy soils.

A two-year field study was conducted to investigate the effects of two drip tape installation depths compared to seepage (SEP) on field grown potatoes. The drip treatments were surface (SUR) drip tape installed 5-cm above seed, and subsurface (SUB) drip tape installed 5-cm below seed. Two fresh market potato varieties: 'Fabula' and 'Red LaSoda', and one chipping variety: 'Atlantic' were tested. The experimental design was split plot replicated four times. Granular fertilizer was applied to all treatments, similar to practices in the area. Water quantity applied, soil moisture content, and water table level were quantified. Tuber yield and quality, aboveground biomass accumulation, nitrogen uptake, and root distribution, were also evaluated. Marketable yield was similar between SUR and SEP treatments within 'Atlantic' and 'Fabula'. The SUB treatment reduced marketable yield by 28% and 42% compared to

SUR and SEP for ‘Atlantic’ and ‘Fabula’, respectively. In contrast, ‘Red LaSoda’ produced significantly higher yield under SEP. Average marketable yield under SUR, SUB, and SEP irrigation treatments for ‘Fabula’ were 17, 10, and 17 Mg ha^{-1}; ‘Red LaSoda’ produced 13, 13, and 24 Mg ha^{-1}; ‘Atlantic’ produced 27, 20, and 28 Mg ha^{-1}. Drip treatments required 48% and 88% less irrigation water compared to seepage in 2011 and 2012, respectively, which was translated into average irrigation efficiency (IWUE) of 8, 6, and 3 kg m^{-3} for SUR, SUB, and SEP, respectively.

Aboveground biomass was higher under seepage compared to drip. There were no differences in root distribution among irrigation treatments for ‘Atlantic’.

‘Atlantic’ showed yield and quality improvement under SUR. Drip irrigation increased internal quality. Particularly, SUR reduced incidence of brown center disorders, hollow heart and internal heat necrosis. It was concluded that SUR drip irrigation increased IWUE while maintaining ‘Atlantic’ and ‘Fabula’ yield, and enhancing tuber quality.

CHAPTER 1
BACKGROUND AND LITERATURE REVIEW

The Potato Industry

Potato (*Solanum tuberosum* L.) ranks fourth among the world's agricultural products in production volume, after wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and corn (*Zea mays* L.) and is a major food crop in many countries (Fabeiro et al., 2001; FAO, 2012). Potato is widely grown in the United States under many climatic conditions and management practices (Levy and Veilleux, 2007). Potato is the leading vegetable crop in U.S., contributing to about 15 percent of farm sales receipts for vegetables (USDA, 2012). The U.S. is the fifth largest potato producer in the world after China, India, Russia, and Ukraine (FAO, 2010). Average U.S. yields have increased over the last 15 years due to improved management practices and adoption of new farming technologies (Guenthner, 2010a).

In Florida, potato production is an important component of vegetable sales. Florida is one of the five states in U.S. that harvest potato in spring (Hochmuth et al., 2001). This production meets specific market needs, has great demand, and results in higher prices than fall potatoes. For instance, from 2007 to 2011, the average price for Florida potatoes has been \$ 0.2 kg^{-1} higher than fall potatoes (ERS, 2012). Potato was ranked with the 6th highest crop value in the 2011 season according to the Florida Department of Agriculture and Consumer Services (FDACS, 2012). Approximately 14,731 hectares of potatoes are grown in Florida and 63% (~9,500 ha) of this production area is located at the Tri-County Agricultural Area (TCAA) in northeast Florida. Moreover, state production and harvested area for the 2010-2011 season increased by 4 and 12%, respectively, compared to the previous season (FDACS, 2012).

Nationally, potato tubers are a versatile staple that can be consumed either fresh or as processed products (chips, frozen, dehydrated, and canned). The fresh market potatoes in North America are classified as russets, whites, reds, and yellows based on skin color. Potatoes grown in northeast Florida are divided into two market categories: fresh and chip market (VanSickle et al., 2012). Fresh market tubers are sold based on their external appearance, and usually prices for fresh potatoes are higher than those for contract-based processing potatoes. Thus, growers aim to produce tubers with high quality features that look appealing to the public and ensure better economic returns (ERS, 2012; Fabeiro et al., 2001).

In terms of the U.S. chipping market, there has been a steady increase (>50% since 1960) in processing use of potatoes to meet consumer preferences and has led to growers adjusting production practices to meet contracts and adapt to this market trend (Guenthner, 2010b).

‘Red LaSoda’ has been the most popular grown red-skinned fresh market variety in the state. However, yellow-fleshed potatoes like ‘Fabula’ are gaining popularity among consumers (Guenthner, 2010b; Hutchinson et al., 2009). In the chip market category, the standard chip potato varieties produced in Florida are ‘Atlantic’, ‘Snowden’, and ‘Harley Blackwell’. These varieties are mainly grown due to their high specific gravity values (measurement of solid content in tubers) for use in the chipping industry (Hutchinson et al., 2002).

‘Atlantic’ is a highly valuable round white variety for the processing market and one of the most planted potato varieties cultivated in northeast Florida. It was released in 1976 by the United States Department of Agriculture and gained wide popularity among growers due to its excellent chip and fry quality. Previous studies have characterized ‘Atlantic’ as a high yield, high specific gravity potato when compared with other varieties in different regions of the country. For example, Webb et al. (1978) conducted a three year experiment and found that yields of ‘Atlantic’ exceeded those of ‘Sebago’, which is a locally adapted variety, by 40% under Florida growing conditions. ‘Atlantic’ ranked in the positions 8^{th} and 9^{th} out of the most cultivated potato varieties in Canada and the continental U.S. during the 2008 season (NPC, 2010).

Northeast Florida Agricultural Water Management

There is a growing competition among urban, recreational, industrial, and agricultural users for water resources in Florida. According to the last U.S. population census; Florida is the state with the third largest population growth per year (Campbell, 1997; Marella, 2004) thereby increasing water resource use from all sources. Therefore, reduced water resources coupled with growing environmentalist pressure and rising public interest for water quality and conservation is pushing water users, especially the agricultural sector, to evolve towards more efficient use of this resource (Boman, 1990; Alva, 2008a).

Irrigation is the largest component of freshwater use in Florida accounting for 49% of total withdrawals from the Floridan aquifer The increasing demand on limited water resources and the need to minimize adverse environmental consequences of food production seem to press for an important role of efficient irrigation technology in the future of Florida vegetable production. The Floridan aquifer is the main source of water in northeast Florida (TCAA). According to St. Johns River Water Management District (SJRWMD), agriculture is the major water user in the TCAA with an estimated average daily usage of 488 million liters of water per day during the potato irrigation season (Durden, 2000a). This high demand for groundwater during potato irrigation season causes problems related to drawdowns in the potentiometric surface of the Floridan aquifer, increased pumping costs as the water level drops down, and salt water intrusion into the aquifer (Haman et al., 1989; Vergara, 1994).

The Tri-County Agricultural Area (TCAA) contains Putnam, St. Johns, and Flagler counties. This area extends from Palatka to south Orange Park in Jacksonville along the northeastern Florida shoreline, and consists of mainly potato, cabbage (*Brassica oleracea* L.), and other cole crops (Chen, 2010). Potato production accounts for the largest planted area with 67% estimated row crop area in the TCAA. The potato growing season starts in late December or early January through late May or early June. After harvest, cover crops such as sorghum sudangrass are generally planted to control wind and water erosion in the field during the summer/fall periods (Munoz-Arboleda et al., 2006).

In 2000, St. Johns, Flagler, and Putnam counties (TCAA) reported a daily water withdrawal for irrigation of 34, 18, and 12 million gallons per day, respectively (Marella and Berndt, 2005). Furthermore, Putnam and St. Johns have been identified as a water resource problem due to the seasonal ground water withdrawals for potato irrigation. Additionally, Flagler County is projected to have critical water shortages in the near future due to the excessive water pumped for agricultural purposes and an increase in population (Vergara, 1994). This large water withdrawal from the aquifer has caused the area to be identified as a “Water Resource Caution Area” resulting in the need to look for strategies to protect groundwater as well as enhance water use efficiency of crops (Durden, 2000a; Trippensee et al., 1995; Vergara, 1998).

Seepage is the predominant irrigation technique in the TCAA for potato production. This method is broadly used because it is low-cost, has low maintenance requirements, and is effective in flatwoods locations where the natural water table is relatively high and can be readily raised. Conventional semi-closed seepage systems use shallow open ditches to distribute irrigation water in the field, and to maintain the height of the water table (Haman et al., 1989; Smajstrla et al., 2000). Water seeps laterally underground and moves from the perched water table by capillary action to the plant’s root zone (Singleton, 1996). Soil moisture status is the principal factor determining the start of a water event, with water pumping in the seepage system continuing until the soil is considered moist “enough” to prevent stress and yield loss in the crop (Casey et al., 1997).

Seepage irrigation has been extensively criticized due to its low delivery efficiency. This method is heavily dependent on soil characteristics and on the depth of the natural water table (Pitts and Clark, 1991). The soils in the TCAA are mainly sand (>90%), with low organic matter content. Therefore, they are characterized by low water holding capacity (i.e. average field capacity of 10-12%). The inefficiency of the seepage system, high sand content, irregular rainfall distribution, and the use of fertilizers increase the risk for nutrients leaching often leading to nonpoint source pollution in the St. Johns River watershed (Locascio, 2005; Munoz-Arboleda et al., 2008). Under Florida climatic conditions with uneven rainfall distribution during the potato growing season, farmers heavily rely on seepage to supply the crop with the water needed. However, during heavy rainfall events, the sandy soils have a limited ability to hold large volumes of water and runoff of nutrients to drainage canals occurs, resulting in significant loss of nutrients offsite (Waddell et al., 2000).

The aforementioned characteristics of seepage irrigation and the inaccuracy to determine thresholds that can be used for irrigation scheduling, result in the use of terms such as “enough”, “good”, and “moist” as soil water status commonly used for potato production. However, irrigation scheduling based on these subjective evaluations is often inefficient and unsustainable on a long-term scale. This type of management interpretation can be avoided with technology that 1) monitors the soil moisture and 2) increases control of water delivery to the root zone.

In addition, when soil is maintained excessively wet for prolonged periods, hypoxic conditions occur preventing adequate oxygen reaching the root and tuber and often increase the incidence of blights, rots, and wilts resulting in economic loss (Holder and Cary, 1984; Shock et al., 2007b). Soil moisture uniformity in the field is the most challenging characteristic of seepage irrigation and becomes a severe issue during tuber bulking when excessive water application increases the incidence of tuber internal and external disorders and compromises the plant’s ability to produce the maximum yield (Alva, 2008a). Thus, it is evident that sound water management will have a positive effect on the ability of the plant to absorb nutrients and increase the potential for higher marketable yield (Gudmestad, 2008; Shock et al., 2007b).

A uniform, more efficient seepage schedule is difficult to achieve because of the complexity of the shallow water table dynamics. Quantification of the water table contribution to crop needs is vague due to soil characteristics and water upward flux in sandy soils (Singh and Chauhan, 1996). Limitations of seepage irrigation are the inaccurate ability to determine when to stop irrigation, duration of the water event, and lack of distribution uniformity as well as its excessive dependence on the water table level, which makes it difficult to control since water table depth can widely vary in the field (Pitts and Clark, 1991).

Dry years have an enormous impact on the water table level and directly impact pumping costs and water requirements for seepage irrigation. The need for a more efficient irrigation method is imperative in the TCAA, as well as in other parts of the state of Florida, where agriculture relies on seepage systems (Alva, 2008b; Camp, 1998; Durden, 2000b; Livingston-Way, 2007).

A conversion from seepage to more efficient irrigation alternatives will potentially reduce nutrient loads to the St. Johns River watershed and groundwater that migrates from potato fields (Munoz-Arboleda et al., 2008). To improve the water application efficiency and reduce the leaching and runoff potential of seepage irrigation, alternative water application methods should be explored.

Drip irrigation is a method of delivering water directly to the root zone through a network of low density polyethylene pipes. This method increases the control of water volume used and greater efficiency (80-95%) is achieved (Burt, 1998; Goldberg et al., 1976; Morison et al., 2008). Drip irrigation has also been defined as the frequent low-dose application of water through emitters located close to the crop root zone. It offers many advantages; some of them are: 1) reduction of evaporation and increase of plant transpiration; 2) reduction of weed population; and 3) prevention of drainage and retention of nutrients in the root zone (Lamm et al., 2011). The high frequency application of water improves soil moisture content and reduces the volume of water applied and lost by deep percolation (Vazquez et al., 2006).

The drip system contributes towards increasing crop yield potential, improvement of water and fertilizer use efficiency, and offers the possibility for automation and fertigation through the drip line. High-frequency water events by drip irrigation reduce the use of soil as a water storage reservoir, provide daily moisture requirements to the root zone, maintain a high soil matric potential that reduces plant water stress, and enhances the soil's ability to store rainfall water because of the reduced soil volume wetted by emitters (Badr et al., 2010; Burt, 1998; Phene et al., 1992; Phene and Sanders, 1975; Saffigna et al., 1977).

Drip irrigation has been tested in different potato production areas in the world (Yuan et al., 2003; Onder et al., 2005; Patel and Rajput, 2007). Previous studies have reported similar marketable yield when drip and sprinkler were compared to produce potato. However, an average of 65 mm of water was saved with drip and higher root concentration was reported under the drip treatment (Shalhevet et al., 1983). Another study compared drip to seepage irrigation for tomato (*Solanum lycopersicum*) production and did not find significant differences in terms of yield or quality; but in terms of water use, seepage used an average of 3.5 times pan evaporation while the drip water use ratio was on average 50% of pan evaporation (Pitts and Clark, 1991).

Water resource savings and increasing crop yield per unit of water are becoming a strategic importance for many areas in the U.S. (Morison et al., 2008). Drip irrigation is an option for growers to overcome potential agricultural drought in northeast Florida; it provides water and energy conservation benefits that address many of the challenges facing irrigated lands, and applies water uniformly so that each part of the irrigated area receives the same amount of water (Badr et al., 2010; Patel and Rajput, 2007).

The high soil water content around drippers facilitates better water transmission to the surrounding soil and minimizes soil moisture fluctuations around the crop root zone; however thorough attention should be paid to capillarity and gravity forces that are dependent on soil properties in the field (Segal et al., 2000).

Although it has been documented that drip irrigation has an inherent >90% delivery efficiency, considerations such as grower management, installation, system pressure, and filtration play a fundamental role in attaining this efficiency. Drip tape can be used permanently or a single crop season based on installation depth. The determination of appropriate depth of installation and time of use involves consideration of crop value, soil texture, and crop root development pattern (Burt, 1998).

Surface placement of drip tape generally implies a shallow drip tape positioning (<10 cm) that is retrieved after each growing season in most crops. On the other hand, subsurface drip can be installed anywhere in the depth of root penetration. Subsurface drip irrigation has been defined as the “application of water below the soil surface by microirrigation emitters with discharge rates usually less than 7.5 L h^{-1} (ASAE Standards, 2001). Subsurface drip offers the potential to save water by reducing soil surface wetting and thus evaporation loss (Ayars et al., 1999). Under subsurface drip, water moves by soil matrix suction and eliminates the effect of surface infiltration characteristics, saturated condition of water during irrigation, and surface runoff (Badr et al., 2010; Lamm et al., 2011; Patel and Rajput, 2007). However, deep positioning of drip tape can poorly deliver water to the root system of shallow-rooted crops like potatoes (Clark et al., 1993).

The effects of drip tape placement depth have been previously evaluated on different crop systems. Clark et al. (1993) reported a significant increase of 5% in the marketable yield of field grown tomatoes when drip tape was positioned 3 cm below the soil surface compared to drip tape placed at a 30 cm depth. Patel and Rajput (2007) investigated the effects of five different drip tape installation depths (0, 5, 10, 15, and 20 cm deep) in sandy loam soils (69% sand) and reported that tuber yield was significantly affected by the tape positioning; obtaining maximum yield when drip tape was placed at 10 cm below the soil surface.

Dukes and Scholberg (2005) compared the use of different subsurface drip tape depth placement versus sprinkler irrigation for sweet corn on Florida sandy soils and found that drip tape placed at 23 cm deep used 11% less water than the sprinkler treatment and that no difference in marketable yield was obtained between treatments.

In arid regions like Egypt, subsurface drip irrigation has shown to significantly decrease water use when compared with surface drip. The use of subsurface drip in production areas like Arizona, Texas, and California has increased in previous years; however, this technology has to be thoroughly tested under different large-scale crop production systems to overcome any possible flaws. The outcome of these tests has to be a user friendly system that provides farmers with better decision-making tools to optimize water management (Lamm et al., 2011; Soussa, 2010; Thompson et al., 2003).

It has been mentioned in previous studies that surface drip irrigation is usually used for higher value crops while subsurface irrigation is used for lesser-value crops.

This discrepancy is due mainly to the farmer perception that subsurface drip is harder to manage because of lack of visible hints when there are irrigation problems and use of surface drip decrease this potential risk.

Readily available water to ensure crop establishment is the most challenging issue of subsurface drip irrigation. The adoption of this technology usually tends to bring problems due to lack of experience and knowledge on how to implement it and among growers the biggest concern is the proper evaluation of its performance and measurement of discharge uniformity since there is no visual guarantee that the entire farm production is being well irrigated, which increases economic risks (Lamm et al., 2011; Patel and Rajput, 2007).

The implementation of drip for potato production in sandy soils makes precise depth installation crucial to obtain maximum yield and quality. Therefore, a thorough evaluation of drip tape placement and its effects on soil moisture distribution, plant physiology performance, and tuber yield and quality are important to generate accurate guidelines for growers. The proper use of drip irrigation, either surface or subsurface, is a challenge where research efforts and outreach are necessary to develop reliable tools that can be used by farmers to ensure optimal irrigation practices specific for their local conditions (Lamm et al., 2011).

The goal of this study was to investigate the feasibility of drip irrigation as an alternative strategy to conventional seepage irrigation to increase water savings for potato production in northeast Florida. It was hypothesized that drip irrigation will potentially reduce irrigation water requirements compared to seepage irrigation, while maintaining potato tuber yield and quality.

Objectives

The objectives of this research were as follows:

1. to evaluate the performance of drip irrigation system as a water delivery method for potato production in northeast Florida (Chapter 2 and 3).
2. to evaluate the effects of drip irrigation on potato plant growth, nitrogen accumulation, yield and tuber internal and external quality (Chapter 2).
3. to investigate soil moisture and water table dynamics as influenced by drip and seepage irrigation systems (Chapter 3).

CHAPTER 2
PERFORMANCE OF DRIP IRRIGATION SYSTEM ON POTATO BIOMASS ACCUMULATION, N UPTAKE, TUBER YIELD AND QUALITY CULTIVATED IN FLORIDA SANDY SOILS

Introduction

Potato (*Solanum tuberosum* L.) is a high value crop in Florida. In 2011, potato production covered roughly 15,000 hectares of the state and received a crop value of $ 144 million. The Hastings area, also known as the Tri-County Agricultural Area (TCAA), encompassed 63% of the Florida potato area (USDA, 2012).

In the TCAA, potatoes are grown in sandy soils using seepage (subsurface) irrigation. Groundwater is pumped from deep wells and delivered to furrows spaced 18 m apart using semi-closed pipes. Within each 18 m, there is a group of 16 potato rows (0.35 m height), which make up a single 'bed'. The water is then carried along the furrows and seeps laterally underground. Farmers use a weir structure to hold the water back in ditches along the border of the field to raise the water table level (Livingston-Way, 2010). The goal is to bring the water table up to just below the root zone of the plants located between two water furrows. Hence, the seepage method is based on water table management (Livingston-Way, 2010; Singleton, 1996; Smajstrla et al., 2000).

The advantages of seepage are its low cost, low maintenance, and effectiveness in places like northeast Florida where a natural high water table occurs and plentiful supply of water exists (Haman et al., 1989). However, seepage water use efficiency ranges from 20% to 70% because much of the large quantity of water pumped is not available for crop use, but is used solely to maintain the water table level (Locascio, 2005; Dukes et al., 2012). In addition, seepage has low uniformity of water distribution, high percentage of deep percolation and high runoff potential in the field (Clark and Stanley, 1992). Seepage also causes wide soil moisture fluctuations in the field as a result of lateral flow and distance from the water furrows (Smajstrla et al., 2002). Consequently, due to the length of time that the water table is high, soil saturation tends to occur around the root zone reducing aeration, and affecting the ability of the plant to efficiently uptake nutrients, which adversely impacts tuber quality.

A proper drainage system is required to lower the water table and avoid damage caused by excessive soil moisture and rainfall. However, drainage also brings additional issues regarding accurate water level control. For example, unexpected heavy rain can have severe negative consequences when the water table is high. It results in loss of nutrients via runoff and percolation. However, if seepage irrigation ceases for a prolonged period, the potato hill is the first soil layer to be drained of moisture due to evaporation and high hydraulic conductivity of sand (infiltration rate 19 mm hr^{-1}) resulting in plant stress (Gudmestad, 2008; Livingston-Way, 2010).

Potato is extremely sensitive to water stress and water excess. Tuber yield, grade, and quality can be reduced by either over or under-irrigation. Over-irrigation creates low oxygen conditions in the soil and increases nutrient leaching from the active root zone, which stresses the plant. Under-irrigation of potato has a detrimental impact on nutrient uptake with further biomass and productivity reductions due to the plant sensitivity to water depletion (Shock et al., 2007).

It is well documented that potato plants rapidly close their stomata as response to slight reductions in water supply (Alva, 2008a). The timing and duration of water stress during different growth stages decrease plant canopy and biomass accumulation.

The low tolerance for water stress of potato’s shallow root system (85% of the root system is typically in the upper 30 cm of soil) makes readily available water a priority in order to avoid this type of detrimental situation (Onder et al., 2005 Shock, 2010; Wang et al., 2006).

In addition, the occurrence of tuber physiological disorders such as brown center, hollow heart, growth cracks, bruise susceptibility, and heat necrosis have been associated with wide variations in soil moisture content. A direct relation between low soil moisture conditions and misshapen tubers has been reported (Eldredge et al., 1996; Shock et al., 2007).

Faced with the need to increase water use efficiency by agricultural systems, alternative water delivery methods to seepage irrigation are being sought by producers to improve water management and savings, uniformity of distribution, and minimize tubers affected with the aforementioned disorders. Irrigation methods with high distribution uniformity are important to minimize losses and avoid to irrigate based on inaccurate measures of soil appearance and intuition (Fereres et al., 2003; Shock et al., 2006).

Drip irrigation has been tested in the past in several potato production areas in the U.S. in an effort to conserve overall production water use. Additionally, a reduction in off-site nutrient movement due to lowered water volumes applied more frequently is achieved, which results in reduced soil water fluctuation thus retaining fertilizer for a longer period of time in the root zone (Eldredge et al., 2003; Shock et al., 2006; Shock et al., 2007).

In addition, tuber shape defects during the bulking period can be significantly decreased and potato yields increased by minimizing drastic fluctuations of soil moisture content in the root zone (Gunel and Karadogan, 1998; Phene et al, 1976).

Another factor affected by irrigation practices is tuber specific gravity. The specific gravity is a measure of starch content of tubers and an important factor in processing. Yuan et al. (2003) tested five water regimes based on the evaporation values measured by a standard pan evaporation (0.2 m diameter) and found that tuber specific gravity tends to decrease as the amount of water applied increases and vice versa. Other studies reported that more frequent irrigation events have also shown potential to increase the specific gravity value (Gunel and Karadogan, 1998; Westermann et al., 1994). Waddell et al. (1999) reported a significant marketable yield increase (>4 Mg ha^{-1}) and tuber with highest specific gravities for 'Russet Burbank' under drip irrigation compared to sprinkler.

Any irrigation strategy must provide appropriate water quantities to the crop during specific developmental stages. There are five growing stages of the potato crop: 1) sprout development, 2) vegetative growth, 3) tuber initiation, 4) tuber bulking, and 5) maturation (Lynch et al., 1995; Miller and Hopkins, 2008; Yuan et al., 2003). The tuber initiation and bulking stages have been identified as the most sensitive stages to water stress. Inadequate irrigation during the tuber initiation and bulking has been shown to reduce growth and tuber production of marketable size (Ojala et al., 1990; Onder et al., 2005, Steele et al., 2006). Thus, more profitable potato productions can be achieved through efficient irrigation methods that keep soil moisture content constant throughout the season meeting the development-specific plant water requirements (Shock et al., 2007).

The national potato market is divided into two categories, fresh (or table stock) and processed products (chips, frozen, dehydrated, and canned). Fresh market tubers are sold based on their external appearance and thus a grower's target is tuber with appealing external attributes, such as skin, shape, and uniform color. On the other hand, external quality appearance is less important for tubers with processed destination as it is to obtain high specific gravity values (ERS, 2012; Hutchinson et al., 2009).

In Florida, early potato varieties maturing in less than four months are grown. In the TCAA, 'Atlantic' has been the chipping variety most widely grown for the past decades. For 'Atlantic', its high market demand, high specific gravity, adaptation to Florida conditions and high yield potential makes it popular among growers. However, 'Atlantic' is susceptible to brown center, internal heat necrosis, and hollow heart (Hutchinson et al., 2002). For fresh market, 'Red LaSoda' is one of the recommended varieties in Florida. Additionally, yellow-fleshed varieties like 'Fabula' are popular among consumers and growers. 'Red LaSoda' and 'Fabula' are less sensitive to the physiological disorders for which 'Atlantic' is susceptible. However, it has been reported that 'Red LaSoda' is susceptible to scab and corky ring spot in Florida conditions (Hutchinson, 2003; Hutchinson et al., 2009; Webb et al., 1978).

In the context of shorter water supply and expected pumping regulations for potato production in northeast Florida, drip irrigation may provide advantages for growers to enhance water use efficiency as well as achieve better control of soil moisture and nutrients in the potato root zone. However, valid concerns about adverse effects on tuber yield and quality could produce a negative response from growers to adopt this alternative irrigation method. The purpose of this study was to evaluate the effects of two drip tape depths on aboveground biomass accumulation, plant N uptake, yield and quality of ‘Atlantic’, ‘Fabula’ and ‘Red LaSoda’ potato varieties grown in northeast Florida. The hypothesis tested was that use of drip irrigation can maintain productivity and quality of chipping and fresh market potatoes.

Materials and Methods

The field experiment was designed to assess the response of potato varieties to irrigation methods. The experiment was conducted at the University of Florida Partnership for Water, Agriculture, & Community Sustainability at Hastings, Florida (29 41’ 27.58’’ N, 81 26’ 31.37’’ W) in the spring of 2011 and 2012. The soil in the experimental field was classified as sandy, siliceous, hyperthermic Arenic Ochraqualf and belongs to the Ellzey series (USDA, 1981). The proportions of the particle fractions in the topsoil (1 m) layer were 94% sand, 2.5% silt, and 3.5% clay (Campbell et al., 1978). Natural slopes were less than 2%. The water table level is normally within 25 cm of the surface on an average of 6 months annually (USDA, 1981).

The area was laser leveled in 2011 and rows (78 m long, 0.35 m height) were formed with 1.01 m distance between row centers. It is a common practice in the TCAA to hill rows to improve drainage and facilitate harvest operation. At planting, granular fertilizer was banded in the soil surface on top of the potato row, and subsequently incorporated. The fertilizer rates applied were 56, 112, and 168 kg ha^{-1} of N, P_2O5, and K_2O, respectively. In addition, side dress fertilizer application (84-0-140 kg ha^{-1}) was performed when shoot emergence was 13 and 33 days after planting (DAP) in 2011 and

2012, respectively. Final side dress N fertilization (84 kg ha^{-1}) was done when plants were 15-20 cm tall at 46 and 40 DAP in 2011 and 2012 seasons, respectively. No fertilizer was supplied through the drip irrigation system.

The experiment was laid out in a randomized complete block design with treatments arranged in a split plot consisting of surface drip (SUR), subsurface drip (SUB), and seepage (SEP) as main factors and potato varieties: Atlantic, Fabula, and Red LaSoda as sub factors in four replications. Buffer plots were installed between seepage and drip irrigated plots, requiring a total land area of 2.31 ha (5.7 ac). Plots were 21 m long. Entire beds (16 rows) were used for seepage plots. In the case of drip, beds were divided by half (8 rows) and each section received one drip treatment. Potato tubers were mechanically planted on February 17 and January 17 of 2011 and 2012, respectively. Seed pieces (57-85 g) were planted within 20 cm spacing in the row, 15 cm deep. Seeds were ridged immediately after planting.

Drip lines of 16 mm inner diameter, 0.200 mm thickness, 20 cm dripper spacing, and 500 L h^{-1}/100 m discharge rate (RO-DRIP, John Deere Water, Moline, IL, USA) were installed approximately 5 cm below the seed piece before the seed was planted for subsurface (SUB) treatment; and 5 cm above the seed piece one day after planting for surface treatment (SUR).

Temperature, relative humidity, solar radiation, and wind speed data were obtained from a weather station located in the experimental site. Daily reference evapotranspiration (ET_o) was retrieved from the Florida Automated Weather Network (FAWN; www.fawn.ifas.ufl.edu). 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 and respective K_c were as follow: initial (0.6), development (1.15), mid-season (0.75), and late (0.6) (Allen et al., 1998).

After plant emergence, 6 m sections were marked in the center area of each other row in the plot to quantify yield. The number of plants counted were based on the number of stems present in this six linear meter area and used to calculate plant density in each plot. The plant density (32,864 plants ha^{-1}) was used as a reference for further conversion of biomass and tubers into megagram (Mg) per hectare. Biomass accumulation was measured by harvesting biweekly the above ground section of two representative plants in each plot excluding plants in the plot border. Sampling procedures were started when the plant population was well established and plant size was considered homogeneous, which occurred 34 and 55 DAP in 2011 and 2012 respectively. Samples were collected using scissors for clipping each plant at the soil surface; tissue was stored in paper bags for transport back to the laboratory where stem and leaf tissues were separated within 24 hours of field collection. Samples were dried at 65 °C until constant weight and ground using a tissue grinder (Laboratory Mill Model 4, Arthur Thomas Company, Philadelphia, PA) for dry matter determination. Leaves, stems, and tuber samples were digested using the aluminum block digestion procedure of Gallaher et al. (1975) and nitrogen was quantified by the Kjeldahl method at the Analytical Research Laboratory (Univ. of Fla., Gainesville) using U.S. EPA method 351.2 (O'Dell, 1993). Total nitrogen uptake was calculated as the product of the total biomass and N accumulation throughout the crop growth stages.

Biomass accumulation logistic curves were fitted by adapting the equation presented by Witty (1983) as follows:

Crop aboveground biomass accumulation = $N_\infty / [1+ e^{-K\,(t-I)}]$

Where "N_∞" is maximum crop growth, "k" is crop growth rate constant, "t" is time in days, and "*I*" is time to half maximum biomass accumulation.

At plant maturity, when the plant tops began to senesce (which occurred 89 and 92 DAP in 2011 and 2012, respectively), 'Fabula' and 'Red LaSoda' shoots were vine killed using the chemical desiccant Rely 280 (Bayer CropScience, Research Triangle Park, NC). The herbicide was applied at a rate of 1535 ml ha^{-1}. 'Atlantic' tops were not vine killed because chipping varieties do not require this practice.

The final harvest occurred on 109 and 112 DAP in 2011 and 2012, respectively. Total and marketable yields were determined in 36 m^2 of each plot, which was equivalent to 6 m sections replicated six times. During the mechanical harvest, tubers from these sections were separated and labeled according irrigation treatment and potato variety. After harvest, tubers were immediately washed and graded into various size classes on the grading line; tubers with mechanical injuries, greening, decay, or misshapen were separated and quantified. The tubers were graded according to size parameters based on the USDA Standards for Grading of Potatoes (2011) as follows: tuber were deemed of marketable size if they had a diameter between 48 and 101.6 mm, equivalent to categories A1, A2, and A3 (Table 2-1). The diameter was measured at the largest dimension at any angle from the longitudinal axis regardless of the position of the stem end.

A subsample of 20 marketable tubers was randomly selected from each harvested row. Each tuber was sliced into quarter sections cross-sectionally and longitudinal for visual evaluation incidence of brown center, hollow heart, internal heat necrosis, corky ring spot, and any sort of tuber flesh damage affecting the quality of the tuber. Brown center was further divided into three categories: light, moderate, and heavy based on the damage level of the tuber tissue. Specific gravity was measured by weighing a set of 20 potato tubers in air and determining their volume in water. The specific gravity was calculated using the formula:

Specific gravity= (tuber mass (g))/ (tuber volume (cm^3))

After harvest, the experimental area was planted with sorghum sudangrass (var. Sugar Grazer). Before the following potato season the cover crop was incorporated to the soil to add organic matter.

The treatments were tested as a two-factor analysis of variance ANOVA (SAS Institute Inc. Version 9.2, Cary, NC). The PROC GLIMMIX of SAS was used to determine treatments main and interaction effects for the response variables total and marketable yield, aboveground biomass, N uptake, and internal and external tuber disorders. Irrigation and variety treatments were treated as fixed effects. Season, block, and replications were treated as random effect in the statistical analysis. A normality test was performed to check statistical assumptions. When treatment means were significantly different, a Fisher Least Significance test was used to determine where the differences occurred.

Results and Discussion

Climate conditions. Cumulative rainfall from planting to the harvest day was 116 and 178 mm for the spring of 2011 and 2012, respectively. Calculated ET_c in the same period was 380 and 306 mm in 2011 and 2012, respectively. Although precipitation was higher by 62 mm during 2012 season, 38% of rain occurred at the end of the season during tuber bulking, after the potato vines were desiccated for the fresh market varieties (Figure 2-1). Rain after vine kill was 5.3 and 68 mm in the 2011 and 2012 seasons, respectively.

The subsequent cover crop planted after the first potato season was not fertilized to evaluate the ability of the sorghum sudangrass to grow with the residual nutrients left in the field. In the TCAA, vegetable growers are allowed to fertilize the subsequent cover crop with nitrogen at a rate up to 67 kg ha^{-1} (60 lbs ac^{-1}). Thus, the cover crop in the experimental area showed reduced growth and very low biomass was incorporated to the soil, which had a negative impact on wind erosion protection in the following potato season.

In the beginning of 2012, high windy conditions during the potato sprout development stage (between 33 and 40 DAP) adversely affected the emergence of the plants (Figure 2-2). Potato rows were mechanically covered with soil several times to protect seed pieces and surface drip tape. The wind erosion caused a delay in emergence and a decrease in the amount of established stems, especially under drip treatment, where the drip tape was also displaced from the original location or damaged during labor to reform the potato hills. This damage was more severe in replicates 1 and 2 for the drip treatments that were located at the highest position of the experimental site. Landscape anchor pins were used along the drip tape to keep it in the row during windy conditions. Irrigation of the experiment started 30 DAP (3 days before the windy conditions). The wind gusts highlighted one of the possible deficiencies of using drip tape in sandy soils in northeast Florida at the beginning of the crop season; where the localized irrigation water bulb did not maintain enough moisture in the soil surface and dry soil was easily eroded. In addition, early irrigation with drip is risky because it could lead to prolonged periods of saturation following planting and initial sprout development, which could increase seed piece decay as well as poor and erratic tuber emergence (Shock et al., 2006). Seepage plots were also affected, but to a lesser extent due to higher soil moisture in the rows and between rows. The use of cover crops to improve organic matter that can retain soil moisture during the beginning of the season is fundamental to minimize damage by wind erosion in seepage and drip irrigated plots.

In both experimental years, weather in northeast Florida was influenced by the cold phase of ENSO (El Niño Southern Oscillation), with the predominant phase categorized as “La Niña”. La Niña is a worldwide climate phenomena characterized by unusually cold ocean temperatures in the Equatorial Pacific (NOAA, 2005). La Niña creates warmer than normal temperatures in the southeast continental U.S. In the spring of 2011 and 2012, the Florida peninsula was under abnormally dry conditions, total rainfall amount was lower than normal, and temperatures were above normal. There was an interaction of year by irrigation treatment and year by variety for tuber yield, biomass accumulation, and aboveground N uptake. The interactive effect of year and irrigation was attributed to the different planting dates between seasons (17 February 2011 vs. 17 January 2012) and the fact that the drier conditions in 2012 required the use of irrigation (drip and seepage) to supply moisture for optimum crop establishment and development.

Biomass accumulation and N uptake. There were no interactions between irrigation and variety treatments for biomass and plant N uptake. Irrigation, year, and DAP influenced biomass and N accumulation significantly (Table 2-2). Due to a significant year effect, biomass and N uptake were analyzed separately for each season (Figures 2-3 to 2-8). Aboveground biomass accumulation was significantly ($p<0.05$) higher under SEP treatments for all tested varieties in both years. In 2011, 'Atlantic' aboveground biomass accumulation was 1.9, 2.0, and 2.5 Mg ha^{-1} for SUR, SUB, and SEP, respectively. 'Fabula' aboveground biomass accumulation was 2.6, 2.2, and 3.1 Mg ha^{-1} for SUR, SUB, and SEP, respectively. 'Red LaSoda' aboveground biomass accumulation was 2.0, 2.0, and 2.3 Mg ha^{-1} for SUR, SUB, and SEP, respectively. The SEP treatment increased aboveground biomass accumulation by 22, 13, and 23% for 'Atlantic', 'Red LaSoda', and 'Fabula', respectively compared to both drip treatments.

During the 2012 growing season, the aboveground biomass accumulated was 300 kg ha^{-1} greater on average than in 2011 for all varieties. This was attributed to planting 30 days early in 2012 compared to 2011 season and cooler temperatures at the beginning of the 2012 season. The SEP treatment promoted a higher aboveground biomass accumulation by 1.20, 0.73, and 1.26 Mg ha^{-1} for 'Atlantic', 'Fabula', and 'Red LaSoda', respectively compared to both drip treatments. Similar trends of aboveground biomass accumulation observed in 2011 occurred in 2012.

Although aboveground biomass accumulation was significantly lower for all the tested varieties under the drip treatments, this result did not negatively impact tuber dry matter of 'Atlantic' and 'Fabula' under SUR drip compared to SEP results (Figure 2-5 and 2-6). Nonetheless, 'Red LaSoda' did show significant tuber biomass reductions under both drip treatments compared to SEP irrigation, which was consistent with the reduced aboveground biomass production. Similar results as was found for ‘Atlantic’ and ‘Fabula’ have been reported where reduced aboveground biomass production has a negligible effect on tuber biomass, which is related to “luxury” consumption of the potato crop (Smith et al., 2002). Under seepage, the plant uptakes water beyond their current needs and store it. In the case of drip irrigation, the plant was more efficient with the available water supplied. This was observed for ‘Atlantic’ and ‘Fabula’ varieties where the reduced vegetative growth did not impact tuber dry weight. However, ‘Red LaSoda’ did not perform in the same fashion and tuber dry matter was significantly lower under both drip treatments.

Nitrogen uptake was evaluated in aboveground and tuber tissues. In 2011, cumulative aboveground N uptake was not significantly different among irrigation treatments for ‘Atlantic’. Cumulative aboveground N uptake for ‘Atlantic’ was 62, 61, and 78 kg ha^{-1} for SUR, SUB, and SEP, respectively.

There was no difference for ‘Red LaSoda’ cumulative aboveground N uptake. The N uptake for ‘Red LaSoda’ was 67, 65, and 75 kg ha^{-1} for SUR, SUB, and SEP, respectively. Aboveground N uptake was significantly different for ‘Fabula’ between SUB (72.1 kg N ha^{-1}) and SEP (103.2 kg N ha^{-1}). The SUR (84.1 kg N ha^{-1}) treatment was not significantly different from SUB and SEP.

In 2012, SEP significantly increased the aboveground N accumulation for ‘Atlantic’ by 30 and 23% for SUR and SUB, respectively. The SEP treatment also increased the aboveground N accumulation by 34 and 29% for ‘Red LaSoda’ compared to SUR and SUB, respectively. Aboveground N accumulation was not different for 'Fabula' (119 kg ha^{-1} on average) among irrigation treatments.

In terms of tuber N accumulation, the only difference found among irrigation treatments in 2011 corresponded to 'Red LaSoda', where SEP obtained 39 and 27% higher N accumulation in tubers compared to SUR and SUB treatments, respectively (Figure 2-7). No significant difference was found among irrigation treatments for 'Atlantic' and 'Fabula' in terms of tuber N accumulation.

However in 2012, tuber N accumulation was statistically similar between SUR and SEP treatments for 'Atlantic' (71.2 kg ha^{-1}) and 'Fabula' (54.7 kg ha^{-1}) (Figure 2-8). When compared to SUR and SEP irrigation, the SUB treatment reduced N accumulation by 44 and 52% for 'Atlantic' and 'Fabula', respectively. 'Red LaSoda' N accumulation in tubers followed the same pattern for both years with significantly higher accumulation of 32% under SEP treatment than in the drip treatments. These results suggest that there is potential of 'Atlantic' and 'Fabula' to be irrigated with drip irrigation with surface drip placement.

It is important to state that fertigation (application of liquid fertilizer through the drip tape) was not explored for these trials. Granular fertilizer was used for all treatments to allow a fair comparison between irrigation treatments. Fertigation has proven to be a very effective way to fertilize vegetable crops. This technique may also be beneficial to production of potatoes in the TCAA. The SUR treatment showed similar results in terms of tuber nitrogen accumulation compared to SEP, and offers potential for developing fertigation strategies that can deliver nitrogen close to the root zone minimizing leachate in sandy soils.

Fresh potato tuber total and marketable yield. Potato harvest occurred 109 and 112 DAP in the 2011 and 2012 season, respectively. There were interactions of year by irrigation, year by variety, and irrigation by variety, for total and marketable yield (Table 2-3). The effect of irrigation method was analyzed within each of the three varieties and the performance of each variety was evaluated within irrigation treatments. In addition, the interaction of year by irrigation and variety treatment was also evaluated (Table 2-6).

'Atlantic' produced similar marketable yield in both years when SUR and SEP irrigation was used. The average marketable yields were 26.6, 19.8, and 28.1 Mg ha^{-1} under SUR, SUB, and SEP, respectively. For 'Fabula', marketable yields were 17.4, 9.9, and 16.7 Mg ha^{-1} for SUR, SUB, and SEP, respectively. The 'Red LaSoda' variety underperformed under the drip treatments. 'Red LaSoda' marketable yields were 13.4, 12.8, and 23.5 Mg ha^{-1} for SUR, SUB, and SEP irrigation treatments, respectively.

The SUR and SEP treatments produced similar marketable yield for 'Atlantic' and 'Fabula' varieties. However, SUB with drip tape installed 5 cm below seed drastically reduced tuber marketable yields. The reduction was on the order of 28 and 42% for 'Atlantic' and 'Fabula' marketable tubers, respectively (Table 2-5).

'Red LaSoda' had an average marketable yield reduction of 45% with both drip irrigation methods tested compared to the SEP treatment. The greater yield reduction of 'Red LaSoda' may be a result of a low tolerance of this variety to rapid soil moisture fluctuations caused by both drip irrigation treatments. The generally lower yield with SUB for all the tested varieties could indicate poor capillary movement upwards from the emitter to the root zone in sandy soils causing a lack of moisture supplied to the plant and some level of water stress experienced throughout the season. In chapter 3, the evaluation of 'Atlantic' root distribution showed that 69, 77, and 61% of root length was in the 0-15 cm upper soil layer for SUR, SUB, and SEP respectively. A larger root growth under SUB irrigation showed greater exploration area to uptake water, which could indicate water stress caused by low soil moisture content during initial growing stages. The low capillarity rise has been stated as the most frequent shortcoming of subsurface drip (Lamm et al., 2011; Patel and Rajput, 2007). This underperformance of SUB in sandy soils is consistent with previous studies findings. Attaher et al. (2003) evaluated the performance of surface and subsurface drip in potatoes and reported significantly lower yield under subsurface compared to surface drip irrigation. Subsurface drip tape placed at 0.15 m depth did not maintain optimal levels of soil moisture content in the upper soil layer due to predominant horizontal water movement from emitters.

Potato tuber size distribution. There were interactions between irrigation and variety treatments for tuber size classes A1 (4.8-6.4 cm), A2 (6.4-8.3 cm), B (3.8-4.8 cm), and C (1.3-3.8 cm). Irrigation and variety single effects were important for grading classes A3 (8.3-10.2 cm) and A4 (>10.2 cm). The treatments interaction for grading sizes A1, A2, A3, and undersized (the sum of size classes B, C, and A4) is presented in Table 2-7. 'Atlantic' produced 15.3, 10.6, and 15.4 Mg ha^{-1} tuber size A1 for SUR, SUB, and SEP treatments, respectively. A1 tubers for 'Fabula' were 15.5, 7.7 and 11.6 Mg ha^{-1} when SUR, SUB, and SEP, respectively. Tuber size A1 results was not significantly different when SUR and SEP were used as irrigation methods for 'Atlantic' and 'Fabula' varieties.

‘Red LaSoda’ produced 9.9, 9.0, and 15.1 Mg ha^{-1} under SUR, SUB, and SEP treatment. The SEP treatment outperformed SUR and SUB treatments for ‘Red LaSoda’ variety. SEP produced 34 and 40% increment of A1 tubers when compared to SUR and SUB, respectively.

Similar results were obtained for ‘Atlantic’ tuber size A2 among all irrigation treatments. However, SEP produced statistically better results than the drip treatments for ‘Fabula’ and ‘Red LaSoda’ (Table 2-7). The SEP treatment yielded higher percentage of tubers under the A3 category than drip treatments for the three varieties tested. This significant reduction of tuber size A3 for all varieties under drip irrigation could be a consequence of the minimal schedule adjustment carried out for drip during the experiment. Although small changes in irrigation events and their duration occurred during the study, a fixed watering schedule was used to supply crop and evaporation losses. The drip irrigation schedule can be further improved to increase the number of tubers with marketable size.

It has been stated previously that drip irrigation can improve yield and quality of potatoes. However, significant tuber size reduction occurs if the emitter wetting front does not provide enough moisture to the root zone throughout the whole season, which demands particular attention (Attaher et al., 2003). Additionally, difference among varieties in response to drip irrigation influences the number and size of tubers to be produced. More research is needed to develop specific crop coefficient (K_c) values and scheduling for drip irrigation that better matches specific variety requirements in sandy soils.

Tuber internal quality and physiological disorders. Interaction was observed between irrigation and variety treatments for hollow heart, internal heat necrosis, and brown center internal disorders. In 2011, SUR and SUB treatments significantly reduced the incidence of hollow heart in ‘Atlantic’ tubers by 96% compared to SEP. In 2012, the occurrence of hollow heart in ‘Atlantic’ tubers was decreased by 90 and 72% with SUR and SUB treatments, respectively. No significant difference was found among irrigation treatments for hollow heart in ‘Fabula’ and ‘Red LaSoda’ tubers (Table 2-8).

Although specific causes of hollow heart are not entirely understood, it is known that there is high tendency for some varieties, like ‘Atlantic’, to develop this internal disorder compared to lesser probability of other varieties, like ‘Fabula’ and ‘Red LaSoda’, in Florida conditions (Hutchinson et al., 2006; Webb et al., 1978). Hollow heart is mainly produced by stressful conditions during growing stages, especially due to subsequent periods of moisture level variations (Bussan, 2007; Christ, 1998). The reduction of hollow heart occurrence in ‘Atlantic’ under drip treatments was attributed to adequate soil moisture throughout the season whereas seepage failed to supply continuous moisture levels to the area where tubers actively grow. Lynch et al. (1995) reported that ‘Atlantic’ is extremely sensitive to water stress during tuber initiation and bulking stages, which followed by a period of rapid recovery can cause the development of cavities in the internal cell tissue. The SUR and SUB treatments minimized drastic soil moisture fluctuations during the whole season, impacting soil temperature directly, thus decreasing hollow heart occurrence in ‘Atlantic’ tubers.

Another important physiological disorder occurring under TCAA growing conditions is internal heat necrosis (IHN). The IHN is defined as “cell death of the parenchyma tissue internal to the vascular ring of the tuber" (Sterrett and Henninger, 1997). In 2011, SUR and SUB treatments reduced the severity of IHN in 'Atlantic' by 90 and 61%, respectively when compared with the SEP treatment. However, in 2012 SUB produced higher incidence (>70%) of internal heat necrosis compared to the other treatments for 'Atlantic' tubers. No significant difference was reported between irrigation treatments for 'Fabula' and 'Red LaSoda' in both years.

'Atlantic' was reported to be a susceptible variety to IHN (Hutchinson et al., 2006). Our results showed that is possible to significantly reduce the appearance of IHN with SUR drip irrigation compared to SEP.

On the other hand, the higher incidence of IHN for the SUB treatment in the second season can be a result of reduced soil moisture capillarity failing to provide moisture to tubers growing near to the soil surface where high temperatures occurred.

The appearance of brown center, which is categorized as light, moderate, or heavy depending on the severity and size of dark tissue in the tuber was also significantly reduced with SUR and SUB treatments. The increased reduction of light and heavy brown center incidence was obtained when SUR was used to irrigate 'Atlantic' and 'Red LaSoda' varieties in both experimental years. Surface drip decreased by 90 and 100% on average the occurrence of light and heavy brown center, respectively for 'Atlantic' tubers. The SUR treatment also reduced the incidence of light and heavy brown center by 100% for 'Red LaSoda' in this study. The occurrence of light and heavy brown center was not statistically significant among irrigation treatments for 'Fabula'.

Tuber external quality and specific gravity. There was interaction between irrigation and variety treatments for growth cracks external disorder. Single main effects of irrigation and variety treatment influenced the occurrence of greening, misshapen, and decay external disorders. Greening and growth cracks disorders were further discussed in this chapter because of the severe detrimental impact these disorders provoke in fresh market and chipping tubers in the TCAA.

Greening is a disorder caused by tuber exposure to abiotic factors. Irrigation treatments for ‘Atlantic’ and ‘Fabula’ did not show a statistically significant difference in the incidence of greening. The SUR treatment positively affected ‘Red LaSoda’ tubers with a 65% reduction of green tissue in 2011. However, in 2012 the amount of green tuber tissue was similar among irrigation treatments for ‘Red LaSoda’. Previous studies tested drip irrigation in silty soils and reported additional benefit of this method due to the gentle localized water application compared to furrow and sprinkler irrigation (Shock et al., 2006). We did not find difference in the incidence of greening among irrigation treatments except for ‘Red LaSoda’ in 2011. The similar incidence of tuber greening disorder among treatments was explained due to the sandy soil in the area, which is easy to erode and tuber exposure occur. However, potential exists to set and refine drip irrigation duration so that water is carefully delivered to the root and tuber zone during tuber bulking stage without exposing shallow tubers to the environment.

Growth cracking in tubers appears when soil moisture is replenished after a prolonged dry period (Jefferies and MacKerron, 1987). Growth crack is a fissure of the tuber tissue that heals but severely affects the cosmetic appeal of the tuber. In 2011, development of growth cracks in ‘Atlantic’ was reduced 56% on average by SUR and

SUB treatments. However, in the second year there was no significant difference for this variety. Also, SUR and SUB treatments significantly reduced this disorder in ‘Fabula’ and ‘Red LaSoda’ varieties. The SUR and SUB treatments reduced by 83 and 84% on average the incidence of growth cracks for ‘Fabula’ in 2011 and 2012, respectively compared to SEP. When ‘Red LaSoda’ was tested, SUR and SUB reduced by 82 and 78% the occurrence of growth cracks in 2011 and 2012, respectively compared to the SEP treatment.

‘Atlantic’ and ‘Red LaSoda’ are recognized to be varieties susceptible to developing growth cracks under fluctuating environmental conditions. However, the use of drip irrigation significantly reduced the number of tubers affected with this physiological disorder when compared to seepage.

Another external parameter evaluated was the number of rotten tubers. In 2011, tuber irrigated with SEP had fewer incidences of rotten tubers compared to SUR and SUB treatments. In 2011, drip maintained high moisture content in the soil layers where tuber grew during the bulking stage and caused some tubers to rot. In 2012, the volume of water applied with drip was decreased during tuber bulking stage by 35% (1.49 mm day^{-1}) and the number of rotten tubers was lower for ‘Atlantic’ and ‘Fabula’.

In 2011, SUR irrigation increased the percentage of rotten tubers by 31 and 27% compared to SUB and SEP, respectively. As mentioned previously, irrigation adjustments were carried out in the second season; however, ‘Red LaSoda’ tubers presented the same level of rot under all irrigation treatments. The low performance of ‘Red LaSoda’ suggest that this variety is not well adapted to the characteristics of drip water delivery method.

Finally, there was interaction between treatments for specific gravity. Specific gravity is an important tuber quality attribute related to the processing of the tuber (Yuan et al., 2003). For all the irrigation treatments ‘Atlantic’ was the variety with the highest values (SG ≥ 1.071). High specific gravity value is an important genetic trait of ‘Atlantic’ that can be further improved with optimal irrigation management in the bulking stage. ‘Fabula’ had higher specific gravity under drip treatments than seepage, but was not significantly different. ‘Red LaSoda’ produced higher specific gravity under SUB treatment; however it was not statistically different from SUR and SEP treatments. Yuan et al. (2003) found strong negative correlation between specific gravity and amount of water applied indicating that specific gravity values increased as water applied decreased.

Conclusion

Irrigating potatoes in the TCAA with surface drip is an alternative to supply plant water needs. Surface drip maintained marketable yield for ‘Atlantic’ and ‘Fabula’ varieties. A closer delivery of water to the root and soil area where the tubers are constantly growing is a viable method to improve internal tuber quality for both varieties mentioned above. Yield loss due to tuber defects caused by seepage can be highly reduced with just watering the ridge area where the tubers are located. The SUR and SUB minimized the incidence of hollow heart, internal heat necrosis and brown center disorders in 2011 and 2012 seasons.

Aboveground and nitrogen accumulation by the potato plants was lower for all varieties under drip treatments compared to SEP irrigation. However, this result did not significantly impact the marketable yield for ‘Atlantic’ and ‘Fabula’. In both seasons, varieties irrigated with SUR obtained higher yield than those irrigated with SUB. The SUB treatment consistently produced lower marketable tubers for ‘Atlantic’, ‘Fabula’, and ‘Red LaSoda’ compared to SUR and SEP, which was caused by low capillarity rise in sandy soils. ‘Red LaSoda’ low yield indicates that specific irrigation scheduling and water requirement should be further studied for this variety.

‘Atlantic’ has high potential to be grown using SUR drip. However, irrigation schedule at the end of the season needs adjustment to minimize rotten tubers. Cover crops that increase organic matter content, and help retain moisture early in the season may effectively prevent the effects of wind erosion damage on seed pieces and drip tape.

Finally, more research is needed to combine SUR drip tape with fertigation, and automation practices for maximum water and fertilizer use efficiency to potentially be attained.

Table 2-1. Tuber size classification used to evaluate marketable and non-marketable yield after harvest[Z].

Size identification code	Diameter size range (cm)	Classification
C	1.27 to 3.81	Non-marketable
B	3.81 to 4.78	Non-marketable
A1	4.78 to 6.35	Marketable
A2	6.35 to 8.26	Marketable
A3	8.26 to 10.16	Marketable
A4	> 10.16	Non-marketable

[Z] U.S. No. 1 are tubers not less than 4.78 cm in diameter.

Table 2-2. Analysis of variance summary for aboveground biomass accumulation, aboveground and tuber N uptake, and irrigation water use efficiency (IWUE) as affected by season, irrigation, variety treatment, and treatments interactions.

Main effect	D.F.	Biomass accumulation	N uptake above ground	N uptake tuber	IWUE
Irrigation (I)	2	***	***	**	***
Variety (V)	2	ns	**	***	***
Year (Y)	1	***	***	ns	ns
I x V	4	ns	ns	*	***
I x Y	2	**	**	ns	***
V x Y	2	ns	ns	ns	*
I x V x Y	4	ns	ns	ns	ns

* Significant at $p<0.05$; ** significant at $p<0.01$; *** significant at $p< 0.0001$. ns: not significant; D.F.: degrees of freedom.

Table 2-3. Analysis of variance summary for tuber total and marketable yield, tuber grades, internal and external disorders, and specific gravity, as affected by season, irrigation, variety treatment, and treatments interactions.

Main effect	D.F.	Yield		Size distribution				Internal Quality				External Quality				Specific Gravity
		TOT	MKT	A1[Z]	A2	A3	A4	HH[Y]	IHN	BCL	BCH	GT	GC	RT	MS	
Replication	3	**	**	***	ns	ns	ns	ns	*	**	*	ns	**	ns	ns	*
Irrigation (I)	2	***	***	***	**	***	*	**	*	***	**	ns	***	**	***	***
Variety (V)	2	***	***	*	***	***	**	**	***	**	*	***	***	***	ns	***
Year (Y)	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	*	***	***	ns
I x V	4	**	**	*	*	ns	ns	**	**	**	*	ns	***	ns	ns	ns
I x Y	2	*	*	*	**	ns	ns	ns	ns	ns	ns	ns	***	**	ns	***
V x Y	2	**	**	**	**	ns	ns	ns	ns	*	ns	ns	***	ns	ns	***
I x V x Y	4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	*

* Significant at $p<0.05$; ** significant at $p<0.01$; *** significant at $p< 0.0001$. ns: not significant; D.F.: degrees of freedom.

[Z] Diameter size of classes: A1 (4.8-6.4 cm), A2 (6.4-8.3 cm), A3 (8.3-10.2 cm), and A4 (>10.2 cm).

[Y] HH: hollow heart, IHN: internal heat necrosis, BCL: brown center light, BCH: brown center heavy, GT: greening, GC: growth cracks, RT: rotten, MS: misshapen.

Table 2-4. Effect of surface drip, subsurface drip, and seepage irrigation method on aboveground biomass accumulation of 'Atlantic' 'Fabula', and 'Red LaSoda' potato varieties cultivated in Hastings, FL during 2011 and 2012 spring season[Z].

	2011			2012		
	Variety treatments					
Irrigation treatment	'Atlantic'	'Fabula'	'Red LaSoda'	'Atlantic'	'Fabula'	'Red LaSoda'
	Aboveground biomass (Mg ha^{-1})					
Surface	1.9 b	2.6 b	2.0 a	4.4 b	3.7 a	3.3 b
Subsurface	2.0 ab	2.2 b	2.0 a	4.3 b	2.8 b	3.2 b
Seepage	2.5 a	3.1 a	2.3 a	5.5 a	4.0 a	4.5 a

[Z] Values within columns followed by the same lowercase letter indicate that means are not significantly different at $p<0.05$ significance level according to Fisher's LSD test between potato varieties within the same irrigation treatment.

Table 2-5. Total and marketable tuber yield of ‘Atlantic’, ‘Fabula’, and ‘Red LaSoda’ potato varieties as function of irrigation method (seepage, surface drip and subsurface drip irrigation) during 2011 and 2012 spring season[Z].

	2011			2012		
	Variety treatment					
Irrigation treatment	‘Atlantic’	‘Fabula’	‘Red LaSoda’	‘Atlantic’	‘Fabula’	‘Red LaSoda’
	Total Yield (Mg ha^{-1})					
Surface	33.3 a	24.2 a	20.7 b	30.7 b	23.1 a	19.6 b
Subsurface	25.6 b	16.3 b	24.8 b	23.5 c	10.9 b	14.1 c
Seepage	30.8 a	23.3 a	36.5 a	37.6 a	23.3 a	28.1 a
	Marketable Yield (Mg ha^{-1})					
Surface	26.3 a	16.1 a	12.7 b	26.9 b	18.7 a	14.1 b
Subsurface	19.9 b	12.0 a	16.4 b	19.7 c	7.8 b	9.2 c
Seepage	23.5 ab	15.8 a	26.1 a	32.8 a	17.6 a	20.9 a

[Z] Values within columns followed by the same lowercase letter indicate that means are not significantly different at $p<0.05$ significance level according to Fisher’s LSD test among irrigation treatments within the same potato variety.

Table 2-6. Two-year averaged marketable size (A1, A2, and A3) and undersized class distribution of potato varieties ‘Atlantic’, ‘Fabula’, and ‘Red LaSoda’ affected by irrigation treatment.

Irrigation treatment	Variety treatments		
	‘Atlantic’	‘Fabula’	‘Red LaSoda’
	Size class A1 (Mg ha^{-1})		
Surface	15.32 a [Z]	15.51 a	9.95 b
Subsurface	10.58 b	7.70 c	9.04 b
Seepage	15.44 a	11.64 b	15.09 a
	Size class A2 (Mg ha^{-1})		
Surface	7.26 a	1.81 b	2.49 b
Subsurface	5.26 a	1.87 b	2.82 b
Seepage	6.60 a	3.34 a	5.04 a
	Size class A3 (Mg ha^{-1})		
Surface	4.06 b	0.09 b	0.99 b
Subsurface	3.95 b	0.35 b	0.93 b
Seepage	6.08 a	1.74 a	3.39 a
	Undersized[Y] (Mg ha^{-1})		
Surface	1.94 b	2.50 a	1.55 b
Subsurface	2.04 b	1.59 b	1.74 b
Seepage	2.68 a	1.85 b	2.40 a

[Z] Values within columns followed by the same lowercase letter indicate that means are not significantly different at $p<0.05$ significance level according to Fisher’s LSD test between irrigation treatment within the same potato variety.

[Y] Undersized is the sum of size classes C, B, and A4.

Table 2-7. Tuber internal disorders of 'Atlantic', 'Fabula', and 'Red LaSoda' affected by irrigation treatment during 2011 and 2012 spring seasons.

Irrigation treatments	2011 'Atlantic'	2011 'Fabula'	2011 'Red LaSoda'	2012 'Atlantic'	2012 'Fabula'	2012 'Red LaSoda'
	Variety treatments					
	Hollow Heart [Z] (kg ha^{-1})					
Surface	30.6 b	0.0 a	0.0 a	152.9 b	0.0 a	30.6 a
Subsurface	30.6 b	61.2 a	30.6 a	428.1 b	0.0 a	30.6 a
Seepage	764.4 a	0.0 a	122.3 a	1528.8 a	0.0 a	122.3 a
	Internal Heat Necrosis [Z] (kg ha^{-1})					
Surface	244.6 b	122.3 a	0.0 a	794.9 b	61.2 a	30.6 a
Subsurface	1009.0 b	0.0 a	30.6 a	2598.9 a	91.7 a	30.6 a
Seepage	2568.4 a	122.3 a	0.0 a	1498.2 b	30.6 a	183.5 a
	Brown Center Light [Z] (kg ha^{-1})					
Surface	122.3 b	91.7 a	0.0 b	0.0 b	30.6 a	0.0 b
Subsurface	611.5 a	61.2 a	152.9 b	244.6 ab	0.0 a	122.3 b
Seepage	733.8 a	152.9 a	580.9 a	458.6 a	183.5 a	733.8 a
	Brown Center Heavy [Z] (kg ha^{-1})					
Surface	0.0 b	0.0 a	0.0 a	0.0 b	0.0 a	0.0 b
Subsurface	0.0 b	0.0 a	0.0 a	30.6 b	0.0 a	61.2 ab
Seepage	825.6 a	30.6 a	122.3 a	214.0 a	30.6 a	214.0 a

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

Table 2-8. Tuber external quality and specific gravity of 'Atlantic', 'Fabula', and 'Red LaSoda' affected by irrigation treatment during 2011 and 2012 spring season.

Irrigation treatments	2011 'Atlantic'	2011 'Fabula'	2011 'Red LaSoda'	2012 'Atlantic'	2012 'Fabula'	2012 'Red LaSoda'
			Greening[Z] (kg ha^{-1})			
Surface	790.1 a	197.5 a	524.7 b	1548.3 a	480.0 a	1413.2 a
Subsurface	814.5 a	201.2 a	1669.4 a	1490.2 a	439.7 a	1515.3 a
Seepage	608.5 a	39.14 a	1259.7 a	1271.9 a	864.7 a	1702.4 a
			Growth Cracks[Z] (kg ha^{-1})			
Surface	563.2 ab	667.8 b	152.3 b	181.0 a	20.2 b	237.3 b
Subsurface	291.1 b	467.2 b	468.4 b	291.7 a	274.6 b	415.2 b
Seepage	945.4 a	3371.8 a	1759.3 a	354.1 a	941.1 a	1460.3 a
			Rotten[Z] (kg ha^{-1})			
Surface	3552.2 a	4954.4 a	5596.5 a	81.3 a	779.1 a	2204.5 a
Subsurface	2183.7 a	1968.4 b	3880.6 b	204.9 a	636.6 a	1550.8 a
Seepage	2520.6 a	1962.3 b	4059.8 b	302.1 a	1015 a	1622.9 a
			Misshapen[Z] (kg ha^{-1})			
Surface	77.7 a	303.9 b	22.6 b	21.4 b	23.8 b	134.5 b
Subsurface	100.9 a	151.7 b	115 ab	25.1 b	130.9 b	236.7 ab
Seepage	343.1 a	665.3 a	415.2 a	431.1 a	636.6 a	565.0 a
			Specific Gravity[Z] (g cm^{-3})			
Surface	1.081 a	1.056 a	1.056 a	1.079 a	1.049 a	1.055 a
Subsurface	1.077 b	1.056 a	1.058 a	1.080 a	1.046 a	1.052 b
Seepage	1.071 c	1.050 b	1.055 a	1.080 a	1.046 a	1.055 a

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

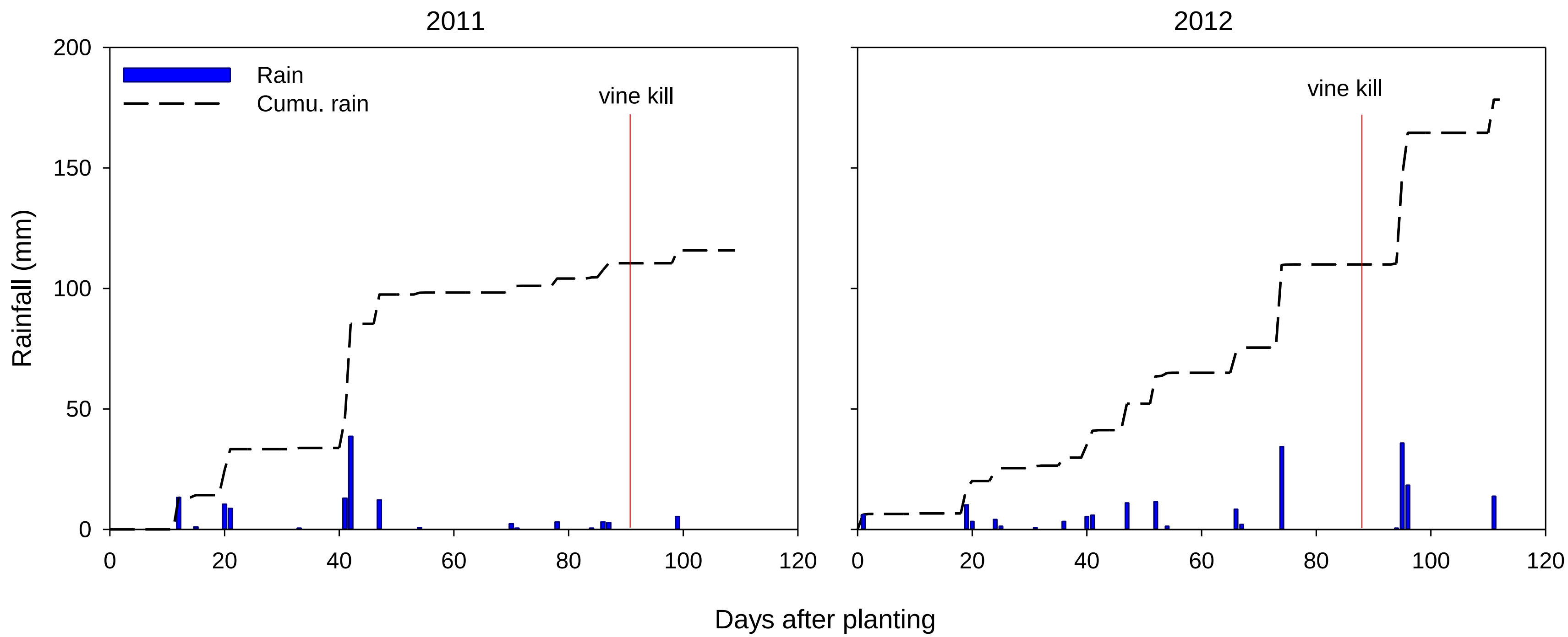


Figure 2-1. Rainfall events and cumulative rain for 2011 and 2012 potato growing seasons in Hastings, Florida.

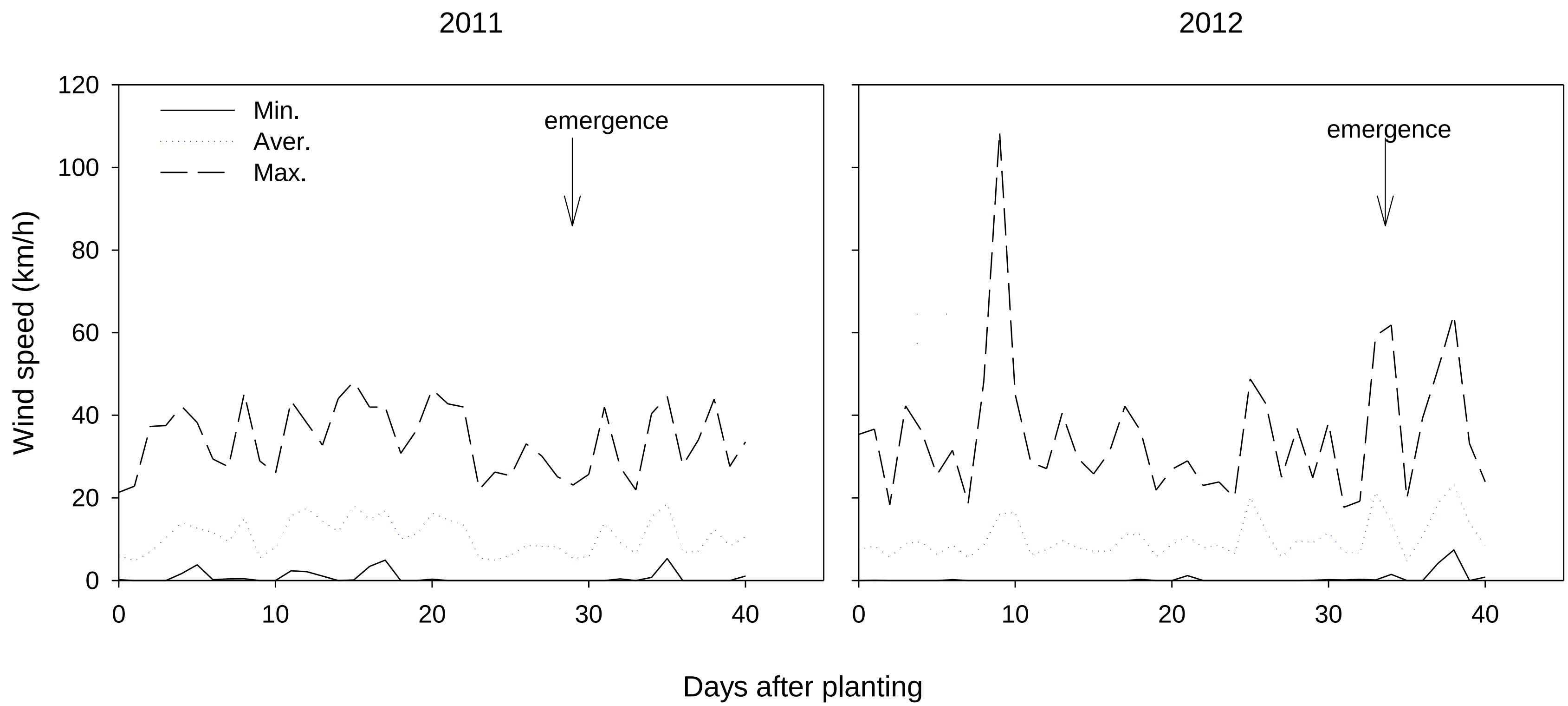


Figure 2-2. Minimum, average and maximum wind speed from planting to 40 days after planting (DAP). Sprout emergence generally occurs at 28-30 DAP.

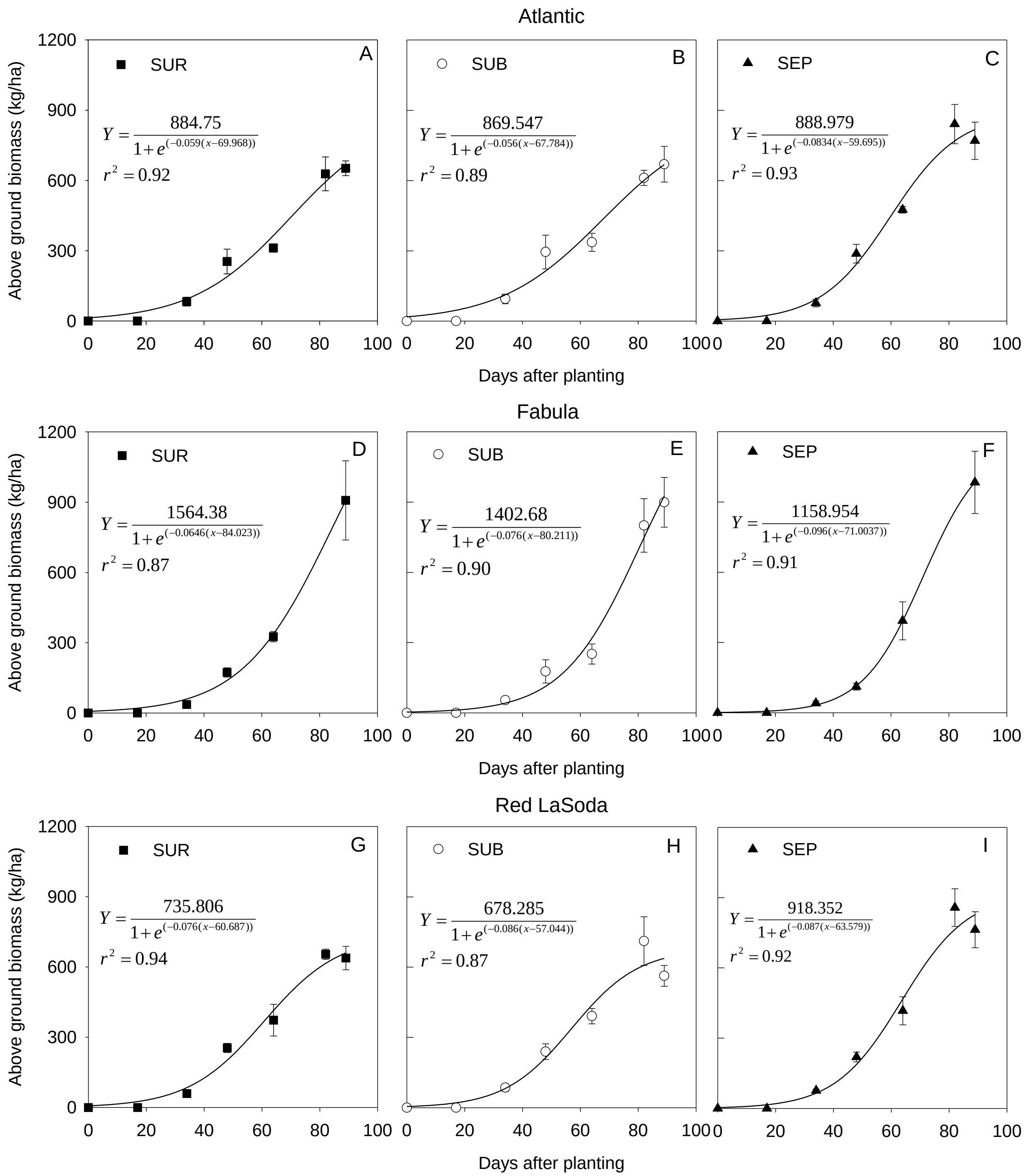


Figure 2-3. Aboveground biomass accumulation of potato varieties affected by irrigation treatment in 2011 season. Irrigation treatments were analyzed within each variety and presented as follows: ‘Atlantic’ (A-C); ‘Fabula’ (D-F); ‘Red LaSoda’ (G-I). Nonlinear regression and coefficient of determination (R^2) is displayed for each treatment.

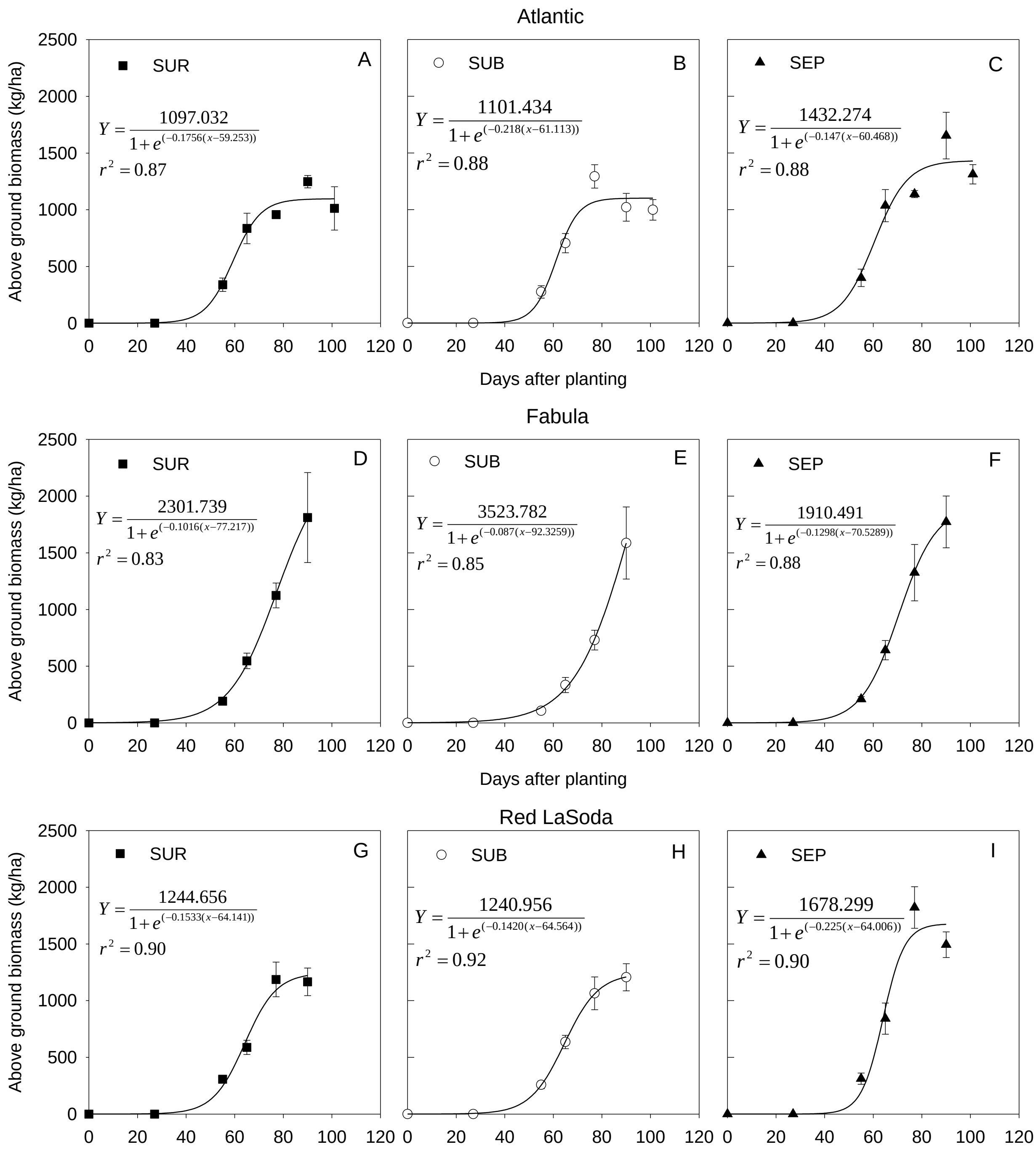


Figure 2-4. Above ground biomass accumulation of potato varieties affected by irrigation treatment in 2012 season. Irrigation treatments were analyzed within each variety and presented as follows: 'Atlantic' (A-C); 'Fabula' (D-F); 'Red LaSoda' (G-I). Nonlinear regression and coefficient of determination (R^2) is displayed for each treatment

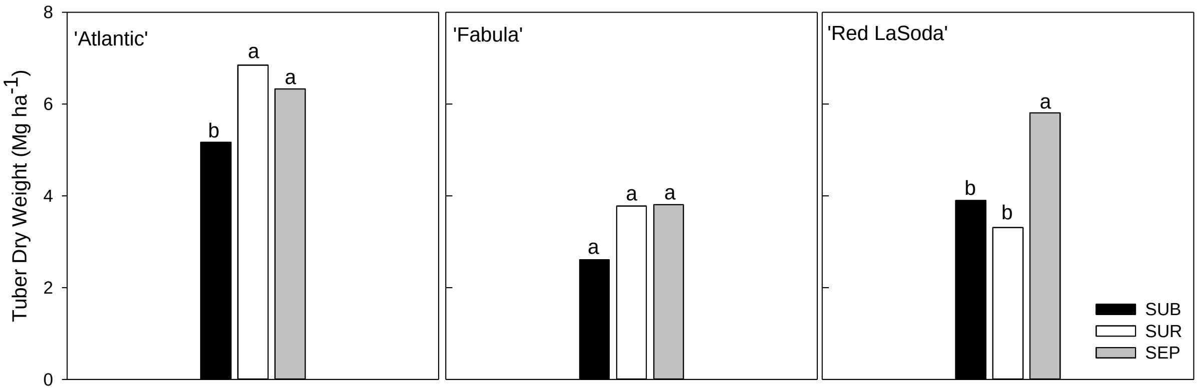


Figure 2-5. Tuber dry weight of ‘Atlantic’, ‘Fabula’ and ‘Red LaSoda’ potato varieties cultivated in Hastings, FL during spring 2011affected by surface (SUR), subsurface (SUB), and seepage (SEP) irrigation treatments. Bars with same lowercase letter are not significantly different at *p*<0.05 significance level according to Fisher’s LSD test.

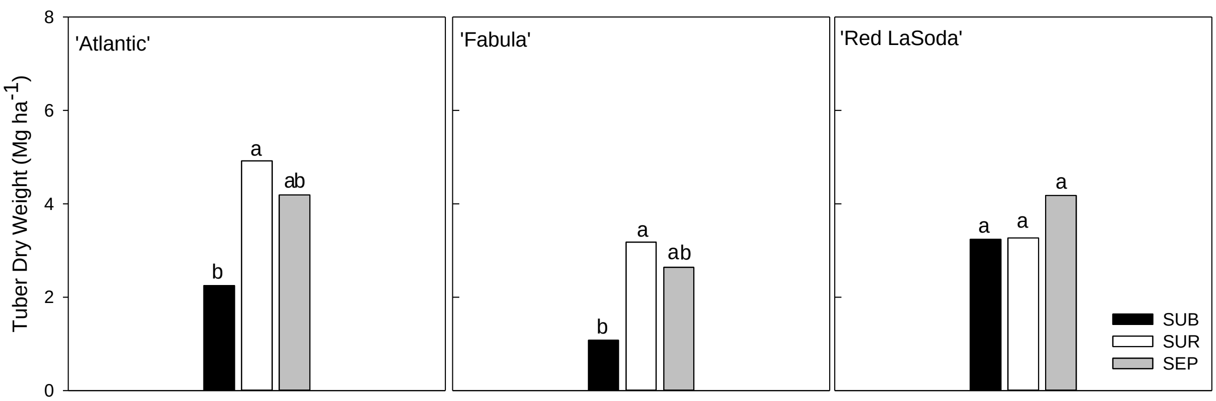


Figure 2-6. Tuber dry weight of ‘Atlantic’, ‘Fabula’ and ‘Red LaSoda’ potato varieties cultivated in Hastings, FL during spring 2012 affected by surface (SUR), subsurface (SUB), and seepage (SEP) irrigation treatments. Bars with same lowercase letter are not significantly different at *p*<0.05 significance level according to Fisher’s LSD test.

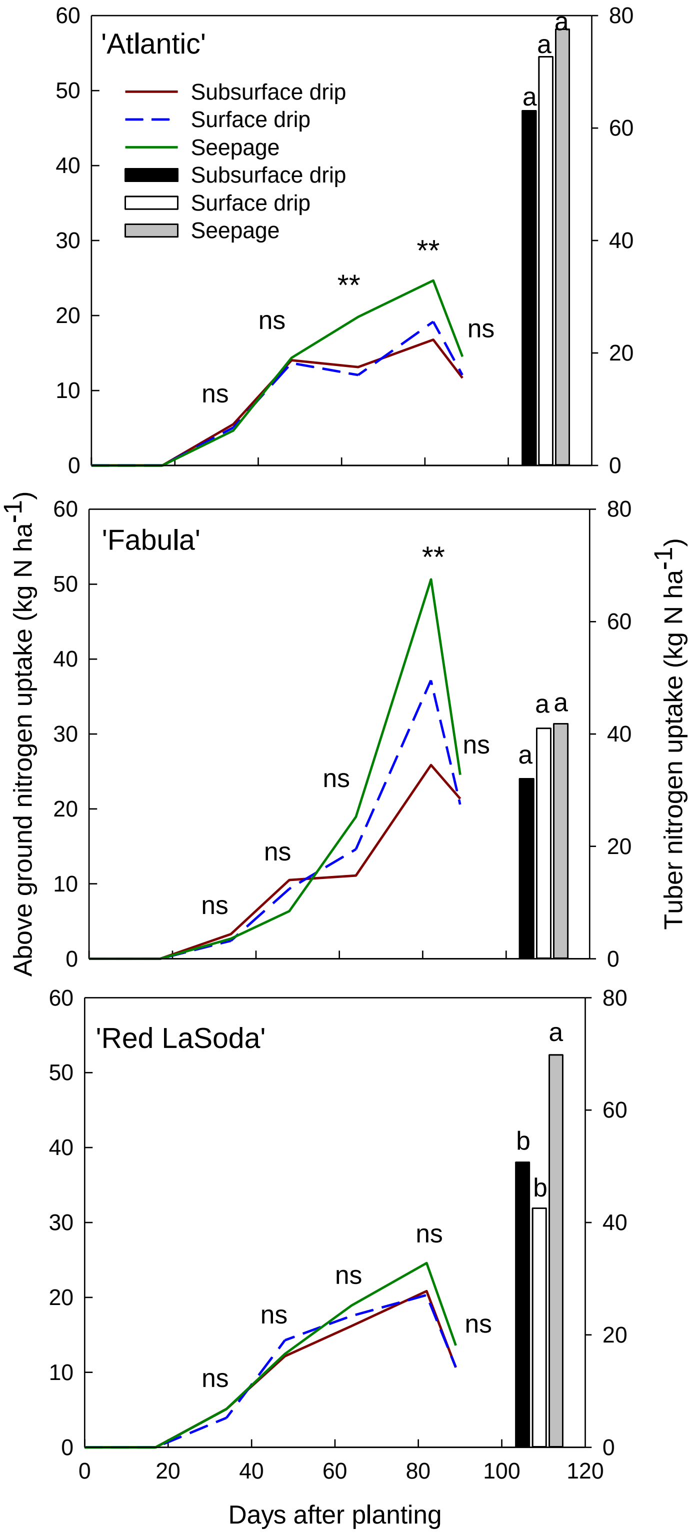


Figure 2-7. Above ground (lines) and tuber (bars) nitrogen uptake of ‘Atlantic’, ‘Fabula’, and ‘Red LaSoda’ varieties affected by surface (SUR), subsurface (SUB), and seepage (SEP) irrigation treatment in 2011 season.

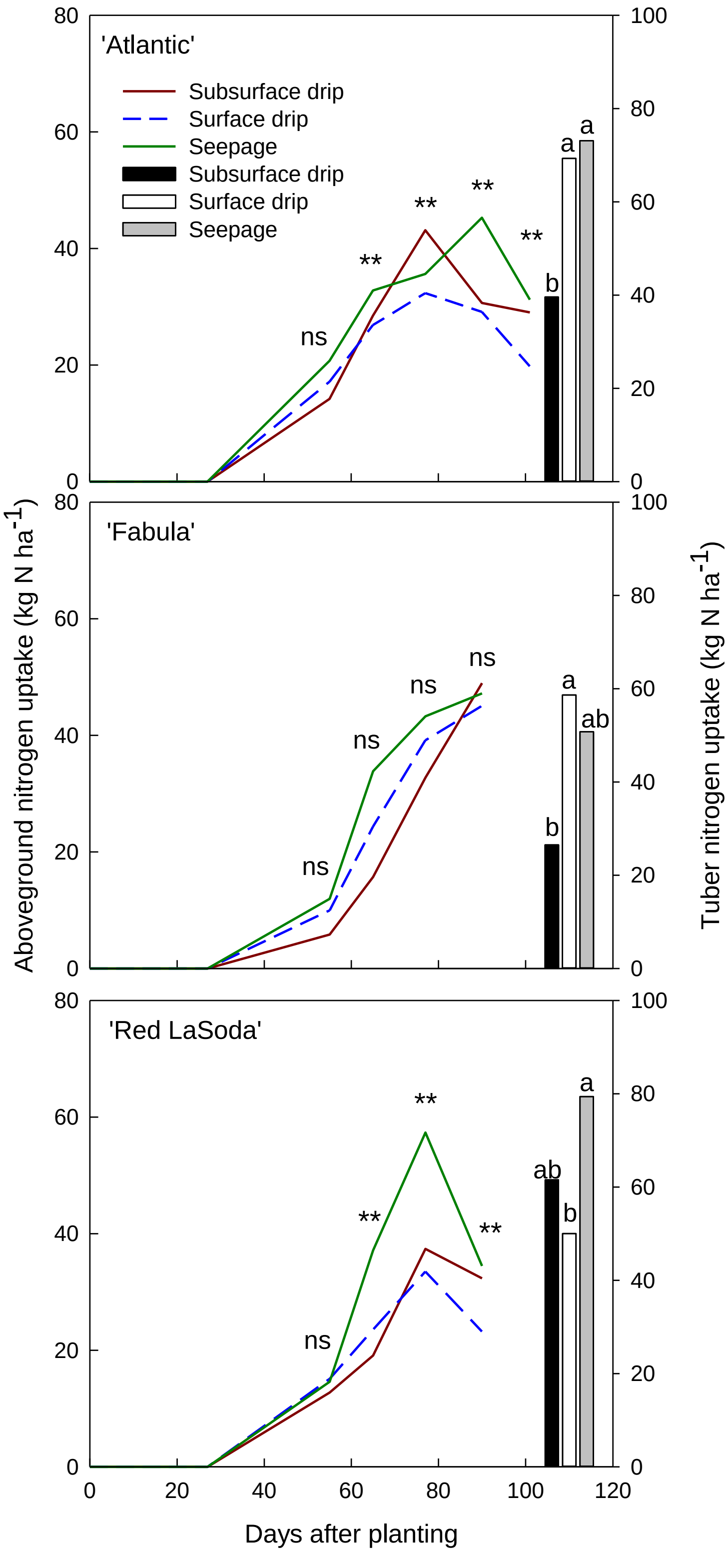


Figure 2-8. Above ground (lines) and tuber (bars) nitrogen uptake of ‘Atlantic’, ‘Fabula’, and ‘Red LaSoda’ varieties affected by surface (SUR), subsurface (SUB), and seepage (SEP) irrigation treatment in 2012 season.

CHAPTER 3
CHARACTERIZATION OF IRRIGATION AND WATER TABLE FLUCTUATION UNDER DRIP AND SEEPAGE SYSTEMS FOR POTATO PRODUCTION IN NORTHEAST FLORIDA

Introduction

Florida is one of the few states in U.S. that produces potato (*Solanum tuberosum* L.) in spring (Hochmuth et al., 2001). The potato production from Florida has great demand in the market and generally obtain higher sales prices than fall potatoes (ERS, 2012). Potato production covered roughly 15,000 hectares in Florida, with a crop value of $ 144 million in 2011. Approximately 9,500 hectares of potatoes are grown in St. Johns, Putnam, and Flagler counties (Tri-County Agricultural Area: TCAA) in northeast Florida (USDA, 2012).

Potatoes are the major irrigated row crop in the TCAA with an average irrigation water requirement calculated to be 483 mm year^{-1} (19 inches year^{-1}) (Singleton, 1996). Seepage is the most common water delivery method for potato production in this area of northeast Florida because it is low-cost and effective in flat locations where natural shallow water tables can readily be raised (Haman et al., 1989).

Potato farms irrigated with seepage irrigation maintains the water table level just below the root zone by either adding or subtracting water (Smajstrla et al., 2000). The low water holding capacity in sandy soils requires constant water supply to avoid plant water stress (Dukes and Scholberg, 2005).

Several factors such as increased demand and competition for water resources, irregular rainfall patterns, saltwater intrusion in the Floridan aquifer, and increased costs of production makes imperative to look for other alternatives that provide growers more options to irrigate their crops and remain competitive (Badr et al., 2010; Payero et al., 2008; Spechler, 1994).

Previous studies have reported a straight correlation between saturated soil conditions created by seepage and its negative effects on root active uptake. Irrigation management needs to be sound from environmental and economic perspectives primarily because potato is an expensive crop to produce, and secondly it is less tolerant to water stress than many other crops (Munoz-Arboleda et al., 2006; Patterson, 2010; Shock et al., 2007).

As stated by the South Florida Water Management District, water is the main limiting factor for crop production in Florida thus, implementing efficient water delivery systems is important to optimize the use of the available water supplies and improve crop yield potential (Badr et al., 2010; Pitts and Clark, 1991; SFWMD, 1986). Irrigation has to be precisely scheduled in Florida due to the irregular rainfall patterns during the growing season. An easily controlled irrigation method provides the benefit of adequate soil moisture that can be readily extracted by plants and in case of heavy rain there is storage capacity in the soil for extra water (Onder et al., 2005).

Irrigation method, scheduling, and amount applied are the most important factors to consider when delivering water to the crop (Shock, 2010). It is possible to increase production by developing well-scheduled irrigation programs throughout the growing season (Shock et al., 2003; Yuan et al., 2003). However, this is difficult to achieve with the seepage system due to its low water distribution uniformity in the field.

Reducing off-site movement of fertilizer and keep nutrients close to the active root uptake zone is a challenge potato farmers could overcome with more efficient irrigation methods to grow potatoes (Alva, 2008a).

Irrigation technologies such as drip irrigation increases the control of water use and offers many advantages for growers; some of them are 1) reduction of evaporation and increase of plant transpiration; 2) reduction of weed population: 3) when well managed, excessive water drainage is unlikely to occur and therefore nutrients are retained in the root zone longer (Burt, 1998; Goldberg et al., 1976; Lamm et al., 2011). Moreover, drip also offers an opportunity to maintain ideal soil moisture levels where plant is not stressed.

In general, drip adoption raises concerns among farmers about the profitability of investing in new irrigation methods with the uncertainty of economic returns. However, drip could be an alternative for farmers to conserve water, reduce pumping energy, and the amount of fertilizer used because the drip tape used for irrigation could also be used to inject fertilizers.

Although drip irrigation has the potential to deliver water uniformly, it is necessary to thoroughly evaluate this technology in sandy soils conditions. Because potato is grown in hilled rows, there is a micro-topographic influence over the water distribution uniformity. This difficulty can possibly be overcome due to the localized water application of emitters (Lamm et al., 2011; Shock et al., 2007).

Installation depth of drip lateral is one of the most evaluated factors to produce drip irrigated potatoes. The 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 lateral installation depths (0, 5, 10, 15, and 20 cm) on potato yield grown in sandy loam soil. They found that drip lateral installation depth significantly affected yield, and reported maximum yield when drip tape was placed at 10 cm soil depth.

Additionally, the use of drip irrigation for vegetable crop production has been reported to diminish NO_3 losses to the groundwater, increase water and nitrogen fertilizer use efficiency, and when properly managed drip irrigation has the potential to greater water savings (Lamm et al., 2011; Thompson et al., 2003). Waddell et al. (2000) found that frequent application of small volume of water using drip irrigation had positive results in maintaining nutrients in a reachable distance to the crop root zone.

Although groundwater has been an inexpensive and accessible source to grow potatoes in the TCAA, the expected declines in water supply combined with scarce rain to replenish aquifers, higher evaporative demand, higher energy and fertilizer costs makes imperative the need to adopt more efficient irrigation methods to produce crops (Pair et al., 1983). Furthermore, in order to produce potatoes, water conservation practices are crucial for farmers in the TCAA. Drip irrigation may be an efficient and sustainable strategy that can optimize potato production in sandy soils and greatly enhance resources use efficiency (Ahmadi, 2010).

Northeastern Florida salinity issues. High soil salinity severely reduces potato yield (Levy and Veilleux, 2007). Saline water restricts root water uptake, reduce water infiltration rate, and have negative effects on soil aeration (Ayers and Westcot, 1985).

Production of commodity crops heavily rely on groundwater supply in the entire state of Florida. Aquifers are used as sources of freshwater to meet the agricultural demands for irrigation (Basdurak et al., 2007). The Upper Floridan aquifer is the principal source of water for potato production in northeast Florida. Overpumping of the aquifer has caused water level decline and upconing of saline water from deeper zones to move into the fresh-water system, increasing chloride concentration in wells, hence affecting water suitability for agricultural and domestic purposes (Spechler, 1994; USGS, 2008). Crop establishment and growth can be severely impacted when saline water is used because salt is accumulated in the wetting front impairing the plant ability to uptake nutrients (Hanson et al., 1997).

The groundwater withdrawals in St. Johns county increased 1.22 million gallons per day from 1965 to 1988. Saint Johns along with Putnam and Flager counties (TCAA) have been identified as one of the principal areas of saltwater intrusion in northeast Florida.

It is urgent to determine the optimum irrigation management to meet potato water requirements without overpumping irrigation wells or wasting water and nutrients. Efficient irrigation methods, such as drip, aims to produce more yield with less water. Additionally, reduction in the volume of water used to grow the potato crop could minimize salt water intrusion and facilitate natural replenishment of fresh-water resources.

Evaluation of potato response to drip irrigation in sandy soils is paramount to provide scientifically based information to growers. Drip tape is commonly placed 3 to 6 cm below the soil surface in Florida vegetable production. Deeper tape installation may not provide moisture to shallow root crops like potato, due to the limited wetting from a point source (Clark and Stanley, 1992; Clark et al., 1993).

Thus, the objectives of this study were to 1) evaluate the distribution uniformity of two drip tape placement 5 cm above and below potato seed piece and its effects on root distribution and fresh tuber yield 2) analyze the water table fluctuations as influenced by drip and seepage irrigation systems, and 3) determine an optimum depth of placement for drip tape in potato hills on Florida sandy soils. It was hypothesized that drip irrigation can reduce crop water requirements, improve irrigation water use efficiency (IWUE), and reduce water drainage and runoff from the crop area.

Materials and Methods

Experimental Design and Layout. Field experiments were carried out at the University of Florida Partnership for Water, Agriculture, & Community Sustainability facility in Hastings, Florida (29 41’ 27.58’’ N, 81 26’ 31.37’’ W). The soil has been classified as sandy, siliceous, hyperthermic Arenic Ochraqualf and belongs to the Ellzey series (USDA, 1981). Prior to the start of the first season, the area was laser leveled and raised rows (78 m long, 0.35 m height) formed. Afterwards, the field was fumigated (60% chloropicrin, 39% 1, 3 dichloropropene) at a rate of 103 L ha^{-1}. Potato seed pieces (57-85 g) of ‘Atlantic’, ‘Fabula’, and ‘Red LaSoda’ were planted on February 17, 2011 and January 17, 2012. Total granular fertilizer banded and incorporated into the soil was at rates of 225-112-308 kg ha^{-1} (200-100-275 lbs ac^{-1}) of N, P_2O_5, and K_2O, respectively. Nitrogen applications were split at three times: at planting, at emergence, and when plants were between 15 and 20 cm tall. No fertilizer was supplied with drip irrigation.

The potato seed piece was used as point of reference for the installation depth of the drip tape. Subsurface drip tape (SUB) was placed 5 cm below the seed piece before planting, and surface drip tape (SUR) was installed after planting 5 cm above the seed piece. The drip system operated at an average pressure of 55 kPa. Pressure was regulated and kept constant at 138 kPa on the inlet of each drip block treatment, which accounted for head losses to the furthest plots.

In the drip irrigated treatments, a single pressure compensated drip line (RO-DRIP, John Deere Water, Moline, IL, USA) flowrate of 1 L h^{-1} at 55 kPa for each emitter, a 20 cm emitter spacing, 16 mm inner diameter, and 8 mm thickness was used to deliver irrigation water (Figure 3-1).

Irrigation treatments were established and replicated four times on 2.31 ha (5.7 ac) field. Plots were randomized within the typical farm design of sixteen, 1 m wide rows per bed. Plots were separated by a 37 m (120 ft) wide buffer zone. This large zone was necessary to eliminate the influence of the high water table in seepage plots on the drip plots (Figure 3-2). Water furrows were spaced 18 m at the border of each bed and used for seepage irrigation and to drain excess water. Field row lengths were approximately 78 m.

Field operations followed typical grower practices in the region. Potatoes were sprayed during the season to control foliar diseases and insects. Temperature, relative humidity, solar radiation, and wind speed data was obtained from a weather station located in the experimental site. Daily reference evapotranspiration (ETo) was retrieved from the Florida Automated Weather Network (FAWN; www.fawn.ifas.ufl.edu). Crop evapotranspiration (ETc) was calculated from the product of crop coefficient (Kc) and evapotranspiration of reference for each specific growth stage (Doorenbos and Pruitt, 1975).

Soil bulk density was evaluated at the end of 2012 season. It was measured in undisturbed samples of known volume. Average bulk density for the 0-15 cm layer was 1.30, 1.45, and 1.31 g cm^{-3} for SUR, SUB, and SEP, respectively. The average bulk density for the 15-30 cm layer was 1.52, 1.57, and 1.57 g cm^{-3} for SUR, SUB, and SEP respectively. Similar bulk density values were found at the subsequent deeper layers (up to 60 cm depth). Bulk density was slightly higher for SEP at 45-60 cm deep when compared to SUR and SUB.

Daily irrigation events were used for drip and seepage treatments. The seepage 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 and until soil surface appearance is wet. Drip irrigation events were 15 minutes, running three cycles per day. In 2011, irrigation schedule remained constant during 36 days and was increased to 4 cycles per day until the last irrigation day because of plant water stress symptoms, increased soil surface temperature, and visual indication that emitter water bulb was not replenishing the evaporation losses.

In 2012, drip schedule started with the previous 4 daily cycles with a depth of 5 mm, equivalent to 49,991 L ha^{-1}. However, fluctuating climate factors and relatively dryer conditions made it necessary to increase the events from 4 to 6 cycles per day. This upgrade was done 28 days after irrigation started and remained this way for 13 days. On March 28th (71 DAP) the duration of each event was increased from 15 to 20 minutes to increase the size of the water bulb in these sandy soils to provide enough moisture to the root system. On April 4th (78 DAP), the duration of irrigation events was reduced to an initial 15 minutes and continued like that until the last irrigation day on April 19th (93 DAP, right after vine killing).

In the spring of 2011, a system consisting of 5 cm T-shaped filters (Amiad filtration systems, Oxnard, Calif.), pressure gauges, a flowmeter, a single station controller with attached solenoid (SVC-100, Hunter Industries, San Marcos, Calif.) and pressure regulator (PRFX-20, Senninger Irrigation Inc. Clermont, FL) were 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 seepage irrigated block. Irrigation events and duration were recorded from the treatments beginning at plant emergence until irrigation was suspended before vine kill. Vine kill is generally 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 larger carbohydrate concentration in the tubers of fresh market varieties. Irrigation water use efficiency (IWUE) was calculated as follows:

IWUE= (MKT)/ (IRRI)

Where MKT is marketable tuber yield (kg ha^{-1}) and IRRI is seasonal water applied (m^3 ha^{-1}) for each irrigation treatment and expressed as kg m^{-3}.

Monitoring soil water content. Volumetric soil moisture content was recorded every 15 minutes throughout the entire season using sixty time domain reflectometry (TDR) sensors (CS615 and CS650, Soil Water Content Reflectometer, Campbell Scientific Inc. Logan, UT, USA). Thirty sensors were installed in the seepage irrigated plots and thirty sensors in drip irrigated plots. Three soil profiles containing 10 sensors each were designed to monitor soil moisture at different potato rows in the plots. Sensors were located 5 cm above drip tape for SUR and SUB treatments. The sensors were buried in cross-sectional pattern from the irrigation furrow and connected to a datalogger (CR10X and CR1000 datalogger, Campbell Scientific, Logan, UT) via channel relay multiplexers (AM16/32B multiplexer, Campbell Scientific, Logan, UT). Data was downloaded weekly throughout the season. They were buried at different depths with 15 cm increments and the lowest probe installed at 75 cm distributed across the potato hill (Figure 3-3). In addition to these sensors, a handheld TDR (FieldScout 300, Spectrum Technologies, Aurora, IL) coupled with 20 cm rods was used to measure weekly soil moisture content in the experimental area.

Water Table Monitoring. Observation wells containing level pressure sensors (piezometers) (PDCR 1830 Series, General Electric, CT, USA) were randomly installed in each experimental block to measure water table depths and observe the effects of rainfall and each irrigation treatment on the groundwater level throughout both potato seasons. Each piezometer was installed in the field using global positioning system (GPS) receiver (60 CSx handheld GPS Navigator, Garmin International, Inc. Kansas City, KS, USA). Measurements of cable depth from soil surface to water table surface were taken during the installation in order to obtain an accurate reading of the water level fluctuations. Probes were coupled with dataloggers that operated wirelessly to upload the data every fifteen minutes to a computer receiver located at the farm main office and through a special software making it available to a website. Devices were calibrated at the beginning of each season as well as operating system updated and regular maintenance practices were performed to keep the devices operating appropriately. Piezometers were removed from the field periodically for a short amount of time when tillage practices were needed.

Root length density distribution. Root sampling of the variety Atlantic was carried out 86 days after planting in the 2012 season in order to quantify the length density (RLD) of the root system affected by three different irrigation delivery systems. At this time (86 DAP) 'Atlantic' has already reached its maximum vegetative growth and rooting depth (Stalham and Allen, 2001). Samples were taken at two different surface positions on a transversal line across the potato hill: (A) adjacent to the plant main stem; and 0.15 m (B) away from the plant. Soil cores were sampled at 0.15 m deeper increments (0-0.15, 0.15-0.30, 0.3-0.45, 0.45-0.6, and 0.6-0.75) until 0.75 m from the soil surface was reached (Figure 3-4). A soil auger (0.1 m diameter and 0.17 m height) was used to collect samples of the root profile of a representative plant randomly chosen in each plot. Samples were placed in plastic bags labeled with irrigation treatment and depth to which they were extracted. Plastic bags were stored in the Horticultural Sciences department (Univ. of Fla. Gainesville) cooler room at 4 °C until further cleaning. A spray nozzle (Metal Body 584, Gilmour USA, Peoria, IL) was used at constant low pressure to separate the soil and organic matter particles from the roots. Special attention was paid to weeds in order to minimize the effect of them in the sample. 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 in petri dishes that were stored in a freezer waiting to be scanned.

The commercial software package WinRHIZO 8.0 (Regent Instruments Inc., Quebec, Canada) digital scanner was used to evaluate the length and volume of roots in the different soil depths sampled. Plastic trays (25 cm x 15 cm) were carefully washed and dried in order to avoid scratches that could be misread by the root scanner.

Results and Discussion

Irrigation started after potato sprouts were fully emerged, which occurred 26 and 30 days after planting in 2011 and 2012 seasons, respectively. The length of irrigation period was 67 and 64 days in 2011 and 2012, respectively. It is a common practice among growers in the TCAA to start irrigation on an average of 25 days after planting. The main pump was shut off when a rainfall was expected.

The calculated ET_c from planting to harvest date was 380 and 306 mm for 2011 and 2012, respectively. The average daily irrigation volume applied using drip was 3.51 mm, while seepage applied 6.24 mm to maintain the high water table in 2011. In 2012 season, it was applied an average rate of 2.73 mm day^{-1} when using drip and 22.04 mm day^{-1} for seepage treatment (Figure 3-6). The difference in the volume of water applied for seepage irrigation between seasons was a combined result of drier conditions at the beginning of the 2012 growing season, which required a large volume of water to raise the water table, and keeping the field wetter a longer period at the end of the season. Seepage was managed based on the soil appearance as the main indicator of adequate moisture for the crop, which is an inaccurate procedure for determining irrigation scheduling, which can be improved. Figure 3-7 shows the soil moisture distribution in the same seepage irrigated plot at different growth stages for 2011 and 2012 growing season. In 2012, more water was applied with seepage irrigation during the vegetative growth and tuber initiation stages maintaining the water table at a shallow depth. Also, erratic and heavier rain storms occurred in 2012, which also impacted the water table level. The rain gauge in the research site recorded 54.1 mm of rainfall between April 21 and 22, 2012 (36 mm in 2 hours). The water retention structures were lowered to drain excess water and due to the low irrigation uniformity of seepage a large volume of water is needed to raise the water table up to a desired level. These types of extreme rainfall events highlighted the lack of accurate control of the water table with seepage irrigation. This system keeps the water table close to soil surface, thus increasing the risk of run off and nutrient leaching during periods of high precipitation.

Root length density distribution. The root length density (RLD) is often closely related to water and nutrient uptake (Lesczynski and Tanner, 1976). The RLD in this study was not significantly different among irrigation treatments. Depth of sampling was the only factor that significantly influenced RLD. Root density 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 0-15 cm soil layer. The RLD decreased in subsequent soil layers as follows: 16-33% in the 15-30 cm layer; 4-8% present in the 30-45 cm layer; and <2% RLD in the 45-60 and 60-75 cm soil depths (Figure 3-8). Although differences among irrigation treatments or interactions between effects were not found, it is important to highlight that the largest RLD found was 2.26 cm cm^{-3} in the 0-15 cm soil layer for SUB irrigation. The behavior of the potato's root system is widely documented (Joyce et al., 1979; Mackerron and Peng, 1990; Tourneux et al., 2003). Researchers mention the influence of genotype over the root's development pattern. Apparently, 'Atlantic' responded to SUB irrigation by lengthening roots deeper and closer to the subsurface water front. We did not measure root development across physiological stages, but we believe that larger roots present in 0-15 cm soil layer could be an effect of low moisture in this layer and caused some level of water stress.

Several studies agreed that regardless of genotype differences, commercially produced potato typically have root systems concentrated in the upper 30-cm of the soil (Ahmadi et al., 2011; Lesczynski and Tanner, 1976; Shock et al., 2006). Our findings showed that 'Atlantic' RLD values were similar under SUR and SEP treatments in the 0-15 cm upper layer (1.90 cm cm^{-3} on average).

Irrigation Water Use Efficiency (IWUE). In both seasons IWUE values were higher for drip treatments. The treatment ranking was as follows: SUR>SUB>SEP for all tested potato varieties. In 2011, the obtained IWUE values were 5, 6, and 4 kg m^{-3} for SUR, SUB, and SEP treatments. 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 control the water table level and produce marketable yield. In contrast, drip treatment consistently achieved higher IWUE levels due to similar marketable yield to those of SEP; however, it was produced with less volume of water. The position of the wetting front is commonly used to describe the soil moisture distribution under different conditions (Badr et al., 2010). When using SUB, the soil surface remained dried due to the low capillarity rise on sandy soils, but lower soil layers between 15 and 40 cm had volumetric water content higher than 15%, which is considered optimum in sandy soil conditions. The SUR treatment also demonstrated an ability to maintain moisture contents higher than 12% at depths between 0-20 cm (Figure 3-10).

In order to make a fair 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. They 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 our drip treatments delivered 2.73 and 19.31 mm less water per day than seepage in 2011 and 2012, respectively. This was translated into irrigation water savings of 48% - 88% when using drip irrigation.

Soil moisture dynamics. One of our hypotheses was that drip irrigation can supply water to the potato plant without relying on water resources from the water table. On average, the water table was maintained 27 and 14 cm lower on drip irrigated plots than on seepage plots in 2011 and 2012, respectively; with the average water table depth for seepage at 55.6 and 69.3 cm from the soil surface in 2011 and 2012, respectively (Figure 3-11 and 3-12). However, there were large ranges in these water table levels, with fluctuations between 19 and 65 cm in 2011 and 36 to 91 cm in 2012. In both seasons rainfall had a significant response bringing the water table up during certain times of the season. Rainfall contribution to the water table depends on the water table level prior to precipitation, outlet board management, and the row location in the field. The closer to the water furrow, the higher the impact of rainfall will be, with minimum effect in the center of the bed (rows 7-10). On average 1 mm of precipitation will bring the water table 4 cm towards the soil surface.

The rain pattern was different in 2011 compared to 2012. In 2011, 85% of the total 116 mm occurred during the initial 55 days of plant development and growth. In

2012, although it rained 62 mm more, 68 mm occurred in the final stages of plant maturation, after the vines were killed.

The second year of this experiment (2012) was the warmest recorded temperature for the United States (since 1895), displacing 1998 from this position. As stated by Pitts and Clark (1991), seepage irrigation is completely dependent on the depth of the water table, so dry, hot years, severely reduce seepage efficiency and increases cost of pumping due to the water level decline in wells (Vergara, 1994).

Figure 3-11 and 3-12 present soil moisture data and water table level at four soil layers for each irrigation treatment in three key growth stages during 2011 and 2012. In the SUR treatment the 0-10 cm sensor showed the highest moisture response and high water content was kept at this depth throughout the growing season. Sensors at deeper layers showed minimum response to the drip treatments, which is a good indicator that water delivered was kept in the intended soil depth and deep percolation was greatly minimized. The depth placement of drip tape for the SUB treatment produced dry soil conditions in upper layer (0-10 cm) and kept high soil moisture content in the 10-20 cm layer. The TDR probes measured soil moisture content fluctuations related to irrigation events determined by the drip tape depth placement. The targeted layer with SUR and SUB were the layers presenting the moisture content variations during irrigation events.

Large soil moisture fluctuations were observed throughout the season in both years in the seepage irrigation treatments.

Soil water distribution. The spatial distribution of soil moisture in the soil profile varied according to the irrigation method used. For SUR and SUB volumetric soil moisture content values were between 12% and 32% between the 0 and 45 cm soil depth layer (Figure 3-10). Vertical movement from the emitter was more pronounced than lateral movement in both drip treatments. Capillary rise was more noticeable in the SUR treatment than SUB. The highest moisture content for SUB was attained at the 35 cm depth while SUR had relative high moisture values at the 20 cm depth and extending to the 45 cm depth. The availability of water in the upper layers for the SUR treatment may be the reason why this drip tape placement performed better than SUB in terms of marketable yield for all the potato varieties (Table 3-2).

On the other hand, the seepage treatment had relative low moisture values of approximately 8% in the top layer between the 0 and 10 cm depths and excessively high values (>32%) at the 30 cm depth and below, which is consistent with raising the water table level up to the root zone.

In both years, the effect of the perched water table to the volumetric water content (VWC) varied primarily as function of the depth at which the soil moisture content was measured, and secondly as function of the row distance to the water furrow (Figure 3-13). Minimum water table influence was measured in the 0-15 cm layer. It appeared that the 15-30 cm layer behaves as interface, as it presented the most dynamic interaction between the depth of the water table and the soil content. As the water table raised, the VWC at 30 cm increased until constant moisture content was reached, suggesting that the water table can be lower without impacting the moisture content at 30 cm. The soil was permanently saturated at lower soil depths (45-75 cm).

Conclusion

The localized water application of drip treatments maintained higher soil moisture in the upper soil layers. Water saved with drip irrigation was 11.02 mm day^{-1} on average. Similar marketable yield between surface drip tape and seepage were achieved, which means that water can be saved using drip irrigation while maintaining yield. In 2011, higher IWUE was obtained with SUR and SUB compared to SEP for 'Atlantic'. However, IWUE values were similar among irrigation treatments for 'Fabula' and 'Red LaSoda'. In 2012, the treatment ranking for IWUE values was as follows: SUR>SUB>SEP for all tested varieties. Root length density of 'Atlantic' potato was not influenced by irrigation treatment. The higher root concentration (>90%) was found in the upper 30-cm of soil layer for all treatments, which is in agreement with other potato root studies. The ability to supply water with seepage to the shallow potato root system is challenging. Potato roots are scarce and do not efficiently extract water from deep soil layers where the groundwater front is coming up in the seepage system. However, water front coming from closely placed emitters can increase root's water and potentially nutrient uptake.

It is concluded that surface drip irrigation can produce similar tuber yield for 'Atlantic' and 'Fabula' varieties compared to seepage irrigation. The benefit of SUR is an ability to conserve water and the possibility of fertigating the crop through the system. Future research is needed to evaluate the feasibility of fertigation using SUR irrigation, and to adjust drip irrigation regimes to growth stages and crop evapotranspiration in sandy soils.

Table 3-1. Analysis of variance summary for root length density (RLD) affected by irrigation, column, depth, and treatments interactions.

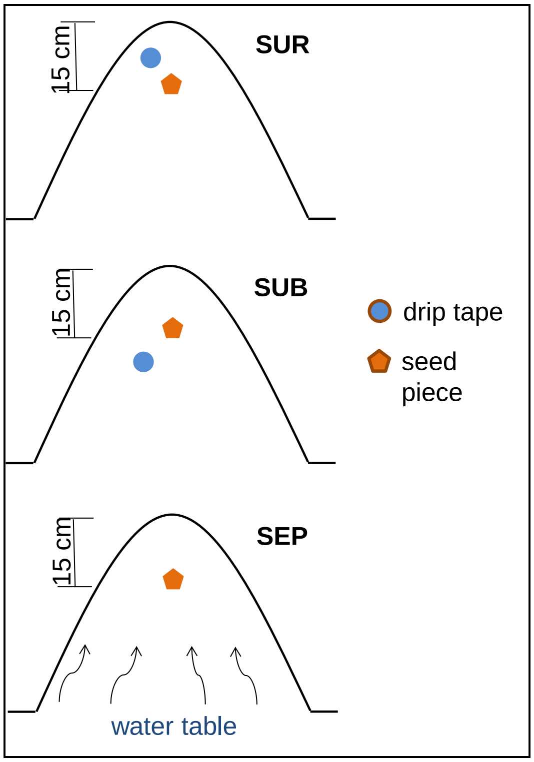
Main effect	D.F.	RLD
Irrigation (I)	2	ns
Depth (D)	4	***
Column (C)	1	ns
I x D	8	ns
I x C	2	ns
C x D	4	ns
I x C x D	8	ns

* Significant at p<0.05; ** significant at p<0.01; *** significant at p< 0.0001. ns: not significant; D.F.: degrees of freedom.

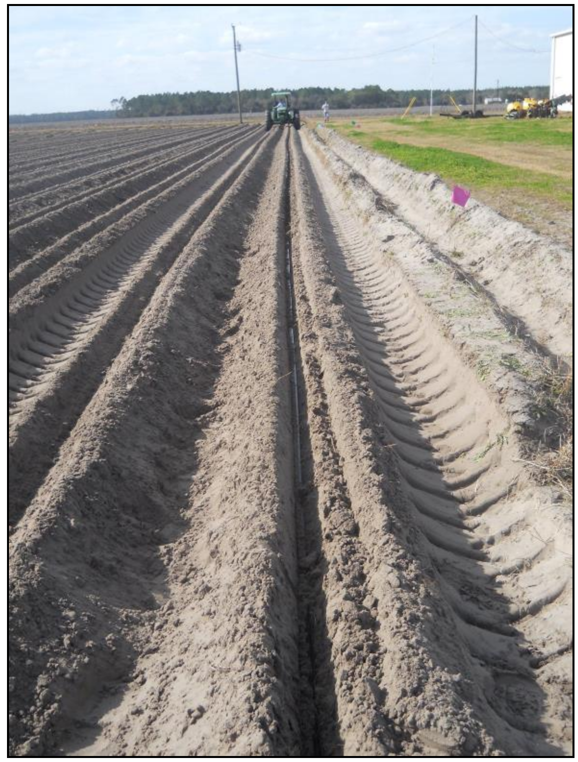
Table 3-2. Irrigation and variety treatments, irrigation depth, marketable yield, and irrigation water use efficiency for 2011 and 2012 potato season.

		2011			2012		
Irrigation treatment	Variety treatment	Irrigation depth (mm)	Marketable Yield (kg ha^{-1})	Water Use Efficiency (kg m^{-3})	Irrigation depth (mm)	Marketable Yield (kg ha^{-1})	Water Use Efficiency (kg m^{-3})
Surface	Atlantic	270	26280 a[Z]	9.7 a	175	27000 b	14.1 a
Subsurface	Atlantic	270	19910 b	7.4 b	175	19680 c	10.3 b
Seepage	Atlantic	518	23460 ab	4.5 c	1411	32790 a	2.3 c
Surface	Fabula	270	16110 a	3.1 a	175	18710 a	9.8 a
Subsurface	Fabula	270	12020 a	4.5 a	175	7820 b	4.1 b
Seepage	Fabula	518	15790 a	3.1 a	1411	17640 a	1.3 c
Surface	Red LaSoda	270	12710 b	2.5 a	175	14130 b	7.4 a
Subsurface	Red LaSoda	270	16410 b	6.1 a	175	9180 c	4.8 b
Seepage	Red LaSoda	518	26140 a	5.0 a	1411	20890 a	1.5 c

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



A



B

Figure 3-1. A. Schematic representation of the irrigation treatments field-tested. SUR and SUB shows the drip tape position referenced by the seed piece position and SEP shows the water table rise. B. Drip tape layout in the field.

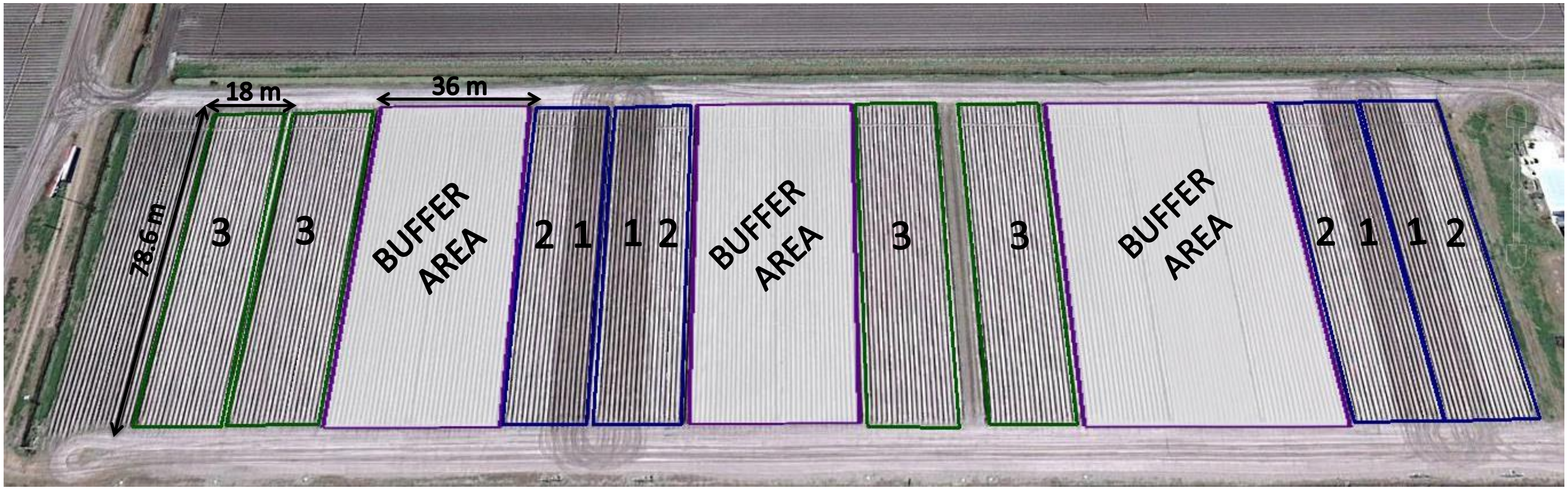


Figure 3-2. Experimental layout in the field showing treatments distribution and block dimensions. SUR (1); SUB (2); and SEP (3) irrigated plots. Seepage and drip plots were separated 36 m apart on average.

Figure 3-3. Time Domain Reflectometry (TDR) probes installed parallel to the potato row in seepage and drip irrigation treatments to monitor soil moisture content every 15 minutes throughout the season.

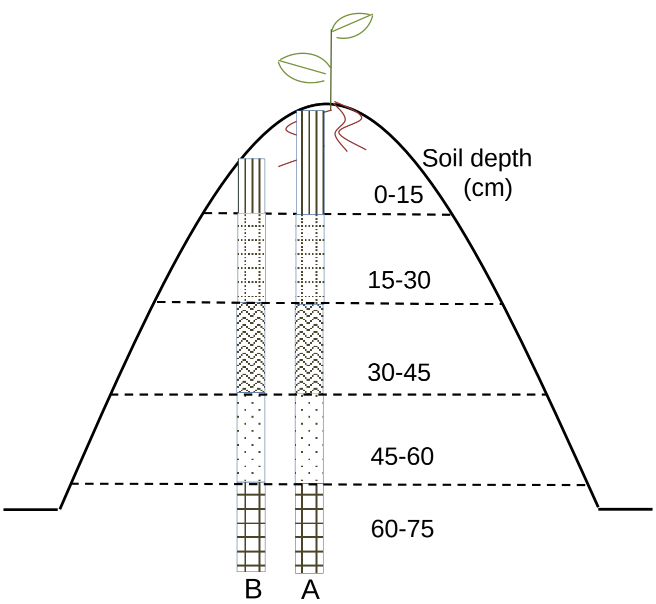


Figure 3-4. Root sampling diagram for 'Atlantic' irrigated with seepage, surface, and subsurface drip irrigation during 2012 spring season.

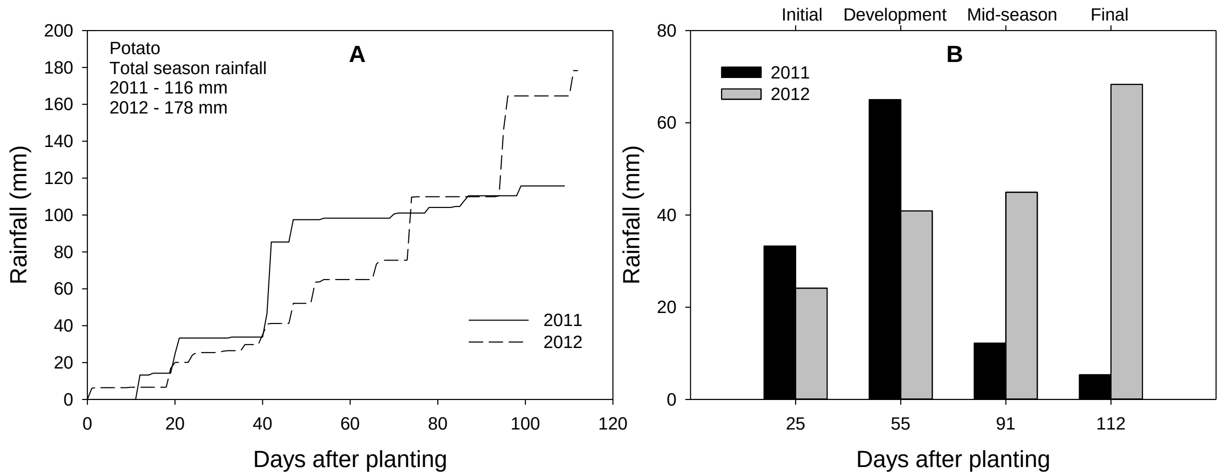


Figure 3-5. Cumulative rainfall measured at Hastings, Florida in potato seasons 2011 and 2012. B. Cumulative rainfall measured at different growth stages: Initial (0-25 DAP); Development (26-55 DAP); Mid-season (56-91 DAP); Final (92-112 DAP).

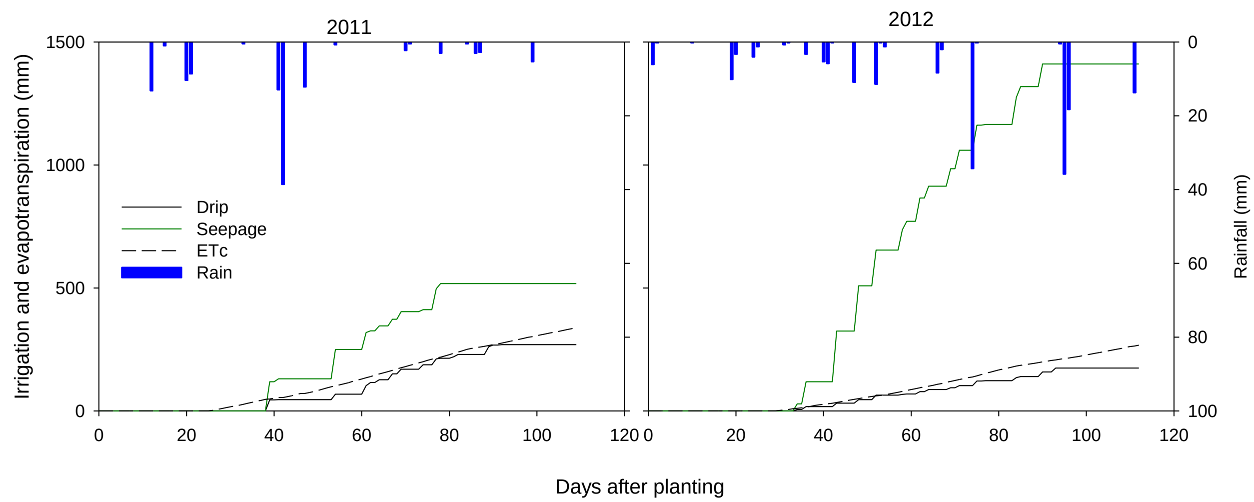


Figure 3-6. Cumulative irrigation and estimated evapotranspiration for drip and seepage irrigation methods used during 2011 and 2012 potato growing seasons.

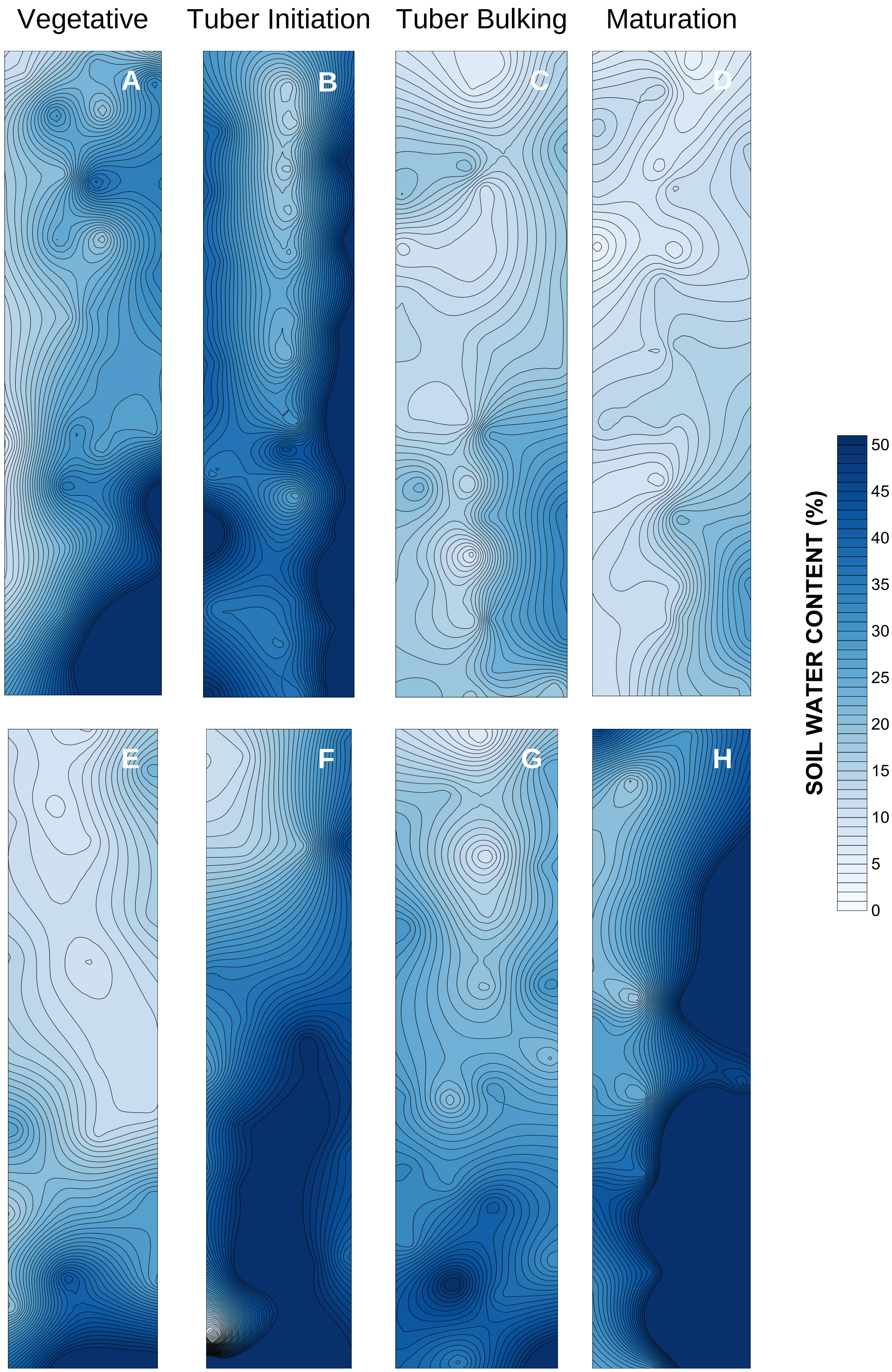


Figure 3-7.Comparison of a seepage irrigated bed during 2011 (A-D) and 2012 (E-H) at different crop growth stages. Field was wetter in the 2012 season.

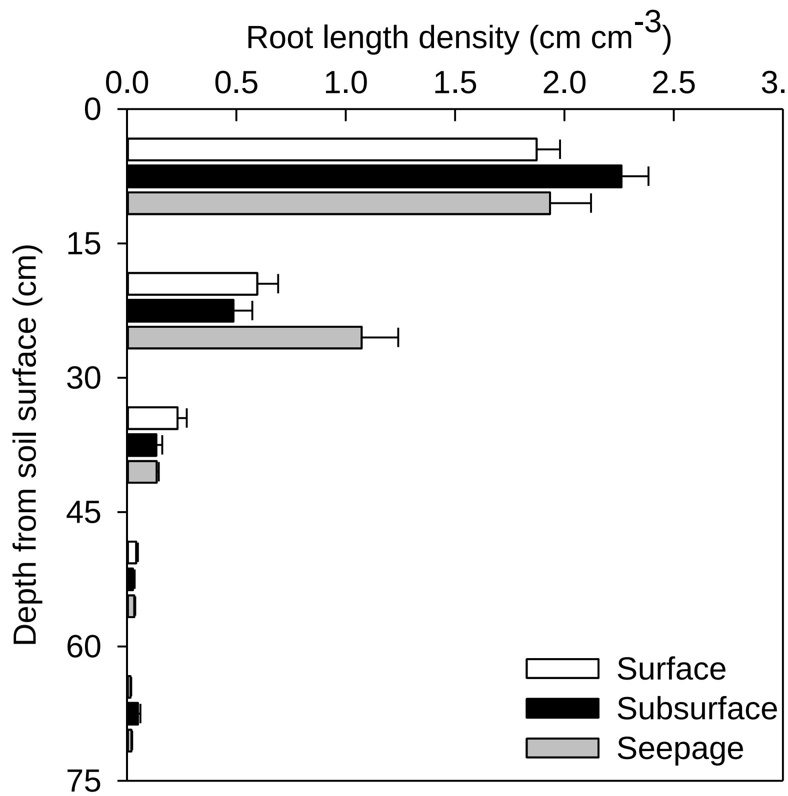


Figure 3-8. Potato root density (cm of roots per cm3 of soil) in five depth intervals (0-15, 15-30, 30-45, 45-60, and 60-75 cm) at 86 DAP in the 2012 season.

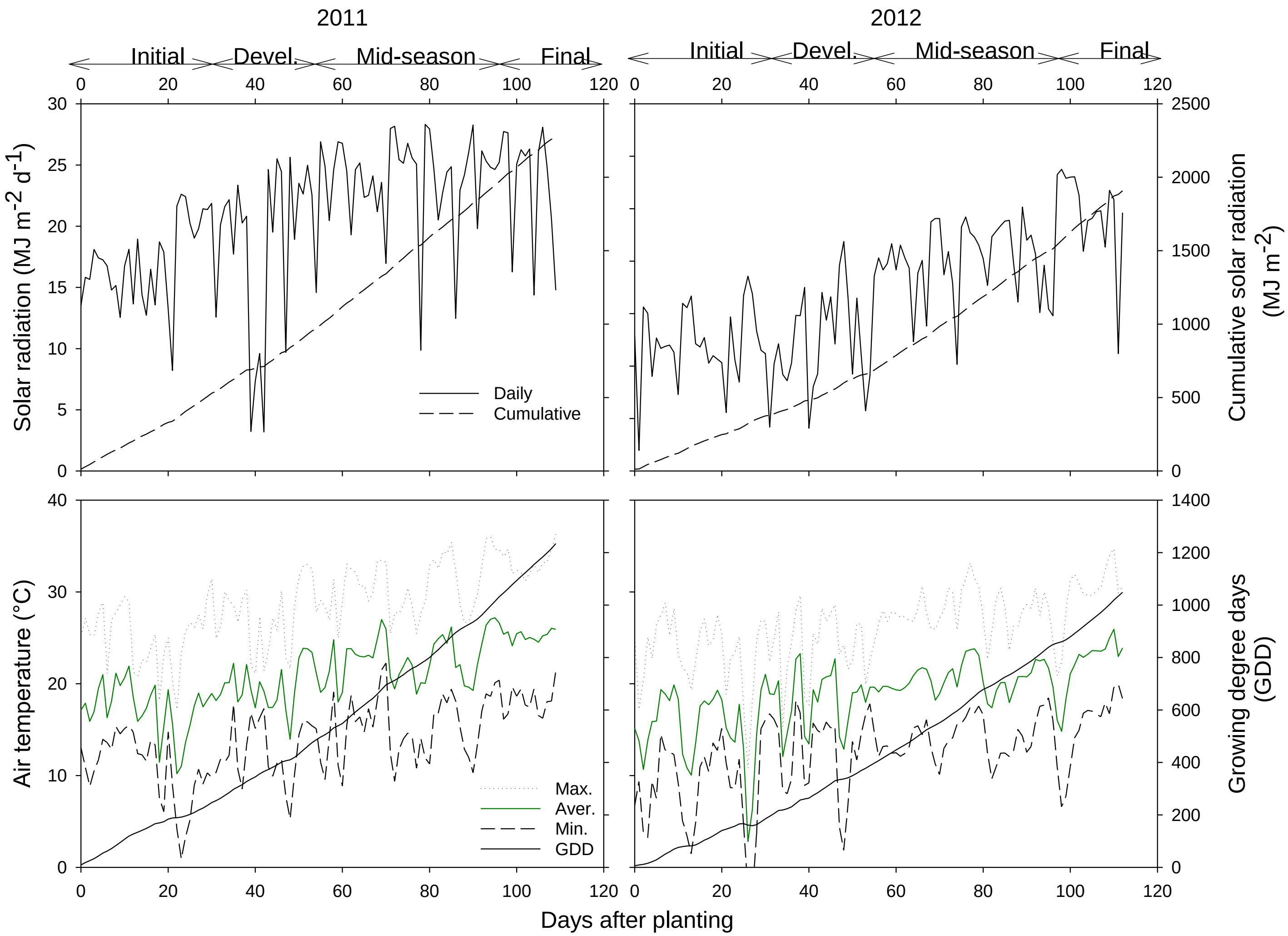


Figure 3-9. Daily and cumulative solar radiation, minimum, average, maximum daily temperatures and cumulative daily growing degree days (GDD, temperature base of 10 C) during the 2011 and 2012 potato growing season in Hastings, Florida.

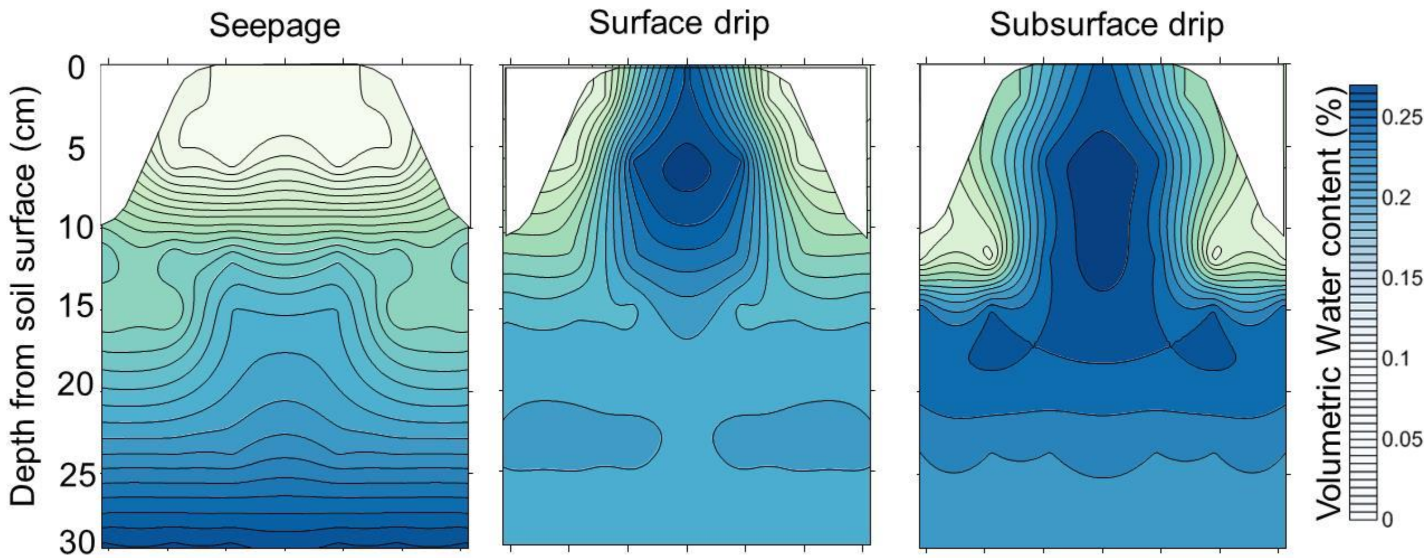


Figure 3-10. Spatial distribution of moisture in the soil profile for seepage, surface drip, and subsurface drip.

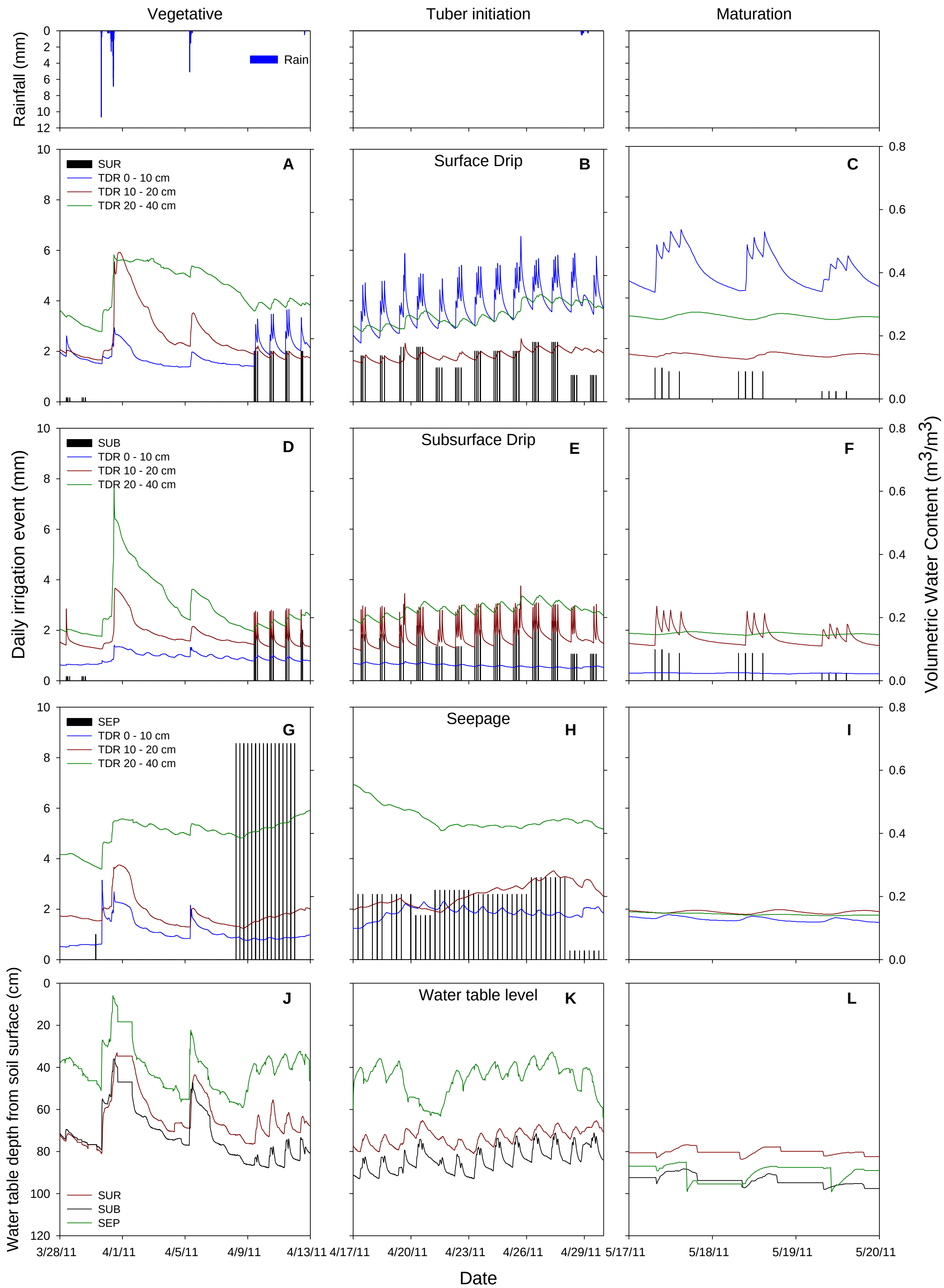


Figure 3-11. Water table level, rainfall, daily irrigation events, and volumetric soil water content at 0-10, 10-20, 20-40, and 40-50 cm depth for potato during three development stages (vegetative, tuber initiation, and maturation) in 2011 for SUR (A-C), SUB (D-F), and SEP (G-I) treatments.

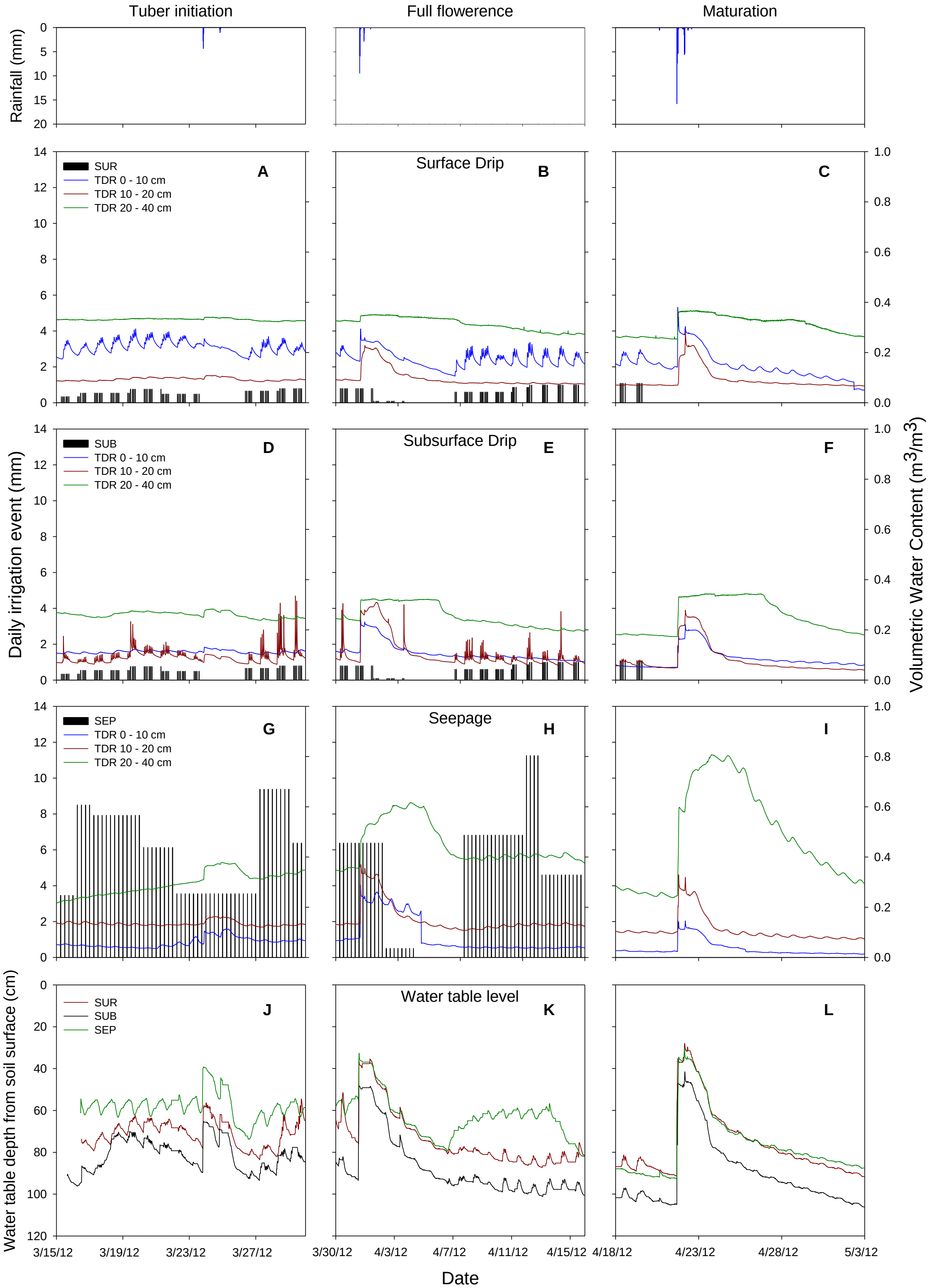


Figure 3-12.Water table level, rainfall, daily irrigation events, and volumetric soil water content at 0-10, 10-20, 20-40, and 40-50 cm depth for potato during three development stages (tuber initiation, full flowerence, and maturation) in 2012 for SUR (A-C), SUB (D-F), and SEP (G-I) treatments.

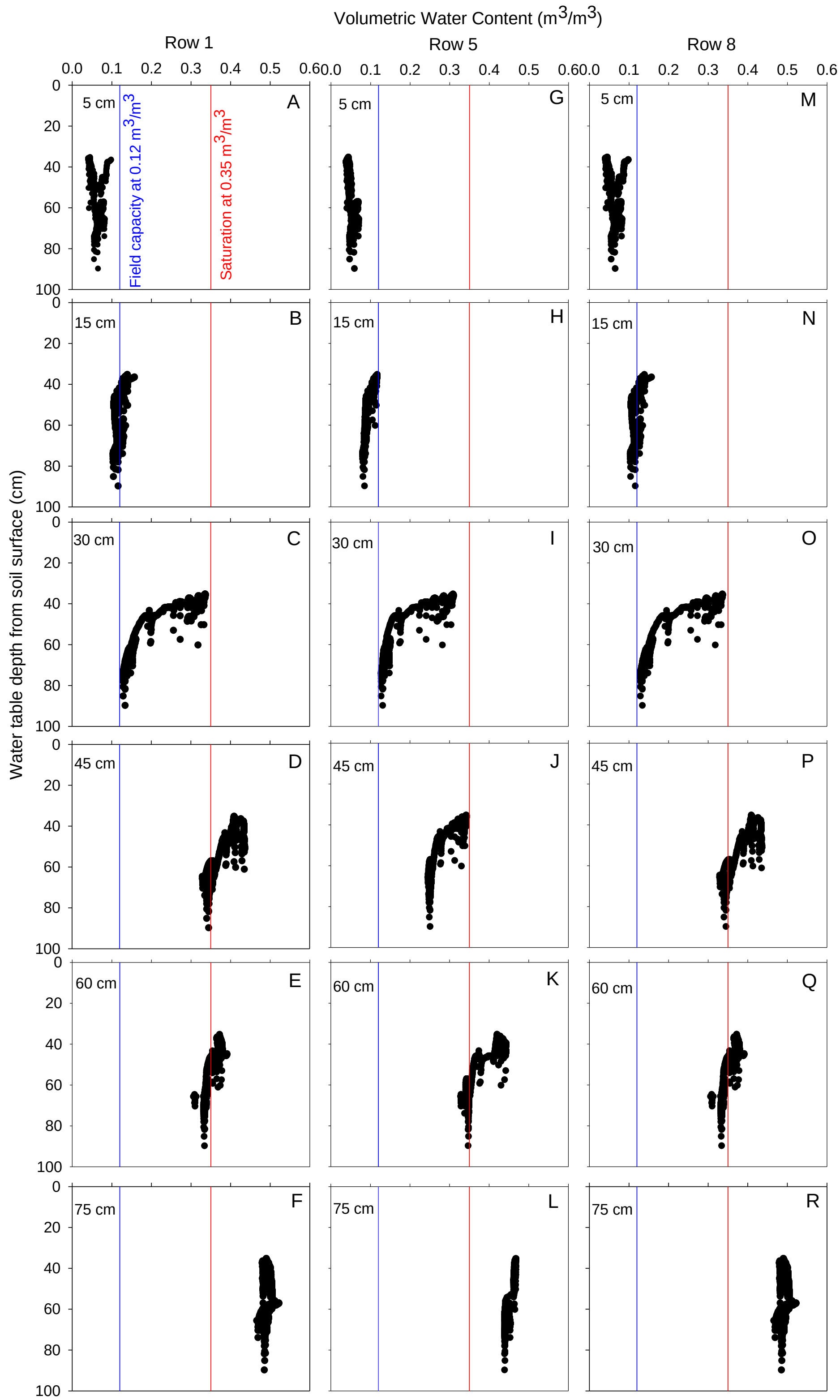


Figure 3-13. Volumetric water content and water table dynamics at 5, 15, 30, 45, 60, and 75 cm depth in potato row 1 (A-F), row 5 (G-L), and row 8 (M-R) on a seepage irrigated block without rainfall input during the 2011 season.

CHAPTER 4
SUMMARY AND CONCLUSIONS

Efficient water delivery systems like drip irrigation are a potential option for potato growers in northeast Florida. However, it is necessary to determine an optimal drip tape depth placement to successfully grow potatoes and attain maximum yield potential. Surface drip tape (SUR) was installed 5 cm above the seed piece and subsurface (SUB) drip tape was installed 5 cm below the seed piece. It was evaluated the impacts of these two different drip tape placement to grow one chipping (‘Atlantic’) and two fresh market (‘Fabula’ and ‘Red LaSoda’) potato varieties. Seasonal water savings with drip irrigation ranged between 248 mm and 1236 mm (10 and 49 inches) in this study. The varieties responded differently to SUR and SUB drip treatments. In general, the SUR treatment outperformed SUB and achieved statistically similar results to the SEP treatment in terms of total and marketable yield. Marketable yield was not significantly different between SUR and SEP treatments for ‘Atlantic’ and ‘Fabula.’

The SUR irrigation high efficiency and low dependence on the water table is paramount for sustainable potato production in sandy soils. In addition, the soil moisture content can be easily controlled with SUR drip in the upper soil layer (0-30 cm depth). According to this research findings,>90% of the ‘Atlantic’ root system is concentrated in this upper soil layer.

Despite these benefits, there are some challenges to using drip irrigation in commercial potato production systems. These include: increased labor, high probability of tape damage from machinery, high potential for leaks to occur in the system, wind vulnerability if soil is not adequately wet, and increased costs of production. However, the possibility of implementing fertigation and automation of drip irrigation system could facilitate its adoption. Additionally, the potential increase of marketable yield due to water and nutrient precisely delivered and maintained in the root zone can alleviate expenses, and moreover augment economic returns.

Improving water use efficiency in the TCAA is a priority in order for growers to remain competitive in the marketplace. Future research should be conducted to evaluate SUR drip tape combined with fertigation practices for ‘Atlantic’ and ‘Fabula’ as well as better tape installation and removal methods. This will help elucidate the performance of different varieties under an optimum supply of water and nutrients. Furthermore, more precise recommendations can be provided to growers with the additional benefit of increasing production efficiency and diminish nonpoint source pollution in the St. Johns River watershed.

APPENDIX
SAS CODES

The SAS codes used for the statistical analyses performed are presented as follows:

1) SAS code for yield (TOT and MKT), size classes distribution, internal and external quality variables, and specific gravity.

```
proc import datafile='c:\rawdata\Yield_2011-2012.xls'  out=yield replace;
sheet='Yield';
run;

proc print data=yield;
run;

proc sort data=yield;
by year rep irri var;
run;

/*average across rows per plot*/
/* the equivalent to Fisher's LSD was obtained through the diff option of the lsmeans statement*/
proc means noprint data=yield;
	by year Rep IRRI VAR ;
	var C B A1 A2 A3 A4 TOT MKT HH BR CRS IHN BCL BCM BCH GT GC Mis ROT SG;
	output out=yield_avg MEAN
	= C B A1 A2 A3 A4 TOT MKT HH BR CRS IHN BCL BCM BCH GT GC Mis ROT SG;
proc print data=yield_avg;
	title 'Yield averaged across plot rows';
run;

PROC GLIMMIX data=yield_avg;
CLASS IRRI VAR Rep Year;
MODEL MKT = IRRI|VAR|YEAR rep (irri)/ddfm=kr;
random rep year;
lsmeans IRRI*VAR/ lines plots=meanplot (sliceby=VAR);
lsmeans IRRI*VAR /slicediff=VAR slice=VAR;
lsmeans IRRI*VAR/slicediff=IRRI slice=IRRI;
title;
run;
```

Note: the independent variables were changed one by one in the Model statement.

2) SAS code for biomass accumulation and aboveground N uptake:

```
proc import datafile='c:\rawdata\Biomass_2011-2012.xls'  out=biomass replace;
sheet='Biomass1';
run;

proc print data=biomass;
run;

proc sort data=biomass;
by year rep irri var dap;
run;

proc means noprint data=biomass;
        by YEAR REP IRRI VAR DAP ;
        var BIOMASS Nitrogen;
        output out=Biomass_avg MEAN
                = Biomass Nitrogen;
proc print data=biomass_avg;
run;

PROC GLIMMIX data=biomass_avg;
CLASS IRRI VAR Rep Year dap;
MODEL biomass = IRRI|VAR|YEAR|DAP /ddfm=kr;
random  rep dap year;
lsmeans IRRI*VAR/ lines plots=meanplot (sliceby=VAR);
lsmeans IRRI*VAR /slicediff=VAR slice=VAR;
lsmeans IRRI*VAR/slicediff=IRRI slice=IRRI;
title;
run;
```

Note: Year effect was significant for biomass accumulation and N uptake. Thus, SAS codes were adjusted for further statistical analysis.

3) SAS code for IWUE

```
PROC GLIMMIX data=IWUE_avg;
CLASS IRRI VAR Year REP;
MODEL IWUE = IRRI|VAR|YEAR /ddfm=kr;
random  rep year;
lsmeans IRRI*VAR/ lines plots=meanplot (sliceby=VAR);
lsmeans IRRI*VAR /slicediff=VAR slice=VAR;
lsmeans IRRI*VAR/slicediff=IRRI slice=IRRI;
title;
run;
```

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BIOGRAPHICAL SKETCH

Joel Reyes Cabrera was born in Leon, Nicaragua. Joel received a Bachelor of Science degree in Agricultural Engineering from EARTH University in Costa Rica in 2009. During his junior year in 2008, he had the opportunity to come to the University of Florida as an intern and learn about irrigation automated controllers under Dr. Michael Dukes' supervision. Upon completion of his B.S., he worked as research assistant under Dr. Johan Perret investigating the benefits of using ethanol byproducts as fertilizer sources in commercial sugarcane plantations. He has been interested in water conservation practices since he was in high school and developed a passion for plants while being at EARTH. In 2010, Joel decided to pursue a Master of Science degree and was accepted to The Gator Nation in spring 2011 to work in Dr. Zotarelli's lab. After getting his degree, he plans to continue his professional career either in academics or industry working on sustainable water management and soil-plant-atmosphere relationships to maximize crop yield.