DETERMINING THE AGRONOMIC AND PHYSIOLOGICAL CHARACTERISTICS OF THE CASTOR PLANT (*RICINUS COMMUNIS* L.): DEVELOPING A SUSTAINABLE CROPPING SYSTEM FOR FLORIDA

By

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To my Wife and Loving Family

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LIST OF ABBREVIATIONS

ai	Active ingredient
AOAC	Association of Official Analytical Chemists, now AOAC International
Ci	CO_2 concentration inside the leaf
Cv.	Cultivar
DAP	Days after planting
DAT	Days after treatment
DOY	Day of year, Julian calendar
ET_c	Crop evapotranspiration
ET_o	Reference evapotranspiration
E	Evaporation
FAO	Food and Agriculture Organization of the United Nations
FAWN	Florida Automated Weather Network
Fv/Fm	Variable chlorophyll fluorescence over maximum chlorophyll fluorescence measures photosynthetic efficiency
HA	Harvest aid
K_c	Crop coefficient
LAI	Leaf area Index
PGRs	Plant growth regulators
Pn	Photosynthesis
PSREU	Plant Science Research and Education Unit, University of Florida
RWC	Relative water content
SPAD	Special Products Analysis Division (a division of Minolta)
SLA	Specific leaf area
T_c	Crop transpiration
US	United States of America

WFREC West Florida Research and Education Unit, University of Florida

Abstract of Thesis Presented to the Graduate School
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Castor (*Ricinus communis*, L.) oil is valuable commodity for the US government and private industries and currently all castor oil is imported. In order to promote domestic castor production, research on cropping systems throughout the US is needed to determine regions and management systems that are able to support sustainable production of the crop. Effective control of excessive vegetative growth, crop termination, and efficient water use are necessary system components for production in a semi-tropical environment such as Florida. To explore Florida cropping system components, research was conducted in the north central and panhandle regions. For two castor cultivars, yield, phenological characteristics, root architecture, and physiological traits were studied in response to a plant growth regulator and harvest aid, and a crop coefficient for irrigation management was developed. Castor yields, seed weights, and oil percentages were lower than production reports from southwestern US regions, possibly linked to increased disease presence in Florida. While the plant growth regulator was ineffective in controlling plant height, one harvest aid was successful at terminating and defoliating the crop in the absence of a freeze. Crop

water use was measured with sap flow collars and appropriate K_c values were determined for efficient irrigation practices for castor grown in Florida. This study demonstrated that a castor production system is possible in Florida but yield potential is limited, likely due to increased disease pressure.

CHAPTER 1
LITERATURE REVIEW

Prospects of Castor Cultivation in Florida

Evidence of castor seeds in tombs as early as 4000 B.C. (Weiss, 1971) suggests that castor oil has been a valuable commodity throughout much, if not all, of human history with scholars projecting a much earlier date of cultivation. The oil is still used today and is considered a strategic material for national defense for use as a lubricant for military equipment in the United States of America (US). Currently commercial domestic production does not exist, but previous research efforts have shown that castor can be grown domestically with yields at and above reported international yields. Therefore, agricultural states, such as Florida, should conduct preliminary tests to determine the feasibility of production to meet strategic needs and explore the potential for domestic production.

Castor oil was historically used as a purgative, skin ointment, and lamp oil (Weiss, 2000). Castor oil is in high demand because it can be chemically broken down into unique subunits which are incorporated in a variety of marketable goods such as paint, coatings, inks, lubricants and a wide variety of other products (Ogunniyi, 2006). In addition, its high oil content (48.2% oil by weight) (Wang et al., 2010) makes it an attractive crop of choice for farmers. India, China, Brazil and Mozambique currently lead the world in castor production, with Paraguay, Thailand, Ethiopia, Angola, Vietnam, and South Africa contributing relatively minor amounts (FAOSTAT, 2013). Manufacturers and companies in the US almost exclusively purchase castor from India because India contributes approximately 90% of the total international export trade market (Kumar, 2012). In 2010, world castor production exceeded one million tons, with an average yield of 999 kg ha^{-1} (Table 1-1). Although the US does not currently commercially produce castor oil, it has been reported that yields of irrigated castor from Texas range from 2,242 to 3,363 kg ha^{-1}, with some fields producing 4,035 kg ha^{-1} (Brigham, 1993), indicating that the US potential yield could easily exceed existing global yields.

Although the US is not currently invested in commercial production of castor, there has been a history of US production during World War I (WWI) and World War II (WWII) with preliminary research on castor in Florida as early as 1917 (Rolfs, 1917). Due to the high viscosity of the oil, the US military found that castor oil was especially useful in hydraulic fluids, greases, and lubricants for military equipment. As a result, the US government started initiatives to explore the feasibility of growing castor in the US and later passed legislation to officially recognize the importance of castor oil for war-time needs. In 1984, congress passed Agricultural Materials Act P.L. 98-284 which classified castor oil as a strategic material and Public Law 81-774 requires that strategic materials be acquired and stored in the US for national defense purposes (Roetheli et al. 1991). The US is required to keep 5 million pounds of castor oil with stocks managed by the Department of Defense (Congress, 1991). Attempts to grow castor domestically started as early as the 1850s, but until the early 1900s varieties were excessively tall, prone to shattering, and harvested by hand. Agronomic efforts during WWI identified the most productive castor cultivation area as "an oval-shaped area extending from the Panhandle of Texas on the Southwest to the southern tip of Ohio on the Northeast. This area was delineated on the West by too little rainfall, on the North by too few frost-free days, and on the South and East by a disease hazard resulting from excessive rainfall and humidity" (Domingo, 1953).

A collaboration between the Baker Castor Oil Company and the US government advanced castor breeding and cultivation efforts especially during WWII by improving site and cultivar (Cv.) selections. Connor, Doughty II, and Kentucky 38 were the highest yielding cultivars without irrigation with the highest yields above 2,390 kg ha^{-1} (Table 1-2). By comparison, in the same study yields from the same cultivars grown in Florida never exceeded 766 kg ha^{-1} (Table 1-2). In 1943, approximately 2,428 ha of castor was grown domestically (Domingo, 1953), and the production area rose dramatically to over 19,830 ha by 1951. In the 1960s, Texas alone had over 29,947 ha in castor production (Brigham, 1993). But in 1972, castor production stopped due to a confluence of factors such as: the elimination of government price support, low castor oil prices, contractual price disagreements, and competitive prices for competing crops (Brigham and Spears, 1996). Since then, castor plantings in the US have been largely conducted by academic research units. Currently, one high yielding cultivar grown in Texas, Hale, has yielded an average of 2,242 to 3,363 kg ha^{-1} with slightly lower yields in the southeastern US (Table 1-2).

This prior research has identified high yielding castor varieties, but Florida has historically been considered an undesirable production area for castor due to excessive rainfall and humidity bringing increased disease pressure. However, with the advent of improved fungicide products, new cultivars, and improved cropping systems combined with the recent severe drought conditions suffered by many of the highest castor producing areas in the US, the potential of growing this valuable oil seed crop in high precipitation regions of the US, including Florida, should be reexamined.

Botanical and Agronomic Characteristics of Castor

Castor is an oil seed crop from the Euphorbiaceae family. Castor has been commonly referred to as a "bean" but it is not a legume and is toxic if eaten raw. Most scholars agree that castor originated in the tropics of Ethoipia where it grows as a perennial up to 12 m tall and will defoliate and die when temperatures reach -4°C for four hours (Weiss, 1971). Dwarf cultivars grown in the Texas High Plains and Trans-Pecos region are 1 to 2 m in height (Brigham 1993) as compared to the normal-internode varieties, which range from 1.8 to 3.7 m tall (Brigham, 1970). The cotyledon leaves are oval shaped and directly opposite on the stem, but true leaves are alternately arranged and born on long and sturdy petioles (Weiss, 1971). The reproductive structure of castor is a raceme, specifically a monoecious inflorescence. The raceme usually bears pistillate (female) flowers on the distal (30-50%) end of the spike and staminate (male) flowers on the proximal (70-50%) end of the spike. The ratio of pistillate to staminate flowers can vary depending on raceme length and environmental conditions, and hybrids are being developed to increase vigor and pistillate flower counts (Severino et al., 2012).

The first, or primary, raceme is typically the largest and can be found between the 6^{th} and 16^{th} node with subsequent racemes arising from branches below the primary raceme (Brigham, 1993). It has been observed that two or three branches can occur at the same time or staggered throughout the growing season and as a result, it is likely that a plant will have racemes at each stage of development in the mid to late growing season. Nodal position of the first raceme is important when considering varieties better suited for mechanical cultivation to ensure the combine is built and set to an appropriate height to effectively harvest and capture most, if not all, of the seeds (Weiss, 1971).

Pollen is discharged from the anthers and is carried to the stigmas mainly by wind (Brigham and Spears, 1960), but the presence of bees and other pollinators in Florida may suggest multiple means of pollination. After pollination, the stamens become dry and fall off, leaving only the pistillate flowers which develop into a spiny or spine-less capsule. Each capsule contains three carpels and each carpel contains a single mottle-patterned seed which varies in color and size depending on the cultivar and region of production. Castor seed is an endospermic dicotyledon and, as opposed to storing oil in the embryo, castor has a small embryo and stores oil in liposomes which occupy a large portion of the endosperm of the seed. After maturation, the dried carpels become brown and, as opposed to earlier varieties that forcefully dehisced and scattered seeds, recent dwarf cultivars have been bred to reduce shatter.

Castor is a diploid (2n=20) with few natural polyploids and demonstrates no loss of vigor when self-pollinated (Moshkin, 1986). Approximately 11,300 accessions of castor seed can be found in germplasm banks in 11 countries with the most extensive collections in India, China, Brazil and the US (Severino et al., 2012). Evaluation of and breeding from these accessions has produced two promising varieties: a high oleic acid mutant (Muñoz et al., 2004) and low ricin cultivars (Auld et al., 2009). High oleic acid mutants are better suited for biodiesel production and low ricin varieties are less toxic.

Castor naturally produces three toxins: ricin (RCA_{60}), *Ricinus communis* agglutinin (RCA_{120}), and ricinine (Severino et al., 2012). Ricin is not found in the processed castor oil because it is insoluble in oil, but is retained in the meal after the refining process. Seed maturation takes approximately 44 days and ricin loading begins around 28 days after pollination (Barnes et al., 2009). Ricin is present in the endosperm of the seed until approximately 6 days after the radicle emerges (Barnes et al., 2009). Because of the high toxicity of ricin (Audi et al., 2005; Balint, 1974) low ricin cultivars inherently result in a reduced risk for growers and processers of castor seed and meal. A low ricin cultivar, Brigham, was bred from castor lines that originated from the former Soviet Union (Auld et al., 2009). The average ricin content for the Brigham cultivar ranges from 0.10-5.60 mg g^{-1} (Auld et al., 2009) as compared to one of it's genetic parents and a commonly studied cultivar, Hale, which averages 12.2 mg g^{-1} ricin (Pinkerton et al., 1999) . Studies on low ricin cultivars are needed as any adoption of castor production will likely be most successful with a less toxic crop that will inherently confer reduced potential health risks for growers, processors and those living near processing plants (Garcia-Gonzalez et al., 1999; Raju et al., 2005).

The percentage of oil in castor seed is high, ranging from 37.2-60.7% with an average of 48.2% oil by weight when measured with NMR technology 40°C at a resonance frequency of 9.95 MHz (Wang et al., 2010). By comparison, the soybean—the largest cultivated oilseed crop in the US—which composes 58% of the world oilseed production in 2010 (Callanan, 2011), averages only 20% oil in its seed. In standard castor varieties, the oil is over 90% ricinolenic acid (Sanford, 2009) with 900 g kg^{-1} ricinolenic acid (C_{18} $H_{34}O_3$; 12-hydroxyl-cis-9-octadecenoic acid) and 30 g kg^{-1} oleic acid ($C_{18}H_{34}O_{2;}$ octadec-9-enoic acid) (Muñoz et al., 2004). Due to the unique chemical structure of ricinolenic acid, the oil can be easily broken down and introduced into many industrial processes. The oil is extracted from the seed by mechanical and chemical processes resulting in a separation of the crude oil from the meal (Akpan et al., 2006). The crude oil is processed and used in multiple forms, for example: hydrogenated oil, dehydrogenated oil, blown oil, cold pressed oil (ACME HARDESTY, 2012), and as a potential feedstock for biodiesel production (Scholz and Nogueira da Silva, 2008). Currently the price for castor oil is higher for industrial processes than biodiesel, but the potential for use as a straight vegetable oil or biodiesel are possible and should be reexamined as cultural and technological advances are achieved (Scholz and Nogueira da Silva, 2008).

Castor is a unique plant with the potential to be a productive oilseed crop. Breeding advances have resulted in cultivars that are better suited to modern day mechanized production. Although toxic elements of the castor seed have yet to be completely bred out, we could be optimistic simply due to the high-yielding nature of castor. By starting with a baseline of knowledge regarding growth patterns, physiological responses to production methods, and cultivar responses to regional conditions, researchers can develop more sustainable cropping systems that will be suitable to regional variability.

Cropping System Considerations for Castor in Florida

Transplanting a crop that originated in the tropics to the semi-tropical environment of Florida will require changes in agronomic management in order to achieve high yields. Tropical plants can live as perennials in their native environment, with hand-harvesting of the seeds occurring multiple times per year, as is the case for some farmers of castor in regions of Africa. Perennial cropping systems for castor such as this require time-consuming harvests with the potential to produce very tall plants with large woody stems (Weiss, 1971). Excessive vegetative growth is undesirable for annual cropping systems due to reduced yield and harvest efficiency. In addition, annual crops as compared to perennials need to develop a fully functional root system quicker and irrigation may be required to meet the water needs of a highly productive crop grown in a single season. Therefore, two important growing considerations for developing a sustainable castor cropping system in Florida include: (1) control and termination of vegetative growth, and (2) effective water application. However, there has been no research examining these two system components in castor production for the state of Florida.

To address the first production requirement, the control and termination of vegetative growth, plant growth regulators (PGRs) and harvest aids are likely essential components of a castor cropping system in Florida. Although most types of castor planted today are dwarf cultivars, the semi-tropical environment of Florida may still promote excessive vegetative growth. Applications of certain PGRs may help control excessive height and internode length and increase the harvest index. Plant Growth Regulators are exogenously applied chemicals that affect plant hormones with the goal of reducing overall canopy growth and internode length. The plant hormone gibberellic acid increases internode length in plants (Taiz and Zeiger, 1998), so many PGRs that function as gibberellic acid inhibitors are effective in reducing internode length, especially in cotton (Reddy et al., 1996; Gencsoylu, 2009). However, the castor height reduction efficacy of giberellic acid inhibitors has been inconclusive in preliminary studies in Texas (Trostle et al., forthcoming) and effective in others (Ostwalt, 2008), whereas yield reduction is directly correlated with increased internode length (Stafford, 1971).

The semi-tropical temperatures and high rainfall of Florida can also make harvest timing difficult. Mechanical harvest of the crop would require termination of the crop to insure some level of standard maturity for this indeterminate crop in Florida. Previous research has shown that harvesting approximately 10 days after a killing freeze (Brigham, 1993) will result in minimal loss of yield due to shattering. Due to the irregularity of a killing freeze in Florida, research regarding the effectiveness of a harvest aid may be necessary to ensure maximum yield. Harvest aids are applied with the goal of desiccating and/or defoliating the crop thereby increasing mechanical harvest efficiency and yield. Defoliation percentage, leaf area index (LAI) and leaf browning are good metrics to assess harvest aid effectiveness in cotton (Supak and Snipes, 2000) and are likely to be useful measurements in castor. Some harvest aids used in the southeast for cotton production are tribufos (Supak and Snipes, 2000) and paraquat (Brecke et al., 2001) and are good test candidates for castor production. Due to the lack of information available, it is essential that the use of PGRs and harvest aids in a Florida castor cropping system be carefully researched and evaluated.

Along with the effect of PGRs and harvest aids, varietal phenotypic expression may differ between the two cultivars of interest, Brigham and Hale. Hale and Brigham were registered in 1970 and 2003, respectively (Brigham, 1970; Auld et al., 2003). Because Hale has been available commercially for a longer time, more research has been conducted on the yield potential and general growth habits as opposed to Brigham. Hale is a dwarf cultivar with the potential for high yields in the US. Original breeding efforts crossing Hale and a known reduced ricin cultivar culminated in the Brigham line which has a reduced RCA 120 and ricin content as well as average heights between 0.3-1.25m (Auld et al., 2003). Research on Hale and Brigham has not been conducted in Florida, and research is needed to determine baseline information on the performance of these cultivars in Florida.

Although the semi-tropical climate of Florida would normally provide adequate moisture for successful castor production, there may be some years or periods during the growing season when plant water availability is scarce. Depending on the soil type and rainfall, castor will normally produce the highest yields with supplemental irrigation, but can be grown without it. A study on castor conducted in Italy showed a positive response between yield and percent of evapotranspiration (ET) replaced with irrigation (Laureti et al., 1995). Although the highest yields in this study were achieved with full ET replacement, depending on cost and availability irrigation above 66% ET replacement may not be financially or otherwise desirable. In addition, trials carried out at the same time found the adjusted mean yields of irrigated versus non-irrigated castor grown in the US to be 32 to 49 % higher (Weiss, 2000). Under non-irrigated farming systems in Kansas, Oklahoma, and Texas, castor grew most successfully when exposed to 38-51 cm of rain between April and September (Domingo, 1945). Current research suggests that maximally yielding castor has an annual requirement of 20.6 to 24.7 cm ha^{-1} to produce the highest yields in parts of Texas and can be irrigated every 10-14 days without measureable water stress occurring (Brigham, 1993).

Because castor yield responds positively to irrigation, a better understanding and quantification of how much water is used throughout the growing season in Florida will ultimately result in higher yields and reduced water consumption. Measuring plant transpiration at full canopy and during optimal conditions (optimum radiation levels as well as void of water stress, nutrient deficiency, and weed stress) will provide data on water use at peak transpiration times under good agronomic management. Total water used in any agricultural field can be quantified as the additive factors of evaporation from the soil surface (E) and transpiration (T_c) of the crop, collectively called evapotranspiration (ET_c) (Allen, 1998) (see Equation 1-1). In a one-step procedure, ET_c can be calculated and is the product of a reference ET (ET_o) and a crop coefficient (K_c) for different phenological stages (Allen, 1998) (see Equation 1-2). Calculations of ET_o vary between location, season and crop chosen. Currently, the standard ET_o is based on a hypothetical grass crop in local climatological conditions and is calculated using the Penman-Monteith model (Monteith, 1965). K_c values indicate the relative difference in water use between the crop and the reference; for example, a K_c value above 1 indicates that the crop is using more water than the reference and K_c values below 1 indicate that the crop is using less water.

$$ET_c = E + T_c \quad (1\text{-}1)$$
$$ET_c = ET_o \times K_c \quad (1\text{-}2)$$

Growers can collect free ET_o values on the Internet from the Florida Automated Weather Network (FAWN), which is the compilation of information gathered from 37 weather stations across the state (FAWN, 2013). With appropriate K_c values for castor, growers can easily make the one-step calculation to determine the crop water requirement and use it to apply supplemental irrigation above rainfall to meet crop water demand. It is important to note that K_c values are relative to the specific environment (latitude, weather patterns, soil type, etc.) and should only be used for crops grown in similar environments, therefore making evaluation of K_c values specific for Florida environments essential.

Due to the semi-tropical nature of the Florida growing conditions, testing a sustainable castor cropping system in this region requires: (1) applying PGRs, (2) applying harvest aids, and (3) evaluating growth patterns and phenology. In addition, because irrigation is often a component of many Florida farms, it is essential to develop crop coefficients that could be used to irrigate efficiently in this particular regional climate.

Assessing the Physiological Impacts of Cultural Practices

The success or failure of a cropping system is usually evaluated solely by analyzing yield differences among treatments. However, truly understanding the causal factors behind yield performance can be evaluated by measuring relevant crop physiological responses to system elements. Evaluating a castor cropping system in Florida would likely include measurements of: (1) phenology, canopy, and root architecture development; (2) assimilation capacity and efficiency; and, 3) seasonal water use.

Of utmost importance is the collection of overall phenology and seasonal development of the crop because cropping systems need to effectively control growth patterns in order to maximize yield for a specific environment. Research on crop growth has been conducted with many different varieties of castor in locations outside of Florida with results that are possibly applicable only to that particular cultivar and /or location. Past research has characterized the following growth patterns: identification of the highest yielding raceme(s) (Brigham, 1993; Weiss, 1971; Russell et al., 2003); optimal growing season length (typically 140 to 160 days; Weiss, 2000); and the optimal height for mechanization (typically 0.3-1.25m; Auld et al., 2003). However, none of this information is available for the growing regions within Florida; therefore, phenological assessment of the LAI, total number of racemes and yield of mature racemes throughout the season will provide valuable information for determining optimum harvest times and crop termination to achieve the highest yield. In addition, an assessment of the root architectural changes throughout the season will be useful to determine cultivation and cultivar differences that may provide valuable information for a cropping system. Plant height assessment throughout the growing season will be useful to determine suitability for mechanical harvesting and effectiveness of PGR application. PGRs may also increase yield with the potential for photoassimilate allocation to seed development as opposed to vegetative structure development.

Any cultural practice that impacts the photosynthetic capacity of the crop should be identified because a reduction in photosynthesis will likely result in a reduction in yield. In addition to controlling height by reducing internode length, PGRs and plant hormones may also affect the photosynthetic capacity of the crop. Zhao and Oosterhuis (1997) found higher stomatal conductance and photosynthesis in water-stressed cotton that was treated with PGR-IV (a plant growth regulator that has been shown to increase yield and growth containing 0.0028% (w/v) gibberellic acid and 0.0030% (w/v) indolebutyric acid). In a later study, Zhao and Oosterhuis (2000) found reduced plant height, improved leaf carbon dioxide exchange rate, and increased leaf starch content of PGR treated plants. Kumar et al. (2001) found that foliar application of giberrellic acid on cotton countered the effects of water stress by increasing photosynthesis, stomatal conductance and transpiration. Stomatal conductance and transpiration are inherently linked to photosynthesis due to the overall gas exchange processes at the leaf level (Taiz and Zeiger, 1998). These processes can be measured with an infrared gas analyzer (IRGA) that is capable of simultaneously measuring photosynthesis, stomatal conductance, and transpiration (Zobiole et al., 2000; Akhkha et al. 2011; Millan-Almaraz, et al. 2009). Due to the paucity of research focusing on the possible side effects of PGRs, this project will include the collection of photosynthetic capacity data after the last PGR application. This data will provide much-needed information regarding the effect of PGRs on photosynthetic capacity and will help by providing preliminary baseline information for future research relating to castor production in Florida.

In addition to photosynthesis, other related leaf level photosynthetic aspects that might be impacted by PGR application include: chlorophyll fluorescence, chlorophyll content, stomatal conductance, and transpiration. Chlorophyll fluorescence often increases with stress (Genty et al., 1989; Schreiber, 1986). Fv/Fm is a measure of photosynthetic efficiency that decreases with increasing stress (Burke, 2007; Burke, 2010). Chlorophyll amounts are also related to photosynthetic capacity and relative chlorophyll content can be reflected in SPAD chlorophyll meter readings (Bullock and Anderson, 1998; Goffart et al., 2008).

Assessment of crop water use or ET_c is another vital piece of information for managing water application in general, but especially for developing K_c values specifically for the Florida environment. Determining ET_c values has historically been, and is still currently, determined by weighing lysimeters in fields and greenhouses. An alternative method that can be employed in the field uses direct measurements of transpiration and soil evaporation separately (Sakuratani, 1981; Ham et al., 1990). Logged measurements of transpiration are possible through the use of sap flow technology (Sakuratani and Abe, 1985; Ham et al., 1990) and measurements of soil evaporation can be carried out in the field using micro-lysimieters (Boast and Robertson, 1982). Plant transpiration collected using the sap flow technology has been proven to be accurate to within 10% of the transpiration of the crop when compared to studies utilizing weighing lysimeters (Baker and Bavel, 1987; Smith and Allen, 1996; Hattan et al., 1990). Soil evaporation measurements using the micro-lysimeter method are reliable when assessing water loss over 1-2 days with measurements consistently within a 0.5 mm range (Boast and Robertson, 1982).

This study will measure the transpiration of the castor crop at full canopy coverage in the field under optimal conditions using sap flow collars attached to the stem below all branches of the plant. The collars utilize the heat balance method (Baker and Bavel, 1987) and are indexed to the stem diameter (Smith and Allen, 1996) to determine sap flow. A heating strip (source of the heat pulse) is located between two thermocouples and the difference in temperature between the thermocouples is used to calculate total amount of water transpired (T_c). Evaporation (E) can be determined in the field using a mini-lysimeter (Boast and Robertson, 1982) and the combination of E and T_c can result in an ET_c measure. Calculated ET_o data from FAWN can be related to the measured ET_c to determine K_c values.

Typically, the growing season is broken into three primary timeframes characterized by varying K_c values as provided by the Food and Agriculture Organization of the United Nations (FAO). These timeframes, based on phenological observations in the field, include initial, mid, and late season, all of which has a separately calculated K_c value (Allen, 1998). The FAO has published preliminary results for the K_c values for many crops, including castor. But, as recommended by the FAO, studies should be conducted in specific environments to determine K_c values that are appropriate for a given location (Allen, 1998). Appropriate crop coefficients for the highest water use period during the growing season will be calculated for castor growing in the north central region of Florida.

Summary

In conclusion, castor oil has been a valuable resource to humans for over 4,000 years and is still highly prized today. The US has publically stated that the oil is necessary for public defense as a lubricant and various industries have chosen to incorporate the oil as a feedstock for many manufactured goods today. Castor is not currently commercially grown in the US, but past research efforts have shown promise for domestic production. Due to the national need, high yield potential, new and improved cultivars, availability of irrigation, and new cultural techniques and chemicals, research efforts are needed to develop a sustainable cropping system in agricultural states such as Florida. This research will provide preliminary information needed to develop a sustainable castor cropping system in the State of Florida. The specific research objectives are to:

- Determine the effect of PGRs on plant height, photosynthetic capacity, yield and other physiological traits of two cultivars of castor, Hale and Brigham
- Determine the effectiveness of harvest aids for crop termination by quantifying leaf browning, leaf drop, and LAI on two cultivars of castor, Hale and Brigham
- Quantify seasonal water use and create a K_c curve for castor in Florida for Brigham

Table 1-1 2010 average castor seed production area, seed yield, and total seed production in ten major producing countries worldwide

Country	Harvested Area 2010 (ha)	Yield 2010 (kg/ha)	Total Production 2010 (MT)
India	910,000	1,264	1,149,967
China	210,000	857	179,991
Brazil	149,803	621	93,028
Mozambique	149,100	259	38,602
Paraguay	11,000	1,182	13,000
Thailand	12,780	954	12,197
Ethiopia	6,800	1,235	8,400
Angola	24,800	302	7,500
Vietnam	8,000	750	6,000
South Africa	7,800	705	5,500
World	1,537,773	999	1,535,479

Table 1-2 Yields across US regions from 1941 to 2003

Location	Latitude	Yield (kg ha-1)	Year
Mesa, AZ[1]	33.4N	2,390	1942
State College, NM[1]	32.5N	2,299	1943
Columbia, TN[1]	35.6N	2,270	1941
Columbia, TN[1]	35.6N	2,121	1942
State College, NM[1]	32.5N	2,036	1942
Tuscon, AZ[1]	32.2N	1,981	1941
Mesa, AZ[1]	33.4N	1,968	1941
Bard, CA[1]	32.8N	1,928	1942
Leesburg, FL[2]	28.8N	766	1942
Gainesville, FL[2]	29.7N	375	1942
Quincy, FL[2]	30.6N	198	1941
Brooksville, FL[2]	28.5N	102	1941
Memphis, TN[3]	35.1N	1,945	2002
Starkville, MS[3]	33.5N	1,944	2002
Shubuta, MS[3]	31.9N	1,160	2003
Poplarville, MS[3]	30.8N	427	2003

[1] Yields above 1900 kg ha^{-1} (adapted from Domingo, 1945)
[2] Yields from Florida (adapted from Domingo, 1945)
[3] Highest yields recorded, latitude and year for Cv. Hale (adapted from Baldwin et al., 2009)

CHAPTER 2
EFFECTS OF PLANT GROWTH REGULATOR, CULTIVAR, AND HARVEST AID ON CASTOR PRODUCTION IN FLORIDA

Chapter Abstract

Castor (*Ricinus communis*, L.) oil is essential to the US government and private industries for paints, coatings, inks, lubricants and a wide variety of other products. However, the US must currently import all castor oil because there is no commercial scale domestic castor production. Therefore, it is important to develop and research castor cropping systems customized to specific US geographic locations in an effort to establish a domestic source of castor oil and reduce imports. Cropping systems in Florida represent a model of castor production in a semi-tropical climate. Effective control of excessive vegetative growth and crop termination with a plant growth regulator (PGR) and harvest aid, respectively, will be necessary components in this environment. In an effort to explore components of a sustainable castor production system in Florida, research was conducted at two locations, Plant Science Research and Education Unit in Citra, FL and West Florida Research and Education Center in Jay, FL. Yield components, phenological characteristics (height, raceme number, LAI, and root architecture), plant response (height and photosynthetic capacity) to a mepiquat chloride based PGR and plant response (LAI decrease, leaf browning and leaf defoliation) to different harvest aids were measured. Yields, seed weights, and oil percentages were lower than values reported from other US regions. Treatment with a PGR did not result in an overall decrease in plant height. Further, PGR resulted in an increase in photosynthesis (Pn) by 8.8% but only in 2011. In contrast for 2012, there was no effect of PGR on Pn but stomatal conductance, SPAD, and Fv/Fm were lower for PGR applied plants by 7.1%, 3.1%, and 0.5%, respectively. The harvest aid

paraquat led to over 6 times more leaf browning and drop within 11 days after treatment and was more effective overall than the tribufos harvest aid.

Introduction

The United States (US) government and private industries are currently dependent on foreign countries for castor oil. The US government required to keep 5 million pounds (Congress, 1991) of castor oil in stock for wartime needs (Roetheli et al. 1991). Private industries use castor oil in paints, coatings, inks, lubricants and a wide variety of other products (Ogunniyi, 2004). India, China, Brazil and Mozambique currently lead the world in castor production, with Paraguay, Thailand, Ethiopia, Angola, Vietnam and South Africa contributing relatively minor amounts (FAOSTAT, 2013). In 2010, world castor production exceeded one million tons, with a maximum yield of 1,264 kg ha^{-1} (FAOSTAT, 2013). Although the US does not commercially produce castor oil, research has shown that yields of irrigated castor grown in Texas, on average, range from 2,242 to 3,363 kg ha^{-1}, with some fields producing 4,035 kg ha^{-1} (Brigham, 1993). These results indicate that the US potential yield could easily exceed existing global yields.

Most scholars agree that castor originated in the tropics of Ethiopia where it grows as a perennial up to 12 m tall and will defoliate and die when temperatures reach -4° C for four hours (Weiss, 1971). Dwarf castor cultivars grown in the Texas High Plains and Trans-Pecos region are 1 to 2 m in height (Brigham 1993) as compared to other varieties which range from 1.8 to 3.7 m tall (Brigham, 1970). Two dwarf cultivars, Brigham and Hale, were bred in the arid environment of Texas and registered in 1970 and 2003, respectively (Brigham, 1970; Auld et al., 2003). Hale has demonstrated the potential for high yields in the US and was used as a parental line for the later released Brigham cultivar, which was bred for reduced ricin seed content (Auld et al., 2003).

Despite being considered as “dwarf” growth types, the cultivars Brigham and Hale still have the potential to produce excessive vegetation under conditions of ample rainfall. Applications of certain plant growth regulators (PGRs) may help control excessive height and internode length and increase harvest index of the crop overall. Plant growth regulators are exogenously applied chemicals that affect endogenously produced plant hormones, normally with the goal of reducing internode length. The plant hormone giberellic acid increases internode length in plants (Taiz and Zeiger, 1998), so many PGRs that function as giberellic acid inhibitors are effective in reducing internode length, especially in cotton (Reddy et al., 1996; Gencsoylu, 2009) and can result in a yield benefit (Stafford, 1971). However, using giberellic acid inhibitors has shown mixed results (Oswalt, 2008; Trostle et al., 2011). In addition to reducing internode length, giberellic acid inhibitors also have the potential to affect the photosynthetic capacity of the crop, and ultimately yield (Zhao and Oosterhuis, 2000). Further, other related leaf level physiological traits may also be impacted by PGR application including chlorophyll fluorescence, chlorophyll content, stomatal conductance, and transpiration.

Mechanical harvest of castor will likely require not only limiting crop stature, but also the chemical termination of the crop to insure some level of standard maturity because of its indeterminate developmental habit. Natural crop termination occurs during freezing temperatures below -4°C (Weiss, 1971) and a minimal loss of yield due to shatter can be achieved if harvested within 10 days (Brigham, 1993). However, due to the irregularity of a killing freeze in many regions of the southeast, a harvest aid that will desiccate and/or defoliate the crop may be necessary when producing the crop in these areas. Some effective harvest aids used in southeast cotton production are tribufos (Supak and Snipes, 2000) and paraquat (Brecke et al., 2001) and would be good test candidates for crop termination in castor production. These chemicals are good preliminary test candidates because paraquat is a non-selective cell membrane disruptor and hormone regulators, like tribufos, have been shown to affect castor growth (Weiss, 2000). Defoliation percentage, leaf area index (LAI) and leaf browning are good metrics to assess harvest aid effectiveness in cotton (Supak and Snipes, 2000) and are likely to be useful measurements in castor.

When considering producing the crop in a southeastern region such as Florida, much of the agronomic, developmental, and physiological assessment of the crop must be studied carefully and specifically for conditions within this humid region. The potential for excessive height and continued growth late into the season in Florida is high and would likely require the use of plant growth regulators and harvest aids; therefore, determining their efficacy in the Florida environment is essential. Along with the effect of PGRs and harvest aids, varietal phenotypic expression may differ between the two cultivars of interest, Brigham and Hale, within this southeastern region as well. These cultivars need to be studied in this semi-tropical environment under different cultural management techniques to determine the suitability and optimal design of a castor production system in Florida. To assess the suitability of producing castor in Florida, field trials were established at two locations within north Florida to test the use of PGRs and harvest aids and quantify the effects on phenology, physiology, maturity, LAI, rooting architecture, and yield components of both the Brigham and Hale cultivars.

Materials and Methods

Field Preparation and Crop Maintenance

Field trials in 2011 and 2012 were conducted at two locations, the Plant Science Research and Education Unit (PSREU) near Citra, FL, (latitude 29.408813N, longitude 82.173041W, altitude 21m) in a Sparr Fine Sand (loamy, siliceous, subactive, hyperthermic Grossarenic Paleudults); and the West Florida Research and Education Center (WFREC) near Jay, FL, (latitude 30.775999N, longitude 87.1400W, altitude 10m) in a Red Bay sandy loam (fine-loamy, kaolinitic, thermic Rhodic Kandiudults). Data was not reported for WFREC in 2012 due to crop failure. Both sites were arranged in a completely randomized block design with 3 replications and 24 plots. The plots at PSREU consisted of 6 rows within each plot with two border rows, while the plots at WFREC consisted of 4 rows within each plot and one border row. Plots in both locations were 7.62 m long with 0.91 m between rows. Bare soil alleys, 7.32 m wide, surrounded all plots in PSREU, while at WFREC, all but 4 of the alleys between plots were planted. Both sites were conventionally tilled and well irrigated prior to planting. Plots were planted on 5 and 1 May 2011 and 2012, respectively, in PSREU and on 18 May 2011 in WFREC. Seed was planted at a 4 cm depth with a two-row Monosem vacuum planter using a large edible bean plate (Edwardsville, KS) in PSREU; and a four-row John Deere vacuum planter with a peanut plate (Moline, IL) in WFREC. All seed was provided by Dr. D.L. Auld from Texas Tech University. Sites were thinned to an intra-row density of 6 plants m^{-1} (120,000 plants ha^{-1}) at both sites in 2011. Due to low yields in 2011, intra-row density was decreased to 3 plants m^{-1} (60,000 plants ha^{-1}) in 2012.

In 2011, PSRUE plots were broadcast fertilized with nitrogen (N) at 112 kg N ha^{-1} at 25 days after planting (DAP) and again with 33.6 kg N ha^{-1} at 89 DAP. In 2011, WFREC plots were broadcast fertilized once with 112 kg N ha^{-1} at 16 DAP. In 2012 at PSREU, fertilizer amounts remained the same, but were side dressed: 11.2 kg N ha^{-1} at planting, 67.2 kg N ha^{-1} 28 DAP, and 67.2 kg N ha^{-1} 49 DAP. Phosphorous, potassium, and other minor nutrients were added based on the recommendations for the region. For weed control, an application of 561.24g active ingredient (ai) ha^{-1} of trifluralin (DOW AgroSciences, Indianapolis, IN) was incorporated pre-plant at WFREC in 2011 and at PSREU in 2012. At both sites in both years, plots were cultivated by tractor at least twice after planting and hand weeded approximately every two to three weeks thereafter.

Plant Growth Regulator

The mode of action chosen for the PGR was a giberellic acid inhibitor with the active ingredient, mepiquat chloride. The PGR was foliarly applied at both PSREU and WFREC: Pix (BASF, Ludwigshafen, Germany) and Stance ™ (Bayer CropScience, Monheim am Rhein, Germany) at PSREU and WFREC, respectively. In 2011, PGR applications were initiated when 50% of the crop was at the 6^{th} node stage (with 2 racemes); while in 2012, the first application was applied when 50% of the crop had one flower. In 2011 at PSREU, 105.68 g ai ha^{-1} and 35.23g ai ha^{-1} of mepiquat chloride was applied 49 and 83 DAP, respectively; while at WFREC, 98.78 and 37.04g ai ha^{-1} mepiquat chloride was applied 41 and 70 DAP, respectively. In 2012 at PSREU, 23.48g ai ha^{-1}, 58.71g ai ha^{-1}, 58.71g ai ha^{-1} of mepiquat chloride was applied at 41, 51, and 62 DAP, respectively.

Harvest Aid

Crop defoliation and termination was accomplished with two harvest aids (HA): Def 6 ®, ai tribufos, (Bayer CropScience, Monheim am Rhein, Germany) and Gramoxone ® Extra, ai paraquat, (Zenica Agrochemicals, Deleware, US). In 2011, plots were sprayed 126 and 143 DAP in PSREU and WFREC, respectively with tribufos (rate of 1,509.72g ai ha^{-1}) and paraquat (rate of 670.99g ai ha^{-1}). In both years, Leaf Area Index (LAI), leaf browning, and leaf drop were assessed 2, 4, 7, and 11 days after HA application at the PSRUE location only.

Yield, 100 Seed Weight and Oil Percentage

Yield was collected by hand from the two inner rows at both locations and occurred twice in 2011 and weekly in 2012. The yield from the harvest(s) during the growing season included mature brown capsules and the last harvest also included green capsules that were enlarged and showing signs of oil-filling. In 2011, PSRUE plots were harvested 105 and 138 DAP and WFREC plots were harvested 109 and 155 DAP. Due to high shatter losses noted before the first harvest in 2011, seed production over the season was followed more closely in 2012 at PSREU, with the first yield collection at 86 DAP and additional harvests conducted weekly thereafter until the final collection at 157 DAP. In both years, yield was determined by first drying in an oven at 60 °C for a minimum of 72 hours (resulting in seeds approximately 2-3% water content) followed by completely hand threshing a random sub sample of approximately 20 g and applying this seed to hull weight ratio to determine final 100 seed weight and yield for each plot. In 2011, the seed oil percentage was determined by sending samples to

Advanced Precision Laboratories, LLC in Sumner, GA where the samples were ground and analyzed in triplicate. The laboratory followed the AOAC Official Method 948.22 “Fat (crude) in Nuts & Nut Products” using a Soxtec 2050 Automated Extractor by Foss. The extraction cups were heated in a 100°C oven for more than 1 hr and then cooled in a desiccator to assure the cups are completely dry prior to extraction. The extracted oil samples were dried at 100°C for 30 minutes to fully evaporate the petroleum ether from the sample and then cooled in a desiccator prior to weighing the final sample. It was noted by the laboratory that the soluble starch concentration in the sample was minimal, thus avoiding a second extraction by water.

Phenological and Physiological Measurements

Season long measurements

In both 2011 and 2012, LAI was measured from late May through mid- to late September approximately every two weeks for both Hale and Brigham using the non-destructive LiCor 2200 instrument (LI-COR Environmental, Lincoln, NE). LAI measurements began 42, 21 and 35 DAP and concluded on 119, 143 and 88 DAP in PSREU 2011, PSREU 2012, and WFREC, respectively. One LAI measurement included regularly spaced measurements underneath the canopy spanning the distance between rows with the sensor head held both parallel (4 readings) and perpendicular (4 readings) to the crop row with each orientation paired with one reading above the canopy.

To determine changes in total height, number of racemes, and nodes to the first raceme, ten randomly selected plants per plot were tagged and reassessed throughout the growing season. Total height was measured to the nearest 1 cm of the tallest plant structure. The number of racemes included structures at initial flower formation and all intermediate developmental stages through mature racemes. In 2011, racemes were omitted from the count if whole raceme failure (failure to produce a harvestable capsule) was observed to better relate reproductive structure to yield; while in 2012, all racemes were counted regardless of raceme failure to better understand the total number of racemes possible. Nodes below the first raceme included a count of all nodes above the soil surface and below the insertion point of the first raceme.

Root architecture and growth was assessed by regularly recording root images in the rooting zone to a depth of almost 80 cm for both Hale and Brigham in 2011 and 2012 at PSREU. Clear plastic mini-rhizotron tubes (182.88 cm in length) were inserted in-row and parallel to the crop at a 45^0 angle with the soil surface. Roots were imaged along the entire length of the tube using a mini-rhizotron camera system (Bartz, Carpinteria, CA). Images were taken 4 to 6 times throughout the growing season and analyzed using the WinRhizoTron software (Regent Technology, Canada) which calculates root length and surface area for each image. Analyses of root architecture (length and surface area) were separated into approximately 10 cm increments corresponding to 7 soil depth zones in 2011, and due to a deeper tube depth, 8 total depth zones in 2012.

Physiological responses to PGR application

To assess the impact of PGR application on leaf level physiological responses, field measurements were conducted on the Brigham cultivar 1 day after PGR treatment (DAT), 8 DAT, and 15 DAT. At each of these time points, field physiological measurements were taken between 0900 and 1100 EDT on the two first fully expanded leaves from two different plants within each plot. Just prior to gas exchange measurements, leaves were dark adapted for at least 30 minutes and the ratio of variable to maximal fluorescence (Fv/Fm) for the dark adapted leaves was measured and calculated using an OS-1 fluorometer (OptiSciences Inc., Hudson, NH). Relative chlorophyll content was then measured on these same leaves using a SPAD meter (Spectrum Technologies Inc.; Plainfield, IL). These same leaves were again used in gas exchange measurements while the leaves were still attached to the plants. Gas exchange was measured using a LI6400-XT infra-red gas analyzer (LiCor Environmental Sciences; Lincoln, NE); leaf conditions were kept constant within the cuvette at 1800 micromoles PAR, 360 ppm CO_2, and ambient temperature and atmospheric humidity. After measuring the gas exchange on a leaf, it was collected and transferred immediately to a plastic bag and stored under cool temperatures for subsequent measurement of relative water content (RWC) in the lab.

At the lab, a leaf section of approximately 1 cm^2 was cut while avoiding the midrib for analysis (results not shown). For the remainder of the leaf, the petiole was removed and leaf area was determined using the LiCor model 3100 leaf area meter (LiCor Environmental Sciences; Lincoln, NE). The leaf was then weighed to determine fresh weight, and after soaking the leaf in distilled water under grow lights for approximately 3 hours, the leaf was weighed again to determine turgid weight. The leaf was dried at 60°C for at least 72 hours and weighed again to determine dry weight. RWC was calculated using the Equation (2-1) according to Weatherly (1950). Specific Leaf Area (SLA) was calculated as the ratio of leaf area to dry weight.

$$\text{RWC} = [\text{fresh weight-dry weight}]/[\text{turgid weight-dry weight}] \qquad (2\text{-}1)$$

Statistical Analysis

Because management practices were different between locations and years, each location/year combination (PSREU 2011, PSREU 2012, and WFREC 2011) was analyzed as a separate factor and heretofore will be referred to as “location/year”. Multivariate and univariate repeated measures along with ANOVA were used to analyze each of the yield, phenological, and physiological characteristics measured (JMP Pro 9 software, SAS Institute Inc., Cary, NC). Depending on the type of measurement, the following fixed factors and interactions were analyzed: location/year, plant growth regulator (PGR), cultivar (Cv.), date after treatment (DAT), and date after planting (DAP). A preliminary multivariate repeat measures MANOVA test was run and if the data passed the test of sphericity (SAS Institute, 2010) the data were rearranged and a univariate repeated measures analysis was conducted identifying statistically significant findings with further separation using Tukey’s multiple comparison test.

Results

Yield, 100 Seed Weight and Oil Percentage

Yield, 100 seed weight, and oil percentage differed among each location/year, while yield and 100 seed weight differed among cultivars (Table 2-1). All other effects and most interactions had no impact on these yield components. The highest yields were seen at PSREU 2011 and the lowest at PSREU 2012; in contrast, the highest 100 seed weights were found at WFREC 2011 and the lowest for PSREU 2011 (Table 2-2). Overall, Hale out-yielded Brigham and had a higher 100 seed weight at each location/year. By examining weekly yield collection in 2012 at PSREU, Hale yielded more than Brigham on a weekly basis until the end of the season when less than 40 kg ha^{-1} was collected at each harvest time (Figure 2-1). In 2012, peak yield occurred 107 DAP and 100 DAP for Hale and Brigham, respectively. Oil percentage was highest at WFREC 2011, averaging nearly 46% across both cultivars (Table 2-2).

Phenological and Physiological Measurements

Phenological measurements showed increasing seasonal growth trends with some cultivar differences. Node numbers below the first raceme was different among cultivars (Table 2-3) with Hale consistently having between 1.6 and 5.2 more nodes below the first raceme than Brigham (Table 2-4). Raceme number was not affected by PGR at any location/year but was different between cultivars and increased during all location/years as the season progressed (Table 2-5). Brigham produced between 3 and 8 more racemes than Hale by the end of the season, depending on location/year (Figure 2-2).

LAI was also not affected by PGR but differences across dates reflected an increasing overall canopy development (Table 2-6). In 2011, a parabolic LAI curve was observed both in PSREU and WFREC; whereas an increasing LAI trend through the end of the season was observed in PSREU 2012 (Figure 2-3). Peak LAI in PSREU 2011 and WFREC 2011 was observed approximately 76 DAP with values of 2.01 and 2.87, respectively (Figure 2-3); while at PSREU 2012, LAI reached a maximum of 2.10 at 143 DAP. Cultivars differed in LAI at PSREU 2012, when Hale averaged a higher LAI than Brigham (Table 2-6; Figure 2-3).

Contrary to expectations, PGR had no significant effect on plant height at PSREU in either year (Table 2-7), but actually increased height for plants in WFREC 2011 (Figure 2-4). Regardless of PGR treatment, plant height increased nearly linearly across the season, except for WFREC 2011 where it reached a plateau at 76 DAP (Figure 2-4). Cultivars had minimal differences for plant height with Hale significantly taller than Brigham only for WFREC 2011 (Figure 2-4).

Root architecture were also not affected by PGR, but only showed differences among dates and soil depth zones for both cultivars (Table 2-8). Cumulative root length (Figure 2-5) and surface area (Figure 2-6) were lower during the first date compared with all other dates. Roots were not well developed in the top layer at soil depth zone 1 (approximately 0-10 cm below the soil surface) with values for both root length and surface area being lower in this zone compared to all other zones. However beyond this depth, the root system was fairly uniform and reached the maximum limits of the measuring tubes at a depth of 73.4 cm in 2011 and 83.9 cm in 2012 (Figure 2-5; Figure 2-6).

Physiological responses to PGR application

The applications of PGR had a limited effect on most of the physiological processes measured in this study but did increase Pn in 2011 (Table 2-9; Table 2-10) with rates at 24.71 and 22.72 μmol CO_2 m^{-2} s^{-1} for PGR treated and non-treated plants, respectively (Table 2-10). However, all other measurements (conductance, Ci, transpiration, SPAD, Fv/Fm, RWC, leaf area, and SLA) were not affected by PGR in this year (Table 2-9; Table 2-10). Although DAT had an effect on Pn and SPAD, there were no obvious increasing or decreasing trends evident (Table 2-10). These effects on photosynthesis were not present in 2012 but PGR lowered conductance, SPAD, and Fv/Fm (Table 2-9; Table 2-10). Conductance for PGR treated and non-treated plants was 0.98 and 1.05 mol H_2O m^{-2} s^{-1}, respectively; while SPAD for PGR treated and non-treated plants was 39.84 and 41.06, respectively (Table 2-10). In the case of conductance readings had not obvious trend with DAT, but with SPAD, readings increased with increasing DAT. Fv/Fm for PGR treated and non-treated plants was 0.817 and 0.821, respectively with no obvious trend with DAT.

Effectiveness of Harvest Aid treatment

In both years, the type of harvest aid and days after treatment did affect LAI, leaf drop and leaf browning, but prior PGR application and cultivar did not influence the response to HA treatment (Table 2-11). Paraquat was overall more effective than tribufos in desiccating and defoliating the crop during both years as indicated by greater decreases in LAI and substantially higher leaf browning and leaf drop percentages. By 7 DAT paraquat decreased LAI 1.3 and 1.7 times more than tribufos when compared to the pre-treatment value during 2011 and 2012, respectively (Figure 2-7). The slight increase in LAI at 11 DAT is likely due to leaf regrowth that was visually noted in the field. Regardless of HA product, leaf browning was observed at 2 DAT, whereas leaf drop lagged and was observed starting at 4 DAT. As with LAI, by the end of the season paraquat had substantially increased levels of visually rated leaf browning and drop over tribufos with 26.7 and 6.64 times more leaf browning and 117.1 and 9.3 times more leaf drop in 2011 and 2012, respectively (Figure 2-7).

Table 2-1 ANOVA of Yield, 100 Seed Weight and Oil Percentage. F values for treatment effects on oil percentage in PSREU and WFREC in 2011

		Yield		100 Seed Weight		Oil Percentage
Effect	df	F Value	df	F Value	df	F Value
Location/year	2	15.0916**	2	21.9179**	1	77.4129**
Cv.	1	6.0342*	1	18.0244**	1	1.1936
PGR	1	1.9776	1	0.0264	1	2.4749
Harvest Aid	1	0.4502	1	0.4918	1	0.1553
Location/year *Cv.	2	2.4633	2	0.3477	1	0.2139
Location/year *PGR	2	1.0859	2	1.3067	1	2.3851
Location/year *HA	2	0.2132	2	1.3687	1	1.7273
Cv*PGR	1	0.1097	1	0.1806	1	0.2551
Cv.*HA	1	0.4802	1	0.1383	1	4.6386*
PGR *Harvest Aid	1	0.0835	1	0.0003	1	0.5010
Location/year *Cv. *PGR	2	0.3824	2	1.2367	1	5.7043*
Location/year *Cv.*HA	2	0.0272	2	1.4347	1	0.4938
Cv.*PGR *HA	1	0.9485	1	0.4447	1	0.0144
Location/year *PGR *HA	2	0.1749	2	0.0866	1	0.3666
Location/year *PGR*HA*Cv.	2	0.2616	2	0.3349	1	1.8719

** Indicates P < 0.01
* Indicates P < 0.05

Table 2-2 Mean values for Yield, 100 Seed Weight and Percent of Oil

Location	Year	Cv.	PGR	Yield (kg ha^{-1})	100 Seed Weight (g)	Percent of Oil
PSREU	2011	Brigham	Yes	1311.24ab	17.79c	43.43bc
PSREU	2011	Brigham	No	1403.29a	18.03c	43.56bc
PSREU	2011	Hale	Yes	1238.31abc	19.25bc	42.71c
PSREU	2011	Hale	No	1382.78a	19.79bc	42.90bc
PSREU	2012	Brigham	Yes	645.61c	21.27bc	n/a
PSREU	2012	Brigham	No	725.55bc	21.55bc	n/a
PSREU	2012	Hale	Yes	1094.22abc	22.36a	n/a
PSREU	2012	Hale	No	942.26abc	23.49a	n/a
WFREC	2011	Brigham	Yes	746.1babc	19.29ab	45.63a
WFREC	2011	Brigham	No	960.26abc	19.52ab	45.64a
WFREC	2011	Hale	Yes	1236.30abc	22.72a	45.66ba
WFREC	2011	Hale	No	942.26abc	20.71a	46.20a

Columns not connected by same letter are significantly different

Table 2-3 ANOVA of Nodes to First Raceme. F values for treatment effects on LAI in PSREU and WFREC in 2011 and 2012

	PSREU 2011		PSREU 2012		WFREC 2011	
Effect	df	F Value	df	F Value	df	F Value
Cv.	1	151.3588*	1	69.8386*	1	108.0846*

* Indicates P < 0.01

Table 2-4. Mean values for nodes below first raceme

Location	Year	Cv.	Nodes
PSREU	2011	Brigham	6.9
PSREU	2011	Hale	12.1
PSREU	2012	Brigham	6.6
PSREU	2012	Hale	8.2
WFREC	2011	Brigham	7.3
WFREC	2011	Hale	11.6

Locations and years were analyzed separately

Table 2-5 ANOVA of Racemes. F values for treatment effects on number of racemes in PSREU and WFREC in 2011 and 2012

	PSREU 2011		PSREU 2012		WFREC 2011	
Effect	df	F Value	df	F Value	df	F Value
PGR	1	0.3286	1	1.7557	1	3.5008
Cv.	1	45.4482*	1	60.1636*	1	47.0187*
Date	5	390.6655*	5	243.9103*	4	78.8326*
PGR * Date	5	0.0961	5	1.6059	4	1.6617
PGR * Date * Cv.	5	0.5815	5	0.0396	4	3.5094*
Cv. * Date	5	9.6645*	5	25.6111*	4	9.2719*
Cv. * PGR	1	1.1558	1	0.0463	1	1.6472

* Indicates P < 0.01

Table 2-6 ANOVA of LAI. F values for treatment effects on LAI in PSREU and WFREC in 2011 and 2012

	PSREU 2011		PSREU 2012		WFREC 2011	
Effect	df	F Value	df	F Value	df	F Value
PGR	1	0.4652	1	0.7301	1	0.6905
Cv.	1	0.0185	1	20.8099*	1	0.3011
Date	8	24.3438*	5	51.4606*	2	77.5382*
PGR * Cv.	1	0.0435	1	2.5737	1	1.1615
PGR * Date	8	0.6518	5	0.2542	2	0.6612
PGR * Cv. * Date	8	0.3645	5	0.5457	2	0.9340
Cv. * Date	8	0.7824	5	3.3368*	2	0.9265

* Indicates P < 0.01

Table 2-7 ANOVA of Height. F values for treatment effects on height in PSREU and WFREC in 2011 and 2012

	PSREU 2011		PSREU 2012		WFREC 2011	
Effect	df	F Value	df	F Value	df	F Value
PGR	1	0.4427	1	0.0001	1	225.8337*
Cv.	1	0.4721	1	0.0450	1	14.6739**
Date	5	263.8146**	7	256.0689**	4	235.1695**
PGR * Cv.	1	0.5711	1	0.4382	1	0.0957
PGR * Date	5	0.4144	7	0.0583	4	0.7212
PGR * Cv. * Date	5	0.7135	7	0.0513	4	0.0716
Cv. * Date	5	2.9457*	7	0.4183	4	6.5616**

** Indicates P < 0.01
* Indicates P < 0.05

Table 2-8 ANOVA of Root Architecture. F values for treatment effects on Surface Area and Length in PSREU in 2011 and 2012

	SA 2011		SA 2012		Length 2011		Length 2012	
Effect	df	F Value	df	F Value	df	F Value	df	F Value
PGR	1	2.8661	1	1.4789	1	1.2196	1	1.5845
Cv.	1	0.2254	1	0.0382	1	0.0001	1	0.6156
Date	3	7.7107*	4	12.2915*	3	11.6541*	4	16.2283*
PGR * Cv.	1	1.0677	1	0.8071	1	1.6246	1	0.8512
PGR * Date	3	0.4252	4	2.0701	3	0.5580	4	2.3277
PGR * Cv. * Date	3	0.2811	4	1.4382	3	0.1458	4	1.8707
Cv. * Date	3	0.7033	4	2.2968	3	0.4387	4	3.1313**
Zone	6	17.2248*	7	10.5288*	6	15.5662*	7	13.2032*
PGR * Zone	6	5.5721*	7	4.3364*	6	4.0056*	7	5.3415*
Cv. * Zone	6	1.5387	7	8.2720*	6	1.0317	7	5.8864*
Date * Zone	18	0.7852	28	1.2724	18	1.1655	28	1.8535*
PGR * Cv. * Zone	18	1.0979	7	9.7399*	18	1.1955	7	8.2005*
PGR * Date * Zone	6	0.2410	28	0.7422	6	0.1561	28	0.8000
PGR * Cv. * Date * Zone	18	0.2678	28	0.6497	18	0.2183	28	0.6432
Cv. * Date * Zone	18	0.1611	28	0.7875	18	0.2259	28	0.7402

* Indicates P < 0.01
** Indicates P < 0.05

Table 2-9 ANOVA of leaf level physiological traits. F values for treatment effects in PSREU in 2011 and 2012. Data was analyzed within each year separately.

Effect	Df	Pn F Value	Conductance F Value	Ci F Value	Transpiration F Value	SPAD F Value	Fv/Fm F Value	RWC F Value	Leaf Area F Value	SLA F Value
2011										
PGR	1	352.4450*	0.4131	2.8925	0.2730	17.7278	0.1135	0.9953	0.1509	0.0176
DAT	2	4.6487*	0.8574	1.3986	1.7362	5.1536*	0.1391	3.9693*	3.0000	1.7000
PGR * DAT	2	0.0177	0.6831	0.0701	0.2198	0.8938	1.2450	2.0131	1.2467	0.9400
2012										
PGR	1	3.4873	48.7054*	0.8402	2.0362	98.0382*	71.7037*	3.3257	0.2732	0.1823
DAT	2	0.6592	0.2605	1.3783	11.5479**	5.5941*	9.2492**	41.3429**	0.7851	15.4288**
PGR * DAT	2	0.9820	1.8156	0.9955	1.5685	0.2832	0.1186	0.1150	0.0467	0.8038

** Indicates P < 0.01
* Indicates P < 0.05

Table 2-10 Mean values for Photosynthetic Effects on Brigham in PSREU in 2011 and 2012

Year	DAT	PGR	Pn (µmol CO_2 m^{-2} s^{-1})	Conductance (mol H_20 m^{-2} s^{-1})	Ci (µmol CO_2 mol air^{-1})	Transpiration (mol H_20 m^{-2} s^{-1})	SPAD	RWC	Fv/Fm	Leaf Area (cm^2)	SLA (cm^2/g)
2011	1	No	24.67	1.53	278.25	14.11	39.19	0.92	0.82	180.28	229
2011	8	No	20.91	1.24	285.06	12.41	35.62	0.91	0.81	217.13	222
2011	15	No	22.59	2.15	284.42	15.44	41.18	0.91	0.83	159.03	237
2011	1	Yes	26.64	1.51	274.17	13.48	41.63	0.92	0.82	162.35	203
2011	8	Yes	22.67	1.33	280.37	12.88	40.26	0.87	0.82	197.61	215
2011	15	Yes	24.50	1.42	277.86	14.31	42.80	0.91	0.79	186.02	277
2012	1	No	26.19	1.04	262.12	11.68	39.23	--	0.83	174.51	227
2012	8	No	27.28	1.14	265.34	10.61	40.58	0.92	0.81	163.45	198
2012	15	No	26.38	0.95	260.05	9.18	43.36	0.89	0.83	173.87	183
2012	1	Yes	25.12	0.93	258.88	11.10	38.38	--	0.82	169.93	221
2012	8	Yes	25.36	0.95	263.51	9.71	39.92	0.90	0.8	157.45	188
2012	15	Yes	27.48	1.07	263.31	9.68	41.24	0.86	0.82	174.78	190

Table 2-11 ANOVA of Post Harvest Aid Application: LAI, Leaf Drop and Leaf Brown. F values for treatment effects on height in PSREU in 2011 and 2012

	LAI		Leaf Drop		Leaf Brown	
Effect	df	F Value	df	F Value	df	F Value
2011						
PGR	1	0.9058	1	2.4694	1	0.1176
Cv.	1	0.0008	1	0.0089	1	0.7517
DAT	3	27.1423**	3	28.9952**	3	92.3673**
HA	1	79.5182**	1	12870.75**	1	531.5715**
PGR * HA	1	1.6186	1	1.0000	1	0.0294
Cv. * DAT	3	0.4315	3	0.8024	3	1.8459
PGR * HA * Cv.	1	2.6214	1	0.0089	1	1.1230
PGR * Cv.	1	3.7979	1	0.0089	1	0.5940
PGR * DAT	3	0.7096	3	0.3687	3	0.7300
HA * Cv.	1	0.7797	1	0.0089	1	1.3364
HA * DAT	3	0.9477	3	18.6723**	3	89.7914**
PGR * DAT	3	0.6222	3	2.5373	3	0.4380
HA * Cv. * DAT	3	1.5400	3	0.8892	3	2.0649
2012						
PGR	1	1.1791	1	0.8929	1	0.0063
Cv.	1	2.1385	1	1.2462	1	2.8802
DAT	3	44.8109**	3	757.0751**	3	71.0513**
HA	1	36.0865**	1	3217.687**	1	16660.32**
PGR * HA	1	13.5492*	1	1.7500	1	0.0570
Cv. * DAT	3	2.5285	3	1.2104	3	2.9487*
PGR * HA * Cv.	1	0.0068	1	0.7538	1	0.2258
PGR * Cv.	1	0.3491	1	0.1385	1	0.7788
PGR * DAT	3	0.7618	3	0.9399	3	3.7692*
HA * Cv.	1	1.6460	1	0.3846	1	0.5576
HA * DAT	3	4.5299	3	516.2998*	3	32.2821**
PGR * DAT	3	0.5566	3	0.0744	3	0.6923
HA * Cv. * DAT	3	0.8125	3	0.9399	3	2.3333

* Indicates $P < 0.05$

** Indicates $P < 0.01$

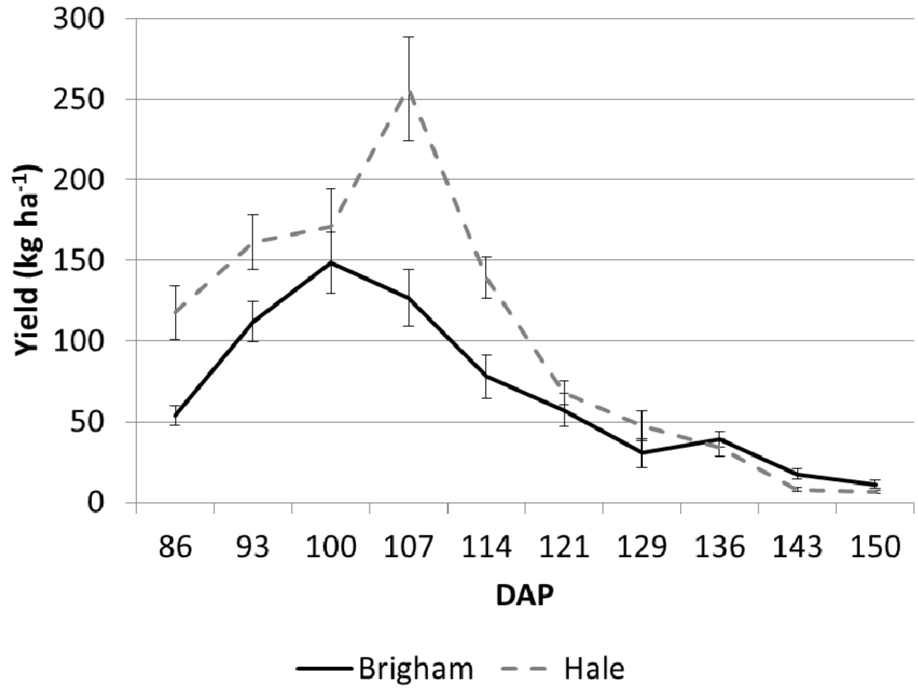

Figure 2-1 PSREU 2012 Weekly yield collection

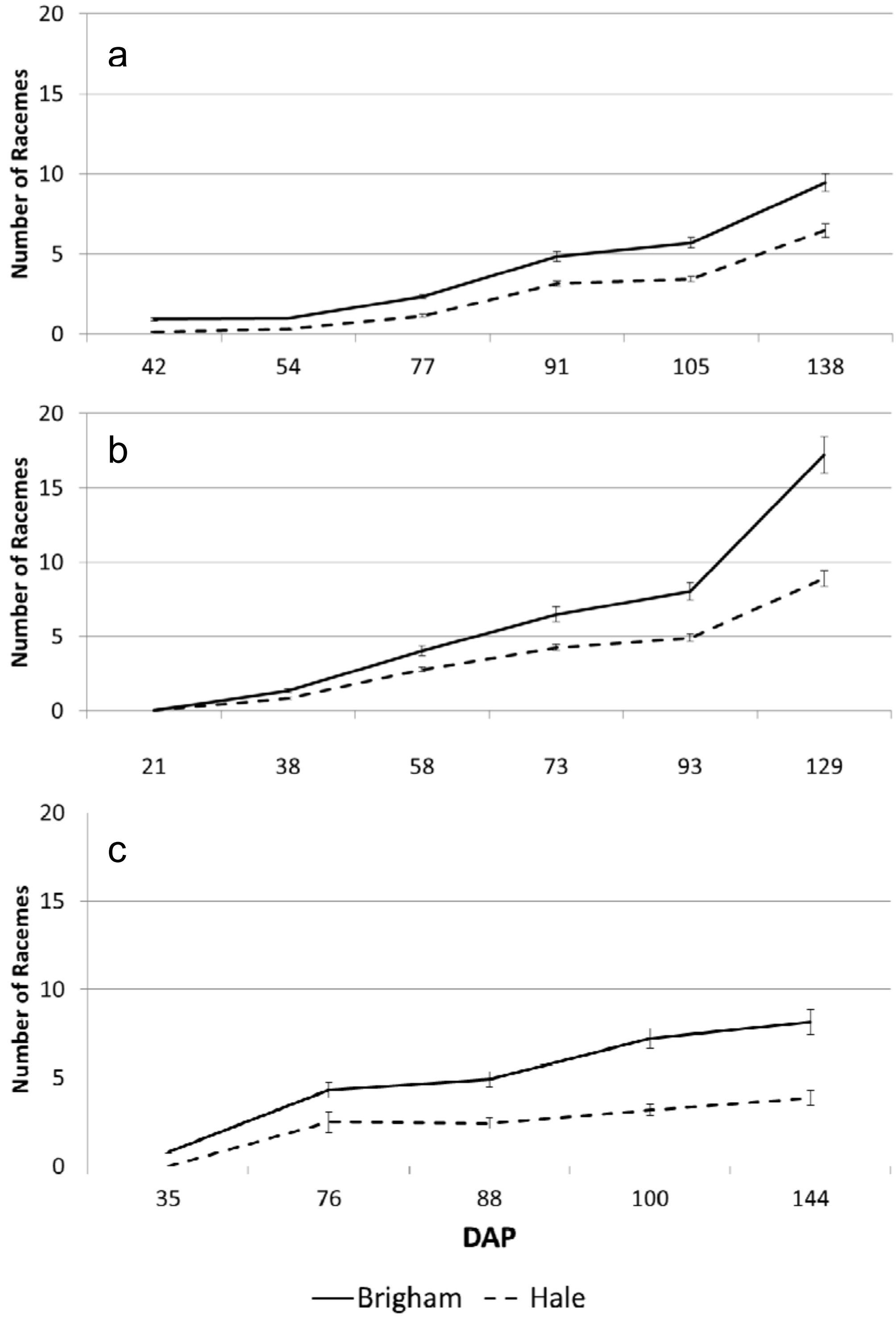

Figure 2-2 Total Number of Racemes. PSREU 2011(a), PSREU 2012 (b), and WFREC (c)

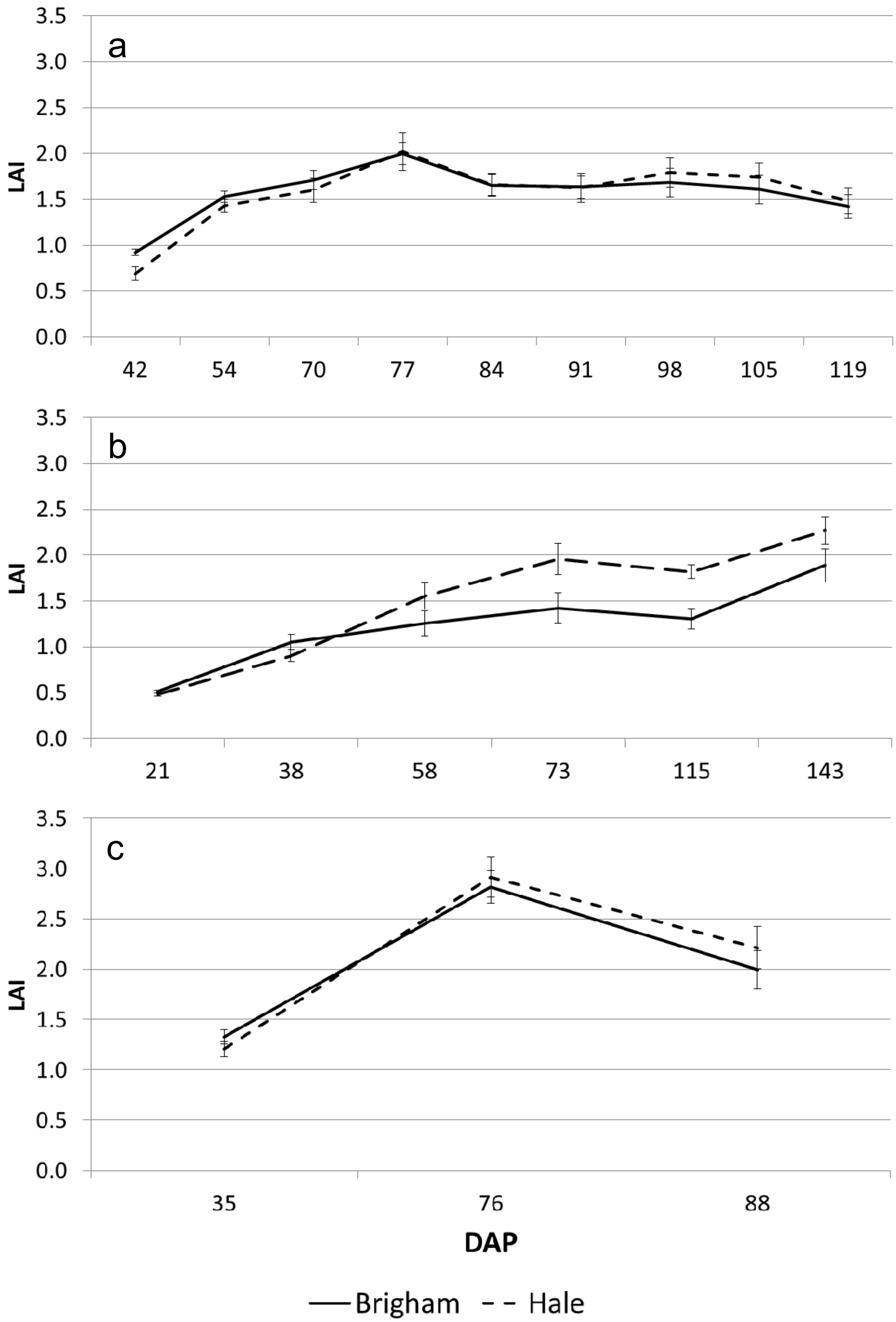

Figure 2-3 Leaf Area Index. PSREU 2011 (a), PSREU 2012 (b), and WFREC (c)

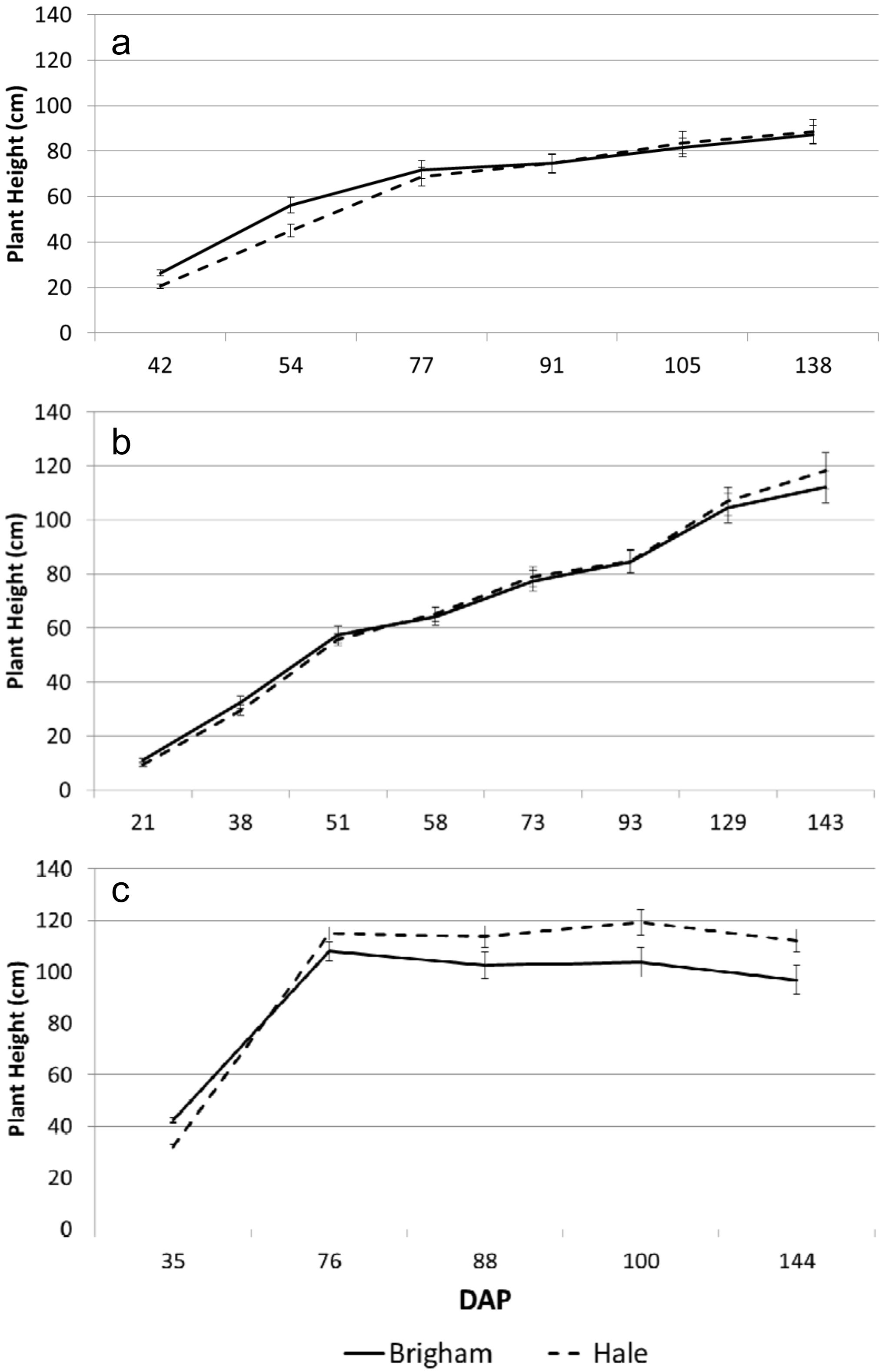

Figure 2-4 Plant height. PSREU 2011(a), PSREU 2012 (b), and WFREC (c)

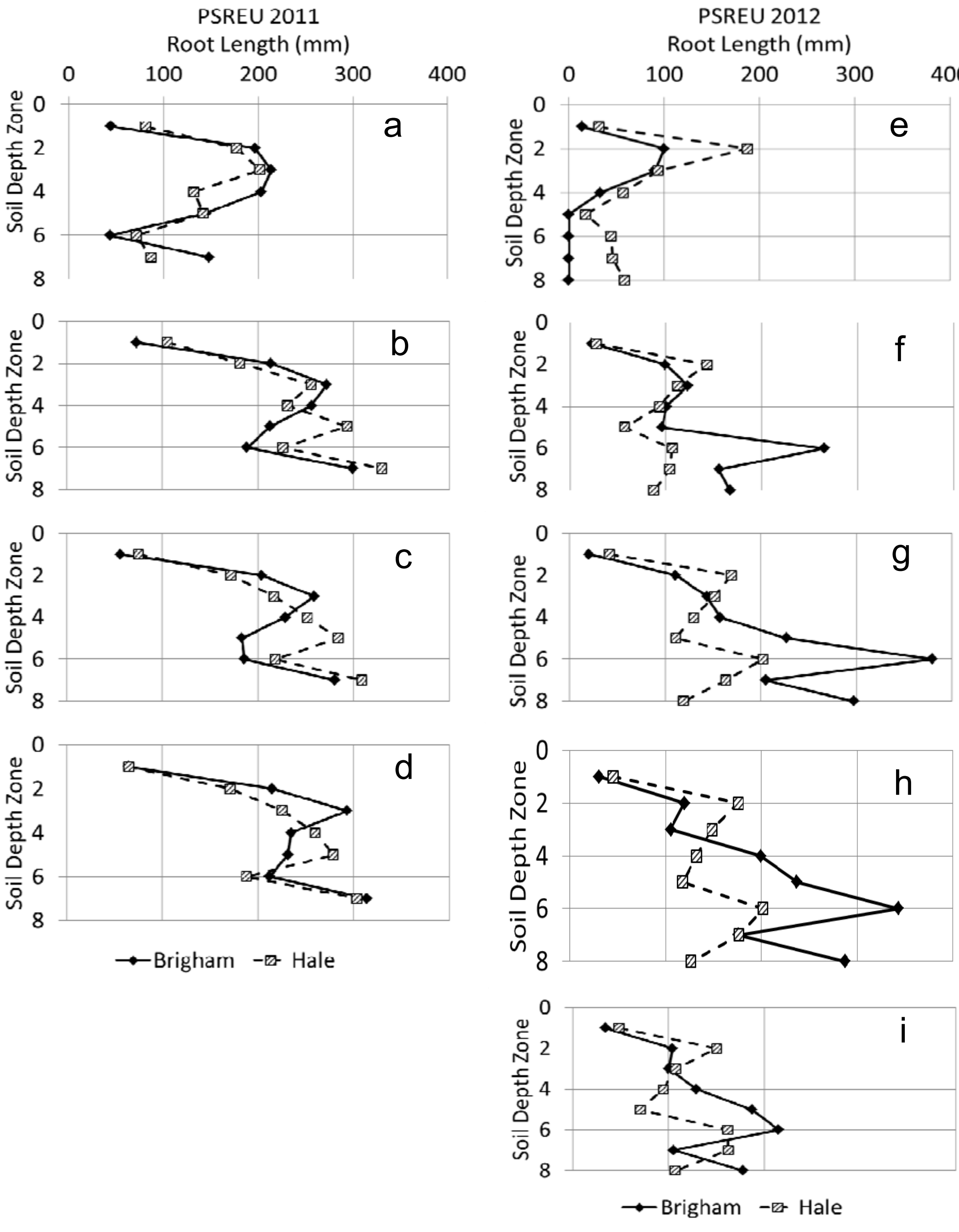

Figure 2-5 Root Length by soil depth zone (in 10 cm increments) for 2011 and 2012 reported by DAP. 50 DAP in 2011(a), 70 DAP in 2011 (b), 92 DAP in 2011 (c), 106 DAP in 2011 (d), 38 DAP in 2012 (e), 58 DAP in 2012 (f), 73 DAP in 2012 (g), 93 DAP in 2012 (h), 142 DAP in 2012 (i),

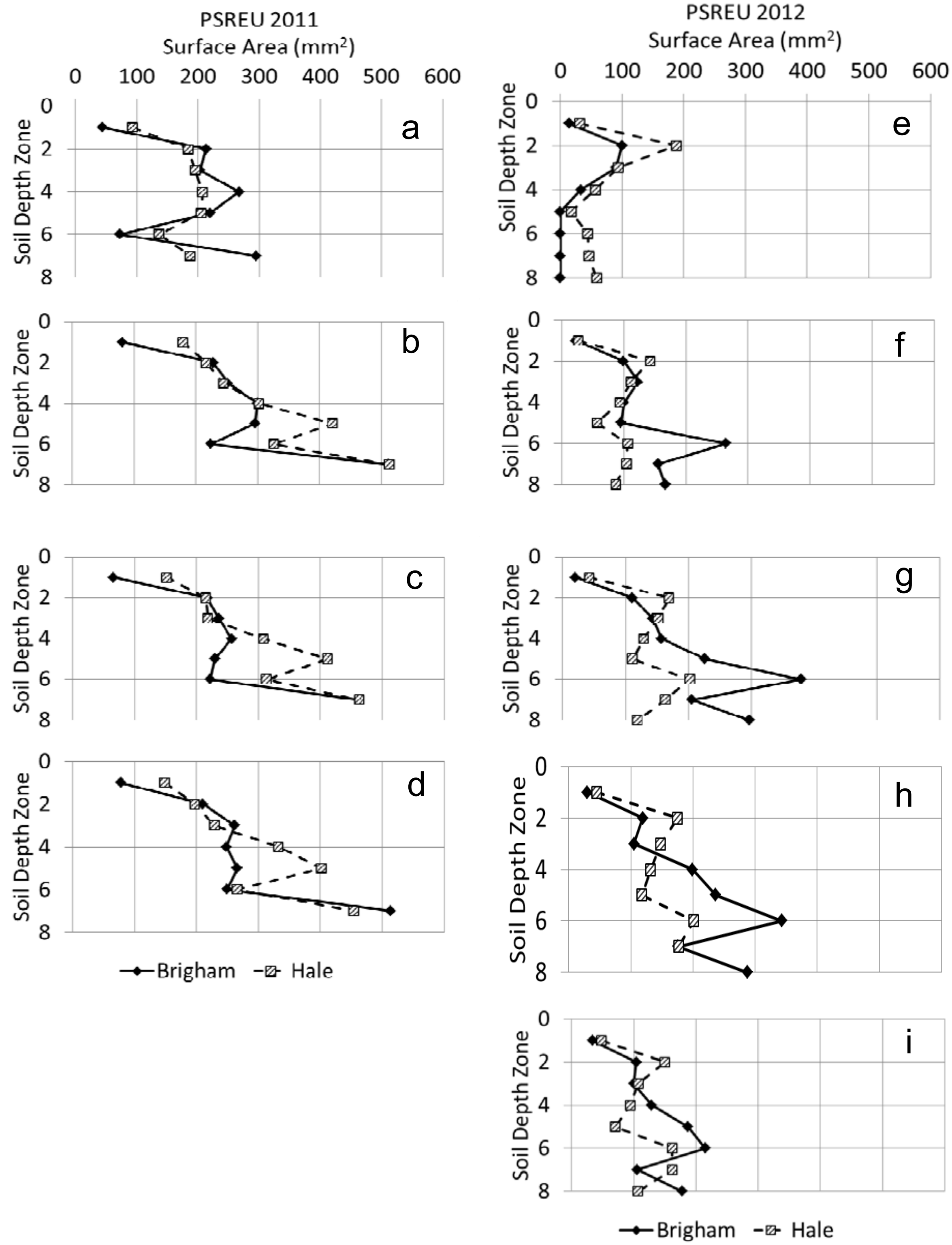

Figure 2-6 Root surface area by soil depth zone (in 10 cm increments) for 2011 and 2012 reported by DAP. 50 DAP in 2011(a), 70 DAP in 2011 (b), 92 DAP in 2011 (c), 106 DAP in 2011 (d), 38 DAP in 2012 (e), 58 DAP in 2012 (f), 73 DAP in 2012 (g), 93 DAP in 2012 (h), 142 DAP in 2012 (i),

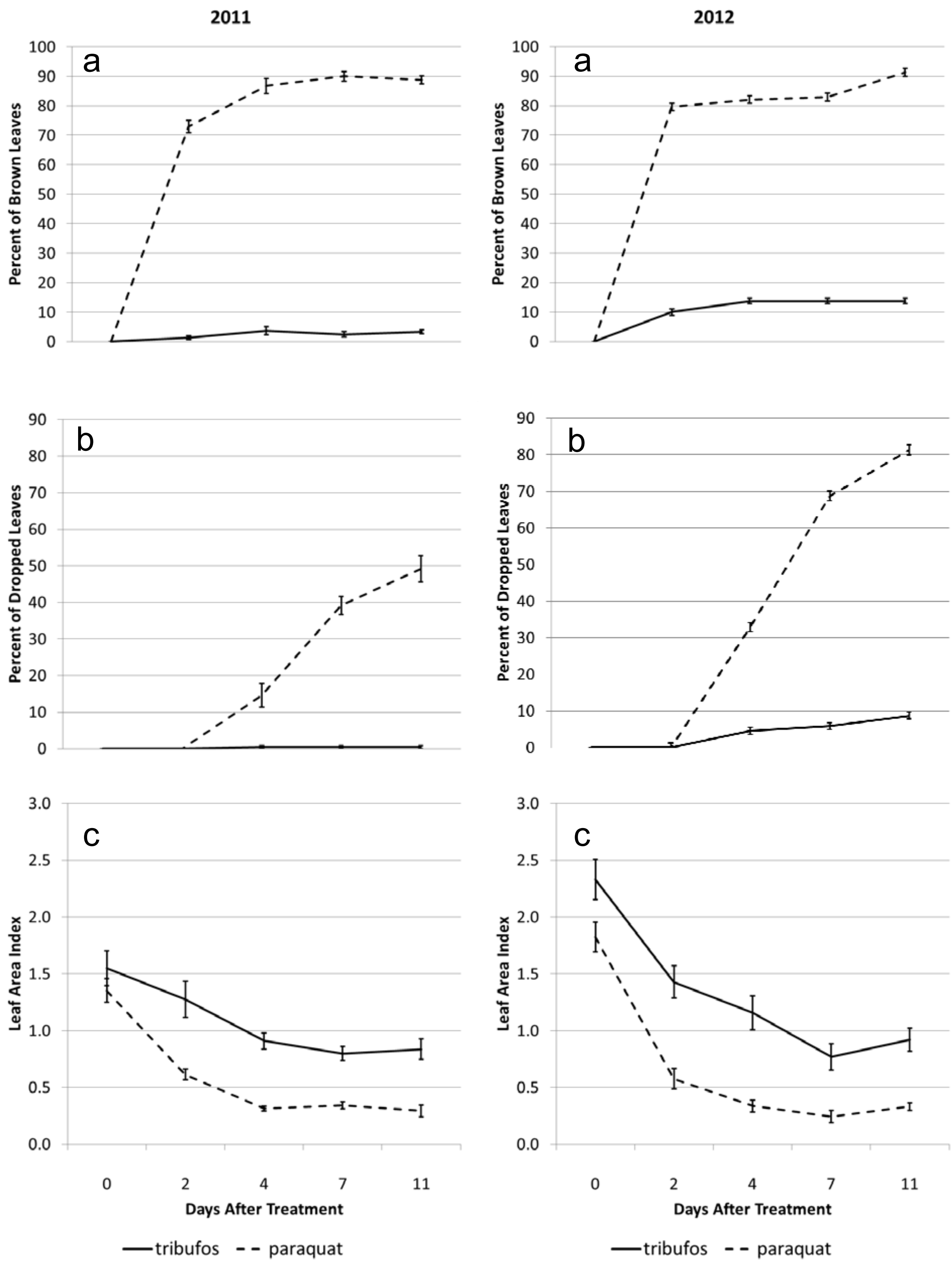

Figure 2-7 Harvest Aid effects in PSREU 2011 and PRSEU 2012. Percent Brown (a), Percent Leaf Drop (b), and LAI (c)

Discussion

By assessing the response of two castor cultivars to agronomic management techniques, the main goal of this project was to evaluate different management techniques that could be employed in a castor cropping system for the southeastern US region. The maximum yields achieved in any treatment in the current study were 1,403 kg ha^{-1} with most treatments averaging below 1,000 kg ha^{-1}. These yields are higher than previous results from Florida and comparable with current yields from other countries (FAOSTAT, 2013), but are low when compared to the optimum production levels achievable domestically in Texas in the range of 2,242 to 3,363 kg ha^{-1}, with some fields producing 4,035 kg ha^{-1} (Brigham, 1993). Several seed factors may have contributed to the yield levels in Florida including relatively low 100 seed weights and low oil percentages. In this study, the 100 seed weight ranged from 17.79 to 23.49 g which are lower in comparison to Texas grown seed (27.60 to 33.22 g) and at the lower range of seed produced globally (10.1 to 73.3 g with an average of 28.3g; Wang et. al, 2010). The Florida seed also had a lower percentage of oil by weight (42.7-46.2%) when compared to the average (48.2%) of the USDA castor germplasm (Wang et al., 2010). One contributing environmental factor to the low yields was the presence of mold on the racemes. Gray mold was previously reported as one of the main limiting factors for successful castor cultivation in the southeast (Domingo, 1953; Weiss, 1971; Godfrey, 1919) and the presence of an unidentified mold was detected in the current study, with the greatest problems noted at WFREC 2011 and PSREU 2012. Whole raceme failure and individual capsule failure—presumably due to mold—was observed in both locations and likely reduced yield. In fact, over 70% of the total harvest in WFREC 2011 was gathered at the first harvest and subsequent periods of heavy rain promoted mold growth and ultimately raceme failure. It is possible that antifungal spray plans may help alleviate this yield-reducing problem in the future. The combination of early maturing habits, raceme size, and propensity to shatter also likely played an integral role in producing low yields in this study. Flowers were first observed around 35 DAP in Florida, which is much earlier than the average flowering times of 47 DAP in the US (Weiss, 2000). The plants likely did not have as much vegetative growth as other castor grown in the US when flowering started and it is possible that this lack of photosynthetic capacity resulted in less photoassimilate for the growing racemes. The early flowering could explain why the primary and secondary racemes were typically smaller than those produced in Texas (Weiss, 2000) or Israeli cultivars that were examined in grower fields in south Florida (personal observation). In 2011, excessive shatter was also noted at the first harvest at 105 DAP and 109 DAP in PSREU and WFREC, respectively.

Quantification and characterization of seasonal growth habits—height, number of nodes below the first raceme, LAI, and rooting architecture—of castor grown in Florida are necessary to evaluate any cropping system for this area. These seasonal growth habits are important because data on height and nodes below the first raceme will affect mechanical harvesting; LAI will characterize canopy growth and development; and rooting architecture will affect cultivation and propensity for deep mining of nutrients in the soil. Overall canopy growth in this study showed a typical increasing pattern throughout the season, with LAI showing a parabolic trend peaking at 76 to 77 DAP for all locations/years except for PSREU 2012, which showed an increasing trend until the end of the season. Maximum LAI was noted as 2.01, 2.87, and 2.10 for PSREU 2011, PSREU 2012, and WFREC 2011, respectively. These peak LAI measurements are somewhat low in comparison to other crops, including sorghum (7.8) (Muchow and Davis, 1988), soybean (3-6) (Shibles and Weber, 1965) and cotton (5-7) (Ashley et al., 1965). In previous research, castor leaf area has been correlated with leaf length (Wendt, 1967), and LAI has been computed (Vijaya Kumar, et al., 1996), but overall LAI has not been reported. Given that, it is not possible to compare these maximum LAI values with previous research to determine whether they are representative. In this research, root length and surface area measurements effectively demonstrated numerical differences in planting density, root senescence, differences in root zone growth, and root growth rate. The lower density planting in 2012 resulted in lower overall cumulative root growth, but growth patterns were similar with a peak around 70 DAP in both years. Measurements in 2012 were conducted longer than 2011 and, as a result, root senescence was observed at 142 DAP. Interestingly, both the root length and surface area in the shallowest depth, zone 1 (0-10cm), were consistently lower than all other depths in both years. Farm managers have been advised to be mindful of the shallow spreading root system of castor plants when cultivating (Weiss, 2000), but unless the cultivation tool reaches well past 10 cm, significant root damage may not occur for castor grown in Florida. Castor roots grew downward at the rate of 14 mm day^{-1} by 50 DAP in 2011 and 20 mm day^{-1} by 21 DAP in 2012. These roots extended past the viewing area (80 cm) by 70 DAP and it is likely that the roots continued deeper in the soil, thus allowing for a greater distribution within the soil profile and a potential for mining for minerals and water. Rooting habit has been noted in previous literature, but data of this type have never been reported for castor and represent important botanical information that could be applied to various US production regions.

One of the most important and perhaps surprising results of the current study is the lack of effect of PGR on the height in either castor cultivar. Because plant height was not affected in 2011, PGR application was initiated earlier in an effort to optimize its effect in 2012. The lower concentration, but higher frequency rates applied in 2012 were more similar to the recommendations for cotton crop management (Supak and Snipes, 2000). However, even with a different application scheme, there were no impacts on plant height. PGR application may not be required for these cultivars as the tallest average height of 115.2 cm noted in the current study was within the upper limit of the suggested range (30-125 cm) for mechanical cultivation (Auld et al., 2003) and is similar to the dwarf cultivars (100-200cm) grown in the Texas High Plains and Trans-Pecos region (Brigham 1993). Although PGRs did not affect height, they did affect photosynthetic capacity differently in 2011 versus 2012. In 2011, the PGR-applied plots had significantly higher photosynthetic rates, while this effect was absent in 2012 which recorded lower values for conductance, SPAD, and Fv/Fm. Giberellic acid inhibitors have been shown to both decrease (Reddy et al., 1996) and increase (Zhao and Oosterhuis, 2000) the photosynthetic rate of cotton and the results from this study show similar gas exchange results for castor. Overall gas exchange rates measured in this study match previously measured photosynthesis, stomatal conductance, and transpiration for castor (Zhao and Oosterhuis 2000; Pinheiro et al., 2008; Dai et al., 1992).

Due to the irregularity of a killing freeze in Florida, the use of a harvest aid is likely to be a necessary cropping system component, and the results of this study reveal that paraquat is a much more effective harvest aid than tribufos. The goal of the harvest aid is to decrease the amount of vegetative material such that a mechanical harvester can more efficiently harvest and separate seed from vegetative material. Leaf browning will increase the harvest efficiency as it is an indicator of leaf desiccation, but leaf drop will increase harvest efficiency even more as no vegetative material will enter the combine. Visual observations of leaf browning and leaf drop were confirmed by a significant decrease in LAI post HA treatment. Paraquat was remarkably more effective than tribufos as a harvest aid averaging 1.5 times more LAI decrease, almost 15 times more leaf browning, and over 63 times more leaf defoliation after 11 DAT. The effects of paraquat as a harvest aid are comparable with past studies in cotton, but tribufos defoliation percentages are much lower. In one study the least effective harvest aid in cotton defoliated 51.2% of the leaves after 7 DAT (Anonymous, 1999) as compared to the leaf defoliation findings in this study with paraquat and tribufos' average of 79.4% and 3.1% after 7 DAT, respectively. Paraquat did not kill all the plants at the 2.1 L ha^{-1} rate, but the fact that it killed some may prevent it from being a harvest aid if rattooning the crop becomes a viable option. It is interesting that the hormone-related leaf abscission inducing mechanism of tribufos was not very effective as a harvest aid given that previous literature states castor is severely damaged by hormone type herbicides (Weiss, 2000). Due to the presence of regrowth at 11 DAT, the recommended harvest date may be 10 days or less to take full effect of the harvest aid, avoid shatter, and avoid regrowth that would reduce the harvest efficiency.

In conclusion, yield needs to be increased if castor production in Florida is to be competitive within a potential US market. Mepiquat chloride, as a plant growth regulator, did not affect plant height and had conflicting effects on the photosynthetic capacity of the crop. Tribufos did not effectively terminate the crop in this cropping system, but Gramxone worked well, as long as the crop is not managed in a rattooning system. Future research is needed to further evaluate the potential to grow castor in Florida, especially by incorporating fungicides and other disease management strategies. This project focused on a cropping system with a single harvest, but the results of this study combined with potential to grow castor in a rattooning system (data not shown) may suggest rattooning is a more economically sustainable cropping system for castor in Florida.

CHAPTER 3
ASSESSING SAP FLOW RATES AND DETERMINING K_C CURVES FOR CASTOR PRODUCTION IN FLORIDA

Chapter Abstract

Innovative location and crop-specific production systems are capable of conserving agricultural water use, and one effective method is the quantification of water-use and development of crop coefficients particular to a production region. To develop irrigation recommendations suited for castor production in north central Florida, research was conducted at the Plant Science Research and Education Unit in Citra, FL. Season-long field measurements of sap flow were collected for the castor (*Ricinus communis* L.) cultivar Brigham in 2011 and 2012 and soil evaporation rates were quantified in 2012. Sap flow was analyzed when the plots had reached complete canopy cover, were fully irrigated, and when daily solar radiation levels were at or above a historical radiation average to ensure optimum growing conditions. Soil evaporation rates were significantly lower than plant transpiration and as a result the season long transpiration was the main factor for the calculation of crop evapotranspiration (ET_c) calculated on an area basis. ET_c was evaluated against a calculated reference evapotranspiration (ET_o) from site specific meterological readings to calculate daily K_c values. 10-day K_c averages were compared to published K_c values from the Food and Agriculture Organization of the United Nations (FAO) for castor. The timeframes were roughly aligned and the mid-season K_c values were similar, but the late season K_c values for castor in Florida were higher as compared to the mid-season. The increase in water use throughout the season could be explained by a lack of physiological cut out and continued irrigation application. These results provide appropriate K_c values for

north-central Florida and will aid growers in irrigation decisions when producing castor in this region.

Introduction

Agriculture uses approximately 80 percent of the nation's consumptive water resources (USDA ERS, 2012). Innovative and location and crop specific production systems are needed to conserve water use by agriculture. Castor requires 20.6 to 24.7 cm ha^{-1} of water (Brigham, 1993) to obtain optimal growth and production and supplemental irrigation can increase yields by 32 to 49 percent (Laureti et al., 1995; Weiss, 2000). Castor can be grown in many regions without supplemental irrigation, including the semi-tropical climate of Florida. However, the combination of sandy soils and periodic drought within this region would likely require a cropping system with irrigation to achieve the highest yields. To optimize the efficiency of irrigation application any cropping system, it is necessary to quantify seasonal crop water-use for crops grown in that particular region. Total water use in any agricultural field can be quantified as the additive factors of evaporation from the soil surface (E) and transpiration of the crop (T_c), which are collectively called crop evapotranspiration (ET_c) (see Equation 3-1) (Allen et al., 1998). Water used by the crop can be directly measured with weighing lysimeters or direct measures of evaporation and transpiration (Sakuratani, 1981; Ham et al., 1990).

$$ET_c = E + T_c \tag{3-1}$$

Alternatively, ET_c can be calculated based on crop and cropping system specific characteristics including albedo, crop height, aerodynamic properties, irrigation, and harvest moisture content (Allen and Pruitt, 1991) which together constitute the crop coefficient (K_c). This K_c value is then multiplied to a modeled reference rate of evapotranspiration (ET_o) derived from meteorological data. ET_c then equals the product of a reference ET (ET_o) and the K_c value for different crop growth stages (see Equation 3-2) (Allen et al., 1998).

$$ET_c = ET_o \times K_c \tag{3-2}$$

Calculations of ET_o vary between location, season and the reference crop chosen. Currently, the standard ET_o is based on a hypothetical grass crop in local climatological conditions and is calculated using the Penman-Monteith model (Monteith, 1965). K_c values indicate the relative difference in water use between the crop and the reference; for example, a K_c value above 1 indicates that the crop is using more water than the reference crop and K_c values below 1 indicate that the crop is using less water. Growers in Florida can collect free ET_o values online, relevant to their particular area, from the Florida Automated Weather Network (FAWN) which collects data from 37 weather stations across the state (FAWN, 2012). With appropriate K_c values for castor, growers can easily make the calculation of ET_c to determine the crop water requirement and use it to apply supplemental irrigation above rainfall to meet crop water demand.

The Food and Agricultural Organization (FAO) has published K_c values for various crops including castor (Doorenbos and Kassam, 1979; Doorenbos and Pruitt, 1977), and further sources have updated the K_c calculation methods (Snyer and Pruitt, 1989; Wright, 1981). Typically, K_c values are assigned to three developmental timeframes: initial, mid, and late for many crops, including castor (Allen et al., 1998). The main factor determining early season K_c values are soil type, frequency and intensity of wetting and duration of soil surface wetness. Mid-season K_c values are based on crop specifics (albedo, crop height, and aerodynamic properties) and environment (relative humidity above 45% and windspeed at 2 m s^{-1}). The late K_c is indicated by yellowing of leaves and a natural senscence where the K_c is more reflective of irrigation practices and soil evaporation (Allen et al., 1998). Deviation from these K_c values according to environment (humidity) and crop management (wetting frequency and intensity, water percentage in harvested crop) occur with arid/windy conditions increasing K_c values and humid/stagnant conditions decreasing the K_c values (Allen et al., 1998). However, the FAO recommends that additional studies should be conducted in specific environments to determine more accurate K_c values and timeframes for each specific location (Allen et al., 1998). Therefore developing K_c values specific for Florida environmental conditions is essential for optimizing the efficiency of irrigation application in the region.

Determining ET_c values for calculation of regional specific K_c values has primarily been determined by weighing lysimeters in the field or greenhouse. An alternative method that can be employed in the field uses direct measurements of transpiration (T_c) and soil evaporation separately (Sakuratani, 1981; Ham et al., 1990). Logged measurements of transpiration are possible through the use of sap flow technology (Sakuratani and Abe, 1984; Ham et al., 1990) and measurements of soil evaporation can be carried out in the field using micro-lysimeters (Boast and Robertson, 1982). Sap flow collected throughout the season is equivalent to plant transpiration (Dynamax Inc., 2005); and sap flow measurements have been shown to be equivalent to within 10% of the crop water use measured in weighing lysimeters (Baker and Bavel, 1987; Smith and Allen, 1996; Hattan et al., 1990). Soil evaporation measurements using the micro-lysimeter method are reliable when assessing water loss over 1-2 days with measurements consistently within a 0.5 mm range (Boast and Robertson, 1982).

To address the need of providing castor K_c values appropriate to the Florida environment, this study measured the transpiration of the castor crop at full canopy coverage in the field under optimal conditions using sap flow collars attached to the stem below all branches of the plant. These measurements of transpiration were combined with direct measurement of soil evaporation in the field using a mini-lysimeter (Boast and Robertson, 1982). The resulting ET_c values were compared on a 10 day time step to ET_o values as measured by a FAWN weather station located and the research site and K_c values were calculated using Equation 3-3:

$$K_c = ET_c/ET_o \tag{3-3}$$

Materials and Methods

Field Preparation and Crop Maintenance

Field trials in 2011 and 2012 were conducted at the Plant Science Research and Education Unit (PSREU) near Citra, FL, (latitude 29.40N, longitude 82.17W, altitude 21m) in a Sparr Fine Sand (loamy, siliceous, subactive, hyperthermic Grossarenic Paleudults). The plots at PSREU consisted of 6 rows 7.62 m long with 0.91 m between rows. Bare soil alleys, 7.32 m wide, surrounded all plots. Plots were conventionally tilled and well irrigated prior to planting and received supplemental irrigation to ensure plants received adequate moisture. Plots were planted on 5 May 2011 and 1 May 2012. The castor cultivar Brigham was planted at a 4 cm depth with a two-row Monosem vacuum planter using a large edible bean plate (Edwardsville, KS). All seed was provided by Dr. D. Auld from Texas Tech University. Sites were thinned to an intra-row density of 6 plants m^{-1} in 2011; however, due to low yields and perceived excessive plant-to-plant competition indicated by some short statured plants and random plant death in 2011, intra-row density was decreased to the rate of 3 plants m^{-1} in 2012. In 2011, plots were broadcast fertilized with nitrogen (N) at 112 kg N ha^{-1} at 25 days after planting (DAP) and again with 33.6 kg N ha^{-1} at 89 DAP. In 2012, fertilizer amounts remained the same, but were side dressed: 11.2 kg N ha^{-1} at planting, 67.2 kg N ha^{-1} 28 DAP, and 67.2 kg N ha^{-1} 49 DAP, with phosporous (P), potassium (K), and other minor nutrients added at planting based on the recommendations for the region. Weed management was accomplished by incorporating 561.24g ai ha^{-1} trifluralin (DOW AgroSciences, Indianapolis, IN) prior to planting, followed by inter-row cultivation and hand weeding as needed.

Soil Evaporation Measurements and Data Analysis

Soil evaporation amount and rates were determined in the field using a mini-lysimeter in 2012 (Boast and Robertson, 1982). Soil evaporation was determined at 50 days after planting (DAP) and at 69 DAP, a date when the soil was dry as characterized by a lack of rain/irrigation event of more than 48 hours prior. Six mini-lysimeters were used, 3 in row and 3 between row to determine the average evaporation rate per plot. Using a section of PVC pipe(dimensions: depth= 70mm, diameter=100mm), a soil core was taken, immediately weighed and returned to the field and placed within the excavated soil core. After 1 to 2 days, the core was weighed again and the difference in weight was equal to the water lost via evaporation (Boast and Robertson, 1982).

Sap Flow and Meteorological Measurements and Data Analysis

In 2011, SGEX-13 sap flow collars (Dynamax Inc., Houston, TX) were installed on eight Brigham plants after the stems were approximately 13 cm in diameter. The collars work according to the heat balance method (Baker and Bavel, 1987) and are indexed to the stem diameter (Smith and Allen, 1996) to determine sap flow. A heating strip (source of the heat pulse) is located between two thermocouples and the difference in temperature between the thermocouples can be used to calculate T_c. Plants that exhibited a growth pattern (height, stem diameter and number of racemes) similar to most other plants in the plot were identified and selected for installation of the collars. The same eight SGEX-13 collars remained on the plant throughout the growing season. In 2012, plants were similarly selected, but the stem diameter was larger than in 2011, with four plants requiring the SGB-16 and four requiring the SGB-25 collars at installation. SGB-16 collars were subsequently changed to SGB-25 collars to accommodate increases in stem diameters. In each year, collars and data were regularly checked and collars were moved to alternative plants as needed. Data from each year were logged every 15 minutes throughout the installation period. Collars were installed 51 DAP and 45 DAP and removed 118 DAP and 143 DAP in 2011 and 2012, respectively.

Data were analyzed similarly in both years. When the collars were working properly missing data points resulting from a lost electrical signal were indicated by the ouput of the datalogger and were eliminated from the analysis. To increase accuracy, data points extending one hour before and after these missing values were excluded from consideration to allow the stem/collar time to thermally equilibrate (representing approximately 1.7% and 4.5% of the data points in 2011 and 2012, respectively). The flow rates reported by the instrument (g hr $^{-1}$) were converted to L minute $^{-1}$ based on the density of water (1 g mL^{-1}) as over 99% of sap flow is water (Dynamax Inc., 2005) and averaged across all collars at 15 minute intervals. These flow rates were also summed on a daily basis to determine total sap flow in a 24 hour period measured in L day^{-1}. Finally, total sap flow on a per area basis was calculated by multiplying flow rates of individual plants by plant density with results expressed on a per land area basis (L day^{-1} ha^{-1}).

In calculating K_c values for the region, the goal was to determine the typical water-use of the crop under conditions that reflected at or above historical meteorological conditions. Because solar radiation is a primary driver of transpiration, historical radiation levels were used to filter sap flow values that occurred under atypical environmental conditions during 2011 and 2012. Historical in-season solar radiation data from 2005 to 2010 was collected from the FAWN network (FAWN, 2012) and averaged at 10 day increments to determine historical baseline typical radiation levels for those time periods. In both 2011 and 2012, daily in-season solar radiation levels that were below the historical baseline were indicative of a sub-optimal growing condition and sap flow readings for those dates were not included in the development of the K_c values; this resulted in exclusion of 42.6% and 40.6% of sap flow values recorded in 2011 and 2012, respectively. For illustrative purposes Figure 3-1 graphically shows the days that were excluded during which daily radiation levels fell below the historical radiation level. After removal of these points, both linear and non-linear regression analysis were used to analyze the shape of the curve of sap flow over time (JMP Pro 9 software, SAS Institute Inc., Cary, NC) and significance of these regressions were determined at the $p < 0.05$ level. K_c values are reported on a 10 day basis by averaging daily K_c calculations for greater resolution than the typical mid- or late-season single values reported by FAO.

Results and Discussion

The average soil evaporation rates were 38 L ha^{-1} day^{-1} and the average transpiration rates were 57,199 L ha^{-1} day^{-1} and 56,560 L ha^{-1} day^{-1}, for 2011 and 2012, respectively. This soil evaporation rate was only 0.07% of the lowest average daily transpiration rate and contributed only 0.001 to the K_c value; therefore, ET_c values were set equal to T_c values. The average measureable daily sap flow occurred between 0800 and 2000 EDT for 2011 and 2012 (Figure 3-2) with peaks at 1415 and 1300 EDT in 2011 and 2012, respectively. Sap flow patterns mirrored daily solar radiation levels (except for a short lag time for sap flow in the early morning hours). Radiation levels increased at 0600 and declined to near zero around 1900 EDT and peaked at 628 and 741 w m^{-2} at 1145 and 1215 EDT in 2011 and 2012, respectively (Figure 3-3). The values in peak sap flow rates per plant in 2011 were much lower than in 2012 with a seasonal average maximum of almost 150 g hr^{-1} in 2011 and almost 300 g $hr^{-1}$and 2012. These flow rates were comparable to maximum rates observed for other crops in Florida including, potato (200 g hr^{-1}) (Byrd, 2012) and cotton (250 g hr^{-1}) (Thompson, 2012). Maximum flow rates are typically standardized according to leaf area in the literature, but flow rates have been reported for cotton (120 g hr^{-1}), maize (150 g hr^{-1}), and sunflower (225 g hr^{-1}) (Loscano, 2000; Kjelgaard et al., 1997). However, when calculating sap flow on an area basis and summing over the measurement period, the difference in planting density between the two years resulted in nearly identical total sap flow values: 57,199 L ha^{-1} day^{-1} and 56,560 L ha^{-1} day^{-1}, for 2011 and 2012, respectively. The similarity of sap flow rates on an area basis can be explained by the offsetting changes in planting density and correlated canopy development. The lower planting density (2012) produced larger plants, as evidenced by the increase in stem diameter, and a closed canopy must have resulted in an increase in leaf area per plant as compared to smaller plants that were planted at a higher density (2011). An increase in leaf area would produce a higher transpiration rate under optimal conditions and could reasonably explain the two-fold increase in rate while maintaining similar flow rate when calculated on an area basis. In comparison, the water use rates for castor were within the range for cotton (44,200 L ha^{-1} day^{-1} to 95,000 L ha^{-1} day^{-1}) (calculated from Dugas, et al. 1994).

Daily sap flow on an area basis and the matched daily ET_o values calculated from the weather station on site oscillated throughout the year in 2011 and 2012, with the values closely matched early in the installation period (55-111 DAP in 2011; 54-89 DAP in 2012) (Figure 3-4). There was evidence of an increasing trend from the beginning of collar installation up to harvest in both years. The best-fit regression for these area sap flow values in 2011 resulted in a third order polynomial, while in 2012, the regression resulted in a second order polynomial best-fit of the data (Table 3-1). These second and third order polynomials reflect daily water-use patterns of the crop following an increasing trend from collar installation to late season, followed by a plateau or slight increase in water use just prior to removal of the collars (Figure 3-5). This late peak in water use may be an due to the indeterminate nature of castor and an increased fruit set as compared to crops that senesce late in the season with corollary decreases in water use (partly due to the stoppage of irrigation).

The calculated 10-day average K_c values for 2011 were fairly constant at approximately 1.15 until approximately 110 DAP, when a spike to a value of approximately 1.5 until the end of the measurement period was observed (Figure 3-6).

Likewise in 2012, the 10-day average K_c values initially started around 1.15 and then showed a step-wise increase starting at DAP 90 with a value of 1.37 and increasing to a peak K_c value of 1.64 at 100 DAP. However unlike 2011, the 10-day K_c value in 2012 decreased to a fairly consistent value of 1.5 from DAP 110 through the end of the measurement period (Figure 3-6). K_c values of 1.5 are larger than any K_c reported by the FAO and the high range is partly due to a decrease in ET_o combined with an extended irrigated growing season. The particular K_c values calculated on a 10 day basis in this study are reported in Table 3-2.

The ten day K_c values calculated in this study show much higher resolution than K_c values reported by the FAO and the significant increase at the late season is quite different from most crops. Maize, cotton and sunflower, have a peak K_c value during mid-season and a much lower late season K_c value while other crops, such as coffee, pineapple, and olives, maintain the same K_c through mid and late season (Allen et al. 1998). Castor grown in Florida does follow the same increasing K_c trend as berseem clover (*Trifolium alexandrinum)*, which is grown in India and the US mid-west with an increasing K_c from 1.11 in mid-season to 1.24 in late season (Tyagi, 2003).

The FAO K_c values for castor with a maximum height of 0.3 m are 0.35, 1.15, and 0.55 for the early, mid, and late season, respectively (Table 3-3) (Allen et al., 1998). The calculated K_c values for the two seasons of this study, based on the timeframes recommended by the FAO, were between 1.17 (2011) and 1.20 (2012) during the mid-season and 1.49 (2011) and 1.51 (2012) for the late season (Table 3-3). Based on these results, the late season K_c values proposed by the FAO may need to be adjusted for castor grown in Florida. Although the late-season K_c values for this cropping system deviated from those reported by FAO, particularly in the late-season, a direct comparison between the two values may not be appropriate. The FAO reports K_c values based on standard irrigation practices and planned harvests when the seed is dry—as is the case with castor and other dry beans— discontinue irrigation or wait until a killing freeze to effectively desiccate the crop. This cessation of irrigation reduces the moisture within the seed and also lowers the K_c due to low evaporation and transpiration rates (Allen et al., 1998). The cropping system used for this study irrigated until the crop was chemically terminated with a harvest aid. Therefore, the increasing K_c values in the late-season found in this study were representative of a crop that was still physiologically active. Further, the FAO values for castor are based on an average crop height of 0.3 m; however, the Florida castor crop in this study reached a maximum height of 0.85 and 1.15 m during 2011 and 2012, respectively, thereby likely contributing to higher overall water-use rates than that reported by FAO.

The increasing water-use pattern in the late season for Florida castor production is interesting as it may indicate that castor grown in this region does not have a physiological cut out. Physiological cut out has been extensively studied in cotton and is characterized as the time in the crop life cycle when cessation or extended lapse in terminal growth occurs that typically signals the end of the effective fruiting period (Oosterhuis et al., 1996; Oosterhuis and Kerby, 2011). An extended lapse in terminal growth was not observed in this study as the castor crop continued to flower and produce reasonable sized racemes past the tertiary racemes. A plant that exhibits a physiological cut out will also decrease water use if the cut out also results in a decrease in activity of the photosynthetic plant parts (green flowers, leaves, etc.).

Again, castor in this study maintained its water use quantity, regardless of decreases in ET_o, up until chemical termination resulting in increasing K_c values until that time.

In summary, the peak transpiration for castor in this study occurred sometime after 1300 EDT and was comparable to rates reported for potato, cotton and sunflower. Castor sap flow rates normalized on an area basis were shown to have relatively consistent water-use values across the two years of the study. Calculated 10 day K_c values were roughly in the range of 1.11 to 1.29 for the mid-season and, contrary to expectation, increased to a range of 1.49 to 1.52 until chemical termination of the crop. This indicates that castor may not have a physiological cut out date as reflected by continued raceme development and increased water use. These results provide appropriate K_c values for north-central Florida and will aid growers in irrigation decisions when producing castor in this region.

Table 3-1 Sap Flow Regression of 2011 and 2012. F values for sap flow amounts on DAP

		2011		2012	
Best Fit	df	F Value	R^2 Value	F Value	R^2 Value
First Order	1	0.2444	0.00639	9.0910**	0.141845
Second Order	2	0.3524	0.01869	9.2280**	0.254721
Third Order	3	4.1894*	0.25877	11.4633**	0.393522

** Indicates $P < 0.01$
* Indicates $P < 0.05$

Table 3-2 Florida 10-day Kc Average

Season	DAP	2011	2012
	50-60	1.15	1.11
Mid	60-70	1.14	1.14
	70-80	1.29	1.12
	80-90	1.13	1.15
	90-100	1.12	1.37
	100-110	1.11	1.64
Late	110-120	1.49	1.52
	120-130	--	1.49
	130-140	--	1.51

Table 3-3 Florida Kc Values based on FAO Timeframes

	Planting 0-20 DAP	Development 20-60 DAP	Peak Growth 60-110 DAP	Late Season 110-135 DAP
Castor (Indonesia)	0.35	--	1.15	0.55
2011 Florida Kc value	Collar not installed	Collar not installed	1.17	1.49
2012 Florida Kc value	Collar not installed	Collar not installed	1.20	1.51

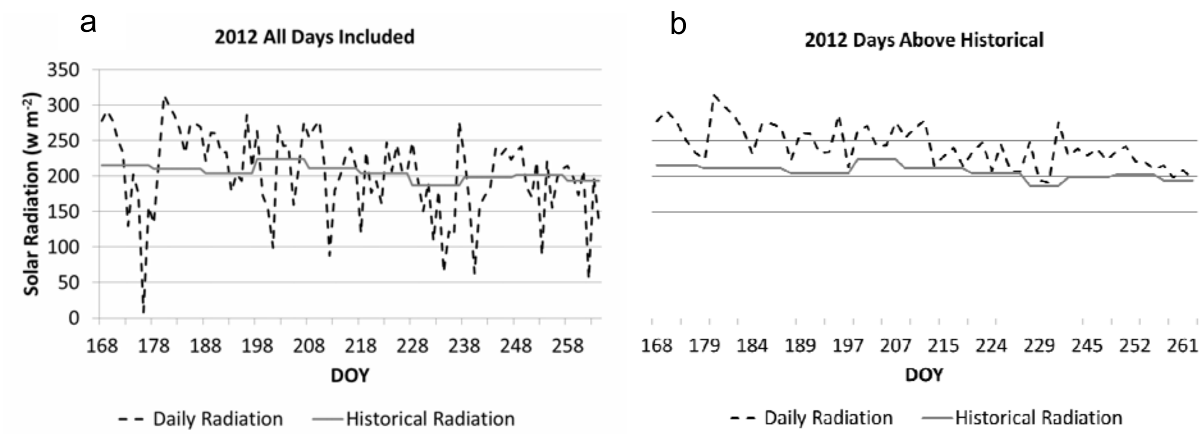

Figure 3-1 2012 Daily versus Historical Solar Radiation. All Days Included (a) and Days Above Historical Average (b)

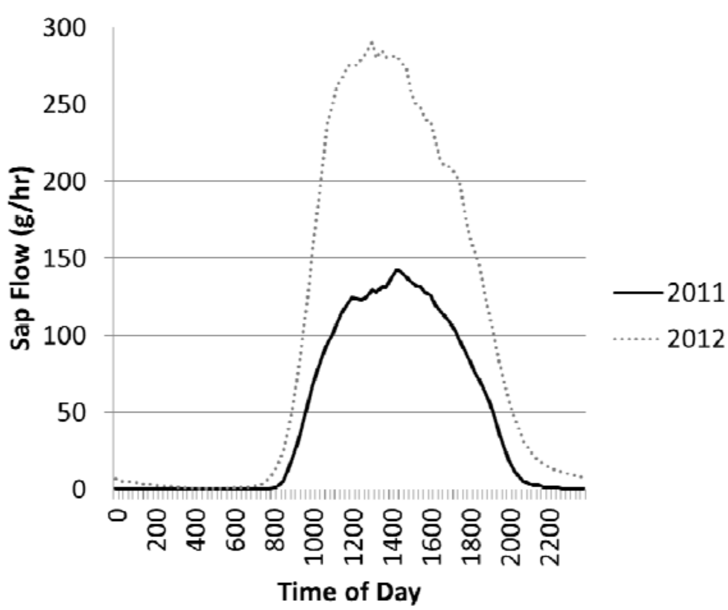

Figure 3-2 Average daily sap flow rates

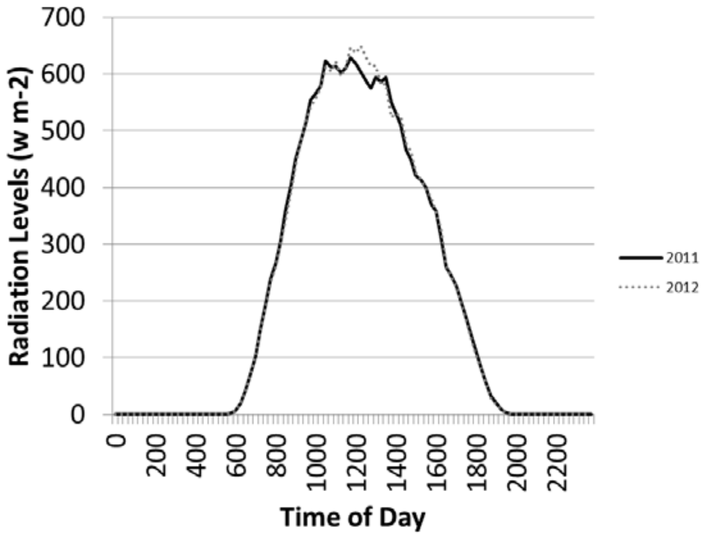

Figure 3-3 Average daily solar radiation

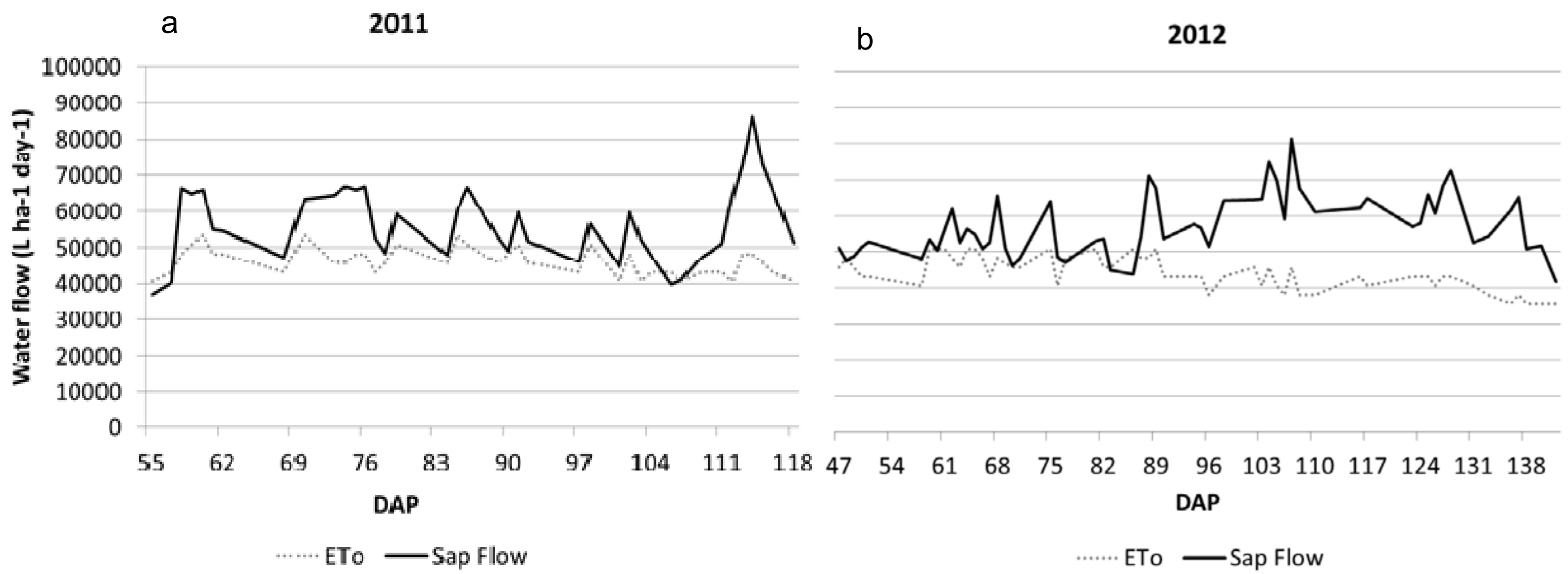

Figure 3-4 Seasonal Sap Flow and ETo measurements in 2011 (a) and 2012 (b)

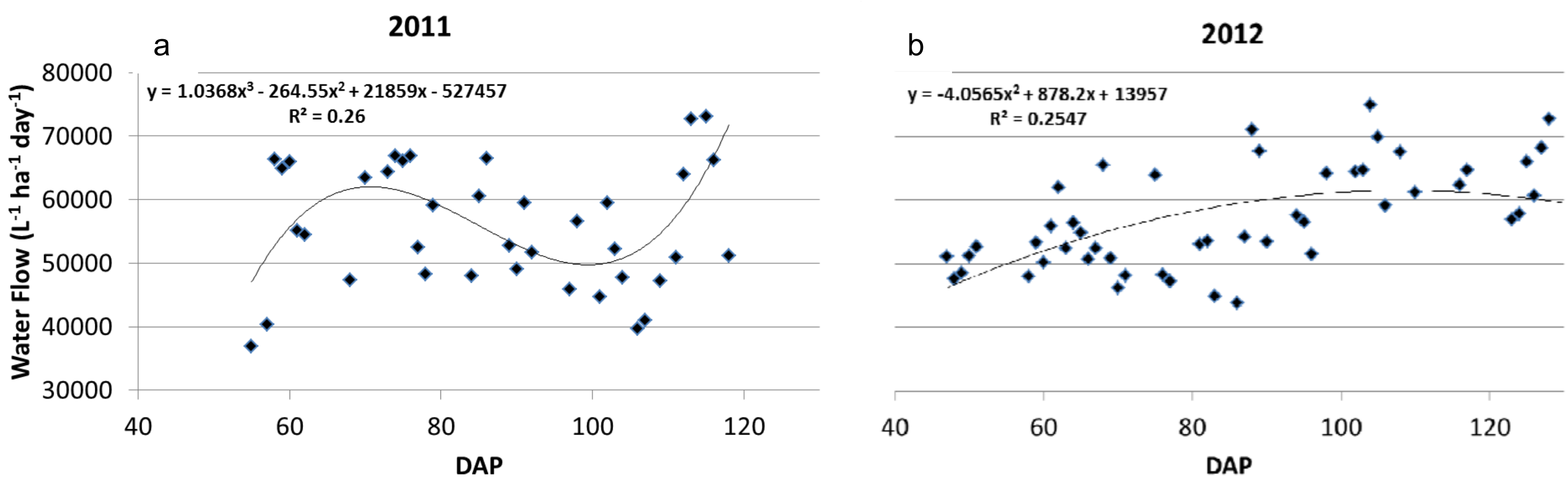

Figure 3-5 Regression of crop water flow per area across DAP for castor grown in 2011 (a) and 2012 (b)

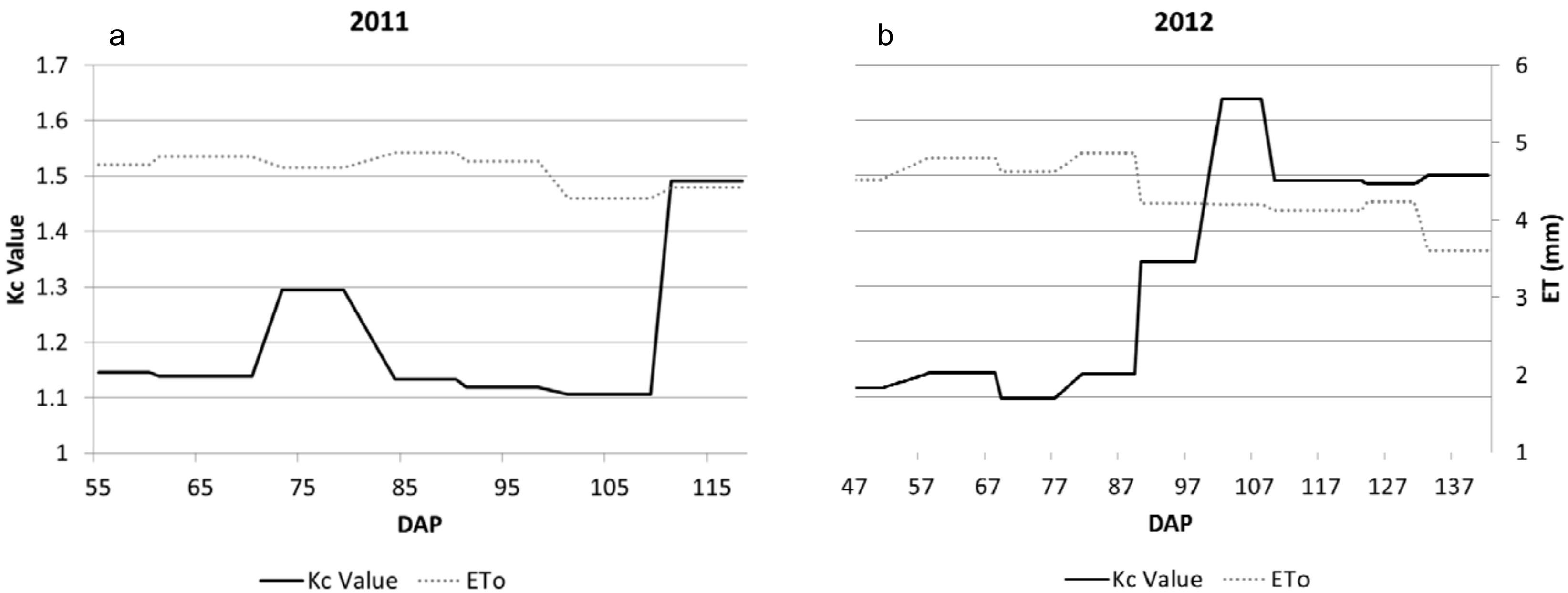

Figure 3-6 10 Day Average K_c Values and ET_o measurements for castor in 2011 (a) and 2012 (b).

CHAPTER 4
SUMMARY

Results from this study suggest that additional cropping system elements that might optimize production need to be developed and tested if castor (*Ricinus communis* L.) production in Florida is going to be competitive within a potential US market. The maximum yields achieved in any treatment were 1,403 kg ha^{-1} with most treatments averaging below 1,000 kg ha^{-1}. While these are above historical Florida yields and are comparable to internationally reported yields, these levels are roughly half of what has been reported for castor production in the southwestern US. Yield could be increased by increasing seed size and oil concentration as well as reducing raceme failure due to mold.

This study provided novel information on the growing habits (flowering time, height, raceme number, and LAI) as well as rooting architecture that has currently not been reported for castor. The stature (height and nodes below the first raceme) found in this study was suitable for most mechanical harvesters currently being tested in Texas. The earlier flowering time for the cultivars grown in Florida needs to be further evaluated as yields may have been reduced due to a lack of photoassimilate allocation to the primary and secondary racemes. Interestingly, the rooting presence in the top 10 cm of the soil profile showed a significantly lower length and surface area, which is contradictory to previous cultural recommendations to avoid shallow cultivation due to the presence of a fibrous root system near the soil surface. In addition to possible increases in mechanical cultivation, the quick growing root system (up to 20 mm day^{-1}) may suggest that these cultivars in Florida are capable of mining water and nutrients deep in the soil demonstrating possible drought tolerance.

This study also tested different production inputs in an effort to develop a sustainable production system in Florida. One of the most important and perhaps surprising results of the current study is the lack of effect of PGR on the height and growth habit in either castor cultivar. Even when applied at different rates and different crop development times, the use of mepiquat chloride based plant growth regulator did not affect plant height and produced conflicting effects on the photosynthetic capacity of the crop after treatment. Due to the irregularity of a killing freeze in Florida, the use of a harvest aid is likely to be a necessary cropping system component, and the results of this study reveal that paraquat was more effective than tribufos. Paraquat would be an effective harvest aid in a cropping system without a rattoon (due to isolated plant death), but regrowth noticed at 11 DAT suggests a harvest date before that time to maximize harvest efficiency.

The ET_c for castor cropping systems in Florida is primarily due to increases in crop transpiration as daily soil evaporation rates were 0.07% of the lowest daily transpiration rate. Peak transpiration for castor in this study occurred between 1300 and 1415 EDT and maximum rates (between 150 g hr^{-1} and 300 g hr^{-1}), which were comparable to rates reported for potato, cotton and sunflower. Average castor sap flow rates normalized on an area basis (56,560 L ha^{-1} day^{-1} and 57,199 L ha^{-1} day^{-1}) were shown to have relatively consistent and slightly increasing water-use values across the two years of the study. Water use throughout the season did not demonstrate the same pattern in 2011 and 2012 with a third order polynomial best-fit in 2011 and a second order polynomial best-fit in 2012. Calculated K_c values were roughly in the range of 1.1 to 1.29 for the mid-season and, contrary to expectation, increased to a range of 1.49 to

1.52 until chemical termination of the crop. The late season peak in water use may be due to several factors including: the indeterminate nature of castor, especially manifested with continued irrigation into the late season; an increased fruit set as compared to crops that senesce; and the lack of a physiological cut-out phenomenon late in the season.

Future research is needed to develop and evaluate additional management methods to increase the yield of castor grown in Florida. This project focused on a cropping system with a single harvest, but the results of this study combined with the potential to grow castor in a rattooning system (data not shown) may suggest rattooning is a better cropping system for castor in Florida. Even if rattooning castor in Florida proves to be unsuccessful, these results do provide appropriate K_c values for north-central Florida and will aid growers in irrigation decisions when producing castor in this region.

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BIOGRAPHICAL SKETCH

David Neil Campbell was born in Groton, MA and earned his bachelor's degree at the University of Florida. David initially pursued a career in Medicine, but switched his academic and career focus to Agriculture and Higher Education. David believes agriculture will play an increasingly important role in society as both the world population increases and natural resources decrease.