CHARACTERIZATION OF G×E INTERACTIONS ON YIELD AND QUALITY OF MUSKMELON (*CUCUMIS MELO* L.)

A Dissertation

by

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ABSTRACT

Muskmelon (*Cucumis melo* L.) genotypes belonging to *reticulatus* and *inodorus* groups were evaluated under natural and modified field-environments. In the genotype × environment interactions studies, yield and fruit quality traits were characterized using GGE Biplot for four TAMU breeding lines and five commercial F_1 hybrids in three years (2010, 2011, and 2012) at three locations (College Station, Uvalde and Weslaco) in the south-central Texas. Genotype 'TAMU Orange Casaba' was identified as the highest mean performing genotype for fruit yield with specific adaptation to the Weslaco area. 'Mission' was confirmed as the most stable and average performing genotype for marketable yield and quality traits at all locations. Uvalde was identified as the ideal location for selecting generally adapted genotypes to south-central Texas.

Under deficit irrigation (DI, 50% ETc), a significant yield reduction of 43% in 2011 and 33% in 2012 was measured in 'Super Nectar' (*inodorus* type), while for cvs. Mission and 'Da Vinci' (*reticulatus* type) the reduction in yield was 24% and 30%, respectively in 2012. No adverse impact of DI was observed on fruit quality. Further, DI enhanced root length intensity (L_a; $cm \cdot cm^{-2}$) in cv. Mission, maintained it in cv. Da Vinci, and decreased it in cv. Super Nectar. Thus, this suggests that the *reticulatus* melons have better adaptation to water deficit condition in south Texas as compared to the *inodorus* melon.

In another experiment, clay (Uvalde) and sandy loam soils (Weslaco) had variable impact on root growth and yield of melon genotypes. Sandy loam soil produced

77% higher L_a as compared to clay soil. Under sandy loam soil, root growth distribution was deeper (40 - 70 cm) while it was shallower (< 30 cm) in clay soils. Melon plants grown in clay soil produced 40% and 24% higher marketable and total fruit yield, respectively as compared to sandy loam soil, a response most likely due to longer growing season and differences in soil characteristics at Uvalde. The great rooting ability of TAMU breeding lines under different soil types and equivalent yield potential to commercial hybrids confirms their potential as parent for developing high yielding and stable cultivars for a wide range of environments in south-central Texas.

DEDICATION

I dedicate this work to my mother (Smt. Duarki Devi), father (Late Sh. Shri Krishan), and lovable niece, Harmanpreet, for their unconditional support, inspiration and love.

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CHAPTER I

INTRODUCTION

Melon (*Cucumis melo* L.) is an important horticultural crop with a worldwide production of 27.3 million metric tons; with China, Iran, Turkey, Egypt and United States accounting for 68% of the World production (FAO, 2013). In the U.S., melons (cantaloupes and honeydews) were grown in 33,510 ha with a production of 986 thousand tons in 2013 having an economic impact of US$ 395 million (USDA-NASS, 2014). The netted muskmelons known as 'Cantaloupes' in the U.S., belong to the *reticulatus* group whereas honeydew and casaba melons are included in the *inodorus* group (McCreight et al., 1993).

Melons are an excellent source of many health promoting compounds (Lester and Crosby, 2002). For instance, orange-fleshed melons, which are rich in β-carotene, rank among the most commonly consumed fresh fruits in the U.S. (Lester and Eischen, 1996). In the past, (up to 2004), Texas had been among the major cantaloupe producing states in the US, but the current average productivity of melons is very low compared to the national average. Thus, in Texas low yield is considered a major factor behind the declining in area under melon cultivation. During 2013, only 10,260 tons of cantaloupes were harvested from 760 ha in the state. The average yield was less than half (13.5 $t \cdot ha^{-1}$) of the national average (29.8 $t \cdot ha^{-1}$) (USDA-NASS, 2014). However, the historical production evidences, soil types and climatic suitability indicates the great potential for reviving melon cultivation in Texas.

Root growth, yield and fruit quality of melon genotypes are very sensitive to climatic conditions, location, soil type, cultivar, and crop management practices (Bhella, 1985; Lester and Eischen, 1996; Sharma et al., 2014). The differential response of cultivars to changing environments, due to the interaction between the genetic makeup of a cultivar and the environment in which it is grown, is known as 'genotype by environment interaction' (G×E). Previous studies have indicated the possibility of a 40% increase in productivity through the utilization of G×E in breeding strategies (Kang, 2002). By default, some cultivars are specifically adapted to specific environments to produce high quality fruits. To take advantage of this natural phenomenon, this project has been formulated to screen elite lines/cultivars specifically adapted to target environments for higher production and exhibiting enhanced levels of β-carotene, vitamin C and sugars.

As commonly seen in other arid and semiarid regions of the world, southwestern Texas is also experiencing frequent droughts and serious irrigation water limitations (Leskovar and Piccinni, 2005). Thus, management technologies which can minimize crop losses under such drought conditions are greatly required. Deficit irrigation is an important strategy for sustaining melon productivity in water limiting regions affected by prolonged droughts. Furthermore, soil types and their physical and chemical characteristics also have interactive effects on root growth patterns of crop plants, such as barley (*Hordeum vulgare* L.) (Andrén et al., 1993).

Muskmelon has a tap root system which grows about two feet deep and four-five feet horizontally (Weaver and Bruner, 1927). A better understanding of root growth

behavior, yield and fruit quality of muskmelon genotypes from diverse groups grown under varying environmental conditions is of critical importance. Faced with water scarcity, varieties tolerant to moisture deficit with improved root systems are required to be identified for the region to regain the historical melon productivity levels in Texas. Therefore, high yielding varieties possessing high levels of nutrients, with stronger root systems capable of efficiently exploring soil for water and nutrients and having a fair degree of tolerance to moisture stress are of utmost importance.

1.1 Goals and objectives

The main goal of this study was to identify genotypes possessing vigorous root systems with higher levels of β-carotene, ascorbic acid and sugars along with high productivity under varying environmental Texas conditions. For these traits, selected genotypes were evaluated under natural and modified micro-environments. Nine orange-fleshed genotypes from the *reticulatus* and *inodorus* groups were evaluated for quality and yield traits at three locations in Texas over three years. Six genotypes including two commercial hybrids were tested for root growth behavior under two types of soils, (silty clay in Uvalde and sandy loam in Weslaco). Three genotypes representing specialty melons were evaluated under deficit irrigation for root, yield and quality traits. Therefore, the study was conducted with the objectives to evaluate the adaptability and suitability of selected genotypes under different environments.

CHAPTER II

GGE BIPLOT ANALYSIS OF GENOTYPE BY ENVIRONMENT INTERACTIONS FOR MELON (*CUCUMIS MELO* L.) FRUIT YIELD AND QUALITY TRAITS

2.1 Background

Muskmelons exhibit a wide variability for vegetative traits, fruit morphology, sweetness, and climatic adaptations for yield and fruit quality (Li et al., 2006). Previous reports have attributed the lack of widely adapted cultivars in muskmelons to its extreme sensitivity to environmental variations and genotype by environment interactions (Ng et al., 1980; Dhakare and More, 2008; Yadav and Ram, 2010).

In field evaluation trials, the performance of a genotype is determined by the genotypic main effect (G), the environment main effect (E) and the interaction between these two (G×E) (Yan et al., 2001). The term stability is used to characterize a genotype that shows a consistent performance across tested environments for a trait of interest. A few G×E interaction studies have been conducted in muskmelons that focused on the stability of yield performance over temporal environments (years and/or seasons) (Ng et al., 1980; Dhakare and More, 2008). However, in a plant spacing by cultivar study (Kultur et al., 2001), and a generation mean analysis study (Zalapa et al., 2006) conducted at two locations (Arlington and Hancock, WI), muskmelons genotypes were reported to vary for their fruit yield as well as yield attributing traits. Thus, muskmelons genotypes give differential responses to both temporal as well as spatial environmental

variation (Yadav and Ram, 2010). In spite of the importance of G×E interactions in cultivar selection, very limited information is available on this aspect, specifically no systematic G×E study has been reported with respect to quality traits of muskmelons (Dhakare and More, 2008; Yadav and Ram, 2010).

Sweetness, flavor, texture and phytonutrient levels of β-carotene and vitamin C in flesh tissue are the determinants of fruit quality in muskmelons (Yamaguchi et al., 1977; Lester, 2008). Orange-fleshed muskmelons are known for their unique flavor and high sugar levels (Yamaguchi et al., 1977). Increased awareness about the benefits of healthful foods have earned melons a reputation as an excellent source of health promoting phytonutrients (Lester, 2006), though consumer preference is still largely determined by sweetness, aroma and texture. Thus, selecting cultivars for high productivity, acceptable sweetness, flesh color, firmness, sensory traits and a fair amount of β-carotene and vitamin C has been a great challenge for muskmelon breeders.

Soluble solids content (SSC) is a reliable indicator of quality that has been routinely used by breeders to screen germplasm for sweetness (Villanueva, 2004). Li et al. (2006) noted that soluble sugars account for more than 97% of the SSC in maturing muskmelon fruits, with sucrose accounting for nearly 50% of all sugars. As per USDA standards, a high-quality muskmelon fruit should have SSC ranging from 9% to 11% (Kultur et al., 2001). Muskmelon SSC varies with climate (Bouwkamp, 1978), location (Kultur et al., 2001), genotype and crop management practices (Bhella, 1985). Edmonds and McFall (1927) observed that soluble solids were higher in a year with sunny and moderately cool conditions than in a year with cloudy days with moderately high temperatures and

frequent rains. At Salisbury, Maryland Bouwkamp (1978) reported that light intensity significantly decreased the SSC in 9 of 16 cultivars studied, whereas, rainfall reduced the SSC in 3 cultivars.

Orange fleshed muskmelons, cantaloupes (*Cucumis melo* L, *reticulatus* group) and honey dews (*Cucumis melo* L., *inodorus* group) are excellent sources of carotenoids (Fleshman et al., 2011). β-carotene (84.7%), ζ-carotene (6.8%), α-carotene (1.2 %) and lutein (1.0 %) are the main carotenoids in muskmelon (Curl, 1966). Watanabe et al. (1991) reported that beta carotene content varied from 9.2 to 18.0 μg g^{-1}depending upon the varieties. Crosby et al. (2007) also reported that carotenoid content changed with the flesh color and ranged from 0 in white-fleshed to 40 μg g^{-1} in dark orange-fleshed genotypes. They also reported that cultivars 'TAM Uvalde' and 'Mission' had more than 36 μg g^{-1} of total carotenoids. Lester and Eischen (1996) reported a genotype and environment interaction effect on β-carotene content of melon fruit. They observed a decrease in β-carotene for the genotype 'Cruiser' when grown in a fine sand soil (15.1 μg g^{-1}) compared to silty clay loam (18.2 μg g^{-1}), while was similar for the genotype 'Primo' (18.1 μg·g^{-1}) in both soils. Thus, the amount of β-carotene in the fruits may vary according to the genotype, environment (i.e. climate, and soil conditions) and G×E interactions.

Numerous studies have reported the protective effects of β-carotene intake against several chronic diseases like cancer, cardiovascular, cataract, and neurological disorders (Mayne, 1996; Kritchevsky, 1999; Palozza et al., 2004). Further, Palozza et al. (2003) argued that the health benefits of β-carotene are dose dependent, indicating that

increased daily consumption of phytonutrient rich foods, and enhanced concentrations in the food stuffs, are potential strategies to obtain maximum health benefits.

Muskmelon ranks in the top three among the nine most consumed fresh fruits in the U.S. for supplying daily requirements of ascorbic acid. Ascorbic acid, a powerful antioxidant, helps in maintaining the immune system by reducing the severity of immune inflammatory responses like cold, and also helps in preventing cardiovascular diseases (Lester, 2006). Park et al. (2006) reported that accumulation of ascorbic acid is sensitive to genotype by environment interaction. This trend was evident from the differential response of this trait when grown at different locations, such as in Weslaco in the lower Rio Grande valley and Uvalde in the Wintergarden region. All genotypes tested produced higher levels of ascorbic acid at Uvalde than at Weslaco. The ascorbic acid content ranged from less than 15 $\mu g \cdot g^{-1}$ in many wild types and some commercial cantaloupe and honeydews to 250-350 $\mu g \cdot g^{-1}$in cultivars like 'TAM Dulce,' 'TAM Uvalde,' 'Mission' and 'TXC 2015'(Crosby et al., 2007). From the previous studies, it can be recognized that melon quality is very sensitive to both temporal and spatial environmental variations. Thus, genotypes rich in phytonutrients and having stability over diverse environments would be of great value for breeding new high-quality melon cultivars.

Various approaches are available to analyze the multi-environment genotype evaluation data. For example in melons, Dhakare and More (2008) used the Eberhart and Russell (1966) model, and Ng et al. (1980) applied joint regression analysis to investigate G×E interaction effects for yield. In the G×E studies, breeders used to focus

only on yield traits, due to the complexity of data analysis (Yan and Kang, 2002). However, the recent advances in statistical models and analysis software have facilitated multi-trait analysis (Yan et al., 2000). These statistical tools can be more useful in vegetable crops where quality traits are also important along with fruit yield. GGE Biplot is such a tool that gives a graphical representation of G and G×E effects, simultaneously and thus, allows researchers to overlook the large degree of environmental variations and concentrate mainly on the typically obscure genotypic and G×E components that are most useful for cultivar evaluation. This technique can be used to evaluate the average yield and stability of a genotype as compared to others in the trial, rank environments based on ability to differentiate genotype performance, distinguish a genotype having best performance in a particular environment and, identify mega-environments within target region based on the specifically adapted genotypes (Yan and Kang, 2002).

Due to the ubiquitous presence of G×E interaction effects and the availability of wide variation in melons for the traits of interest, we hypothesized that some genotypes would give differential response for yield and quality traits across the different environments. The specific aim of the study was to evaluate nine melon genotypes including five commercial cultivars and four elite breeding lines grown in nine environments comprising of three locations and three years. Estimates of G×E interaction might be helpful to exploit genotypic and environment interactions in order to develop cultivars which would be higher yielding and possess good quality, including enhanced levels of phytochemicals over different environments.

2.2 Materials and methods

Five commercial cultivars Mission, Journey, Orange Dew, Oro Duro, Sol Real and four advanced breeding lines TAMU 146, TAMU Orange Casaba, TAMU F39, and TAMU 1405 from the melon breeding program at Texas A&M University were evaluated in this study (Table 2.1). Genotypic evaluations were conducted at College Station, (30° 36” N, 96° 18” W), Uvalde (29° 13” N, 99° 45” W), and Weslaco (26.12° N, 98.0° W) in Texas during 2010, 2011 and 2012. Soil textures of College Station, Weslaco and Uvalde were sandy loam, sandy clay loam and clay respectively. The seasonal rainfall and maximum and minimum temperatures and RH during the 2010, 2011 and 2012 seasons are given in Table 2.2. Thus, the locations were representative of different soil types, and climatic conditions.

The seeds of commercial genotypes were obtained from the following sources: Mission from Seminis Vegetable Seeds, Inc., St. Louis, MO; Journey and Oro Duro from Sakata Seed America, Morgan Hill, CA, Sol Real from Syngenta International AG, Basel, Switzerland, and Orange Dew from Shamrock Seed Company, Inc., Salinas, CA.

The experiment was designed as a randomized complete block design with four replications of nine melon genotypes. Seeds were planted on raised beds (2.03 m between, 0.30 m with in row spacing) covered with black plastic mulch. Planting dates are given in Table 2.2. The crop was subsurface drip irrigated with drip tape (Netafim, 1.14 L h^{-1}, 30 cm emitter spacing) placed at 15 cm depth. The irrigation was applied based on the daily crop evapotranspiration (ETc) as described in Sharma et al. (2014).

Table 2.1 Characteristics of the genotypes included in the study

Code	Genotype	Source	Descriptive traits
146	TAMU146	TAMU	Open-pollinated, *reticulatus* group, medium fruit size, round/ oval, uniform, dense and high netting, dark orange flesh, good firmness, medium maturity, and compact seed cavity
OC	TAMU OC	TAMU	Open-pollinated, *inodorus* group/ orange casaba, large fruit size, fruit shape oval, creamy white smooth skin, orange flesh, high firmness, late maturity, and large and loose seed cavity
F39	TAMU F39	TAMU	Open-pollinated, *reticulatus* group, medium fruit size, round/ oval, uniform, dense and high netting, dark orange flesh, good firmness, medium maturity and compact seed cavity
1405	TAMU 1405	TAMU	Open-pollinated, *reticulatus* group, medium to large fruit size, round/ oval, uniform, dense and high netting, dark orange flesh, high firmness, late maturity and compact seed cavity
Ogdw	Orange Dew	Shamrock Seed Company, Inc.	Open-pollinated, *inodorus* group, large fruit size, oval/ round, creamy white smooth skin, salmon orange flesh, high firmness, and late maturity
MSN	Mission	Seminis Vegetable Seeds, Inc.	F1 hybrid, *reticulatus* group, medium fruit size, round/ oval, uniform and medium high netting, dark orange flesh, medium maturity, high sugar content and small seed cavity
Ord	Oro Duro	Sakata Seed America	F1 hybrid, *reticulatus* group, medium size, round, good netting, yellow flesh, good firmness, mid maturity and seed cavity closed
Slr	Sol Real	Syngenta International AG	F1 hybrid, *reticulatus* group, round, good netting, yellow flesh, good firmness, early maturity and tight seed cavity
Jrny	Journey	Sakata Seed America	F1 hybrid, *reticulatus* group, large size, oval, average netting, yellow flesh, medium firmness, early maturity, and loose seed cavity

Table 2.2 Monthly maximum and minimum temperature and rainfall during 2010, 2011 and 2012 seasons, Uvalde, TX

Env. Code	Location	Year	Rainfall	Temperature (°C)			Planting	Duration
			mm	Min.	Max.	Mean	date	Days
CS10	College Station	2010	400	19	29	24	9-Apr	94
CS11		2011	149	21	32	26	1-Apr	96
CS12		2012	518	21	31	26	5-Apr	94
U10	Uvalde	2010	154	19	31	25	9-Apr	126
U11		2011	129	21	34	27	1-Apr	126
U12		2012	216	20	32	26	15-Apr	106
W10	Weslaco	2010	463	22	31	26	9-Apr	95
W11		2011	197	23	32	28	3-Mar	119
W12		2012	399	23	33	28	18-Mar	91

Insecticide (thiamethoxam, Actara 25 WG, Syngenta, Greensboro, NC), acaricide (Spiromesifen, Oberon® 2 SC, Bayer Crop Science, Research Triangle, NC), fungicide (Trifloxystrobin, Flint® 50 WG, Bayer Crop Science, Research Triangle, NC) were applied at label rates to control white flies (*Bemisia tabaci* Gennadius) and leaf miner (*Liriomyza sativae* Blanch.), mites (*Tetranychus* spp.), and Powdery Mildew (*Sphaerotheca fuliginea* Schlecht.), respectively. Weed control and other practices were consistent with the recommended cultural practices for the regions.

2.2.1 Fruit yield and component traits

Fruits were harvested at half to full slip stage. At each harvest, fruits were counted and graded according to the U.S. commercial trade standards (9-, 12-, 15-, 18-count per 18 kg carton). Fruits that were cracked, damaged, rotten, misshapen, and below commercial categories were grouped under the non-marketable category. Fruit number per plant (FN), average fruit weight (FW; kg), marketable fruit yield (MFY; $t \cdot ha^{-1}$) and total fruit yield (TFY; $t \cdot ha^{-1}$) were recorded. FN was recorded by counting all

fruits from the plot divided by total number of plants. FW was recorded by dividing the total yield by the total number of fruits harvested.

2.2.2 Fruit quality

Fruit quality parameters were determined on three 9 or 12-count class fruits from each plot. Fruits were cut at equatorial position, and firmness was measured on the mesocarp tissue at three random locations per fruit using a digital force meter (DFM 10; Chatillon, Greensboro, N.C.) and soluble solids content (SSC) of the mesocarp tissue (~ 1 cm from the rind) was measured with a digital refractometer (PR-101; Atago Co. Ltd., Tokyo, Japan) (Leskovar et al., 2006; Sharma et al., 2014).

A 100 g sample of edible mesocarp tissue was collected from the same fruits used for above measurements and the samples were stored at -80° C until used for vitamin C and β-Carotene analysis. β-carotene was measured using the procedure described by Sadler et al. (1990) with some modifications. Total ascorbic acid/vitamin C (TA), free ascorbic acid (AA) and dehydroascorbic acid (DHA) were extracted from 10 g of frozen (-80° C) tissue and were determined by using a high performance liquid chromatography (HPLC) analysis method using UV-vis at 254 nm, as described in Sharma et al. (2014) and Wimalasiri and Wills (1983).

2.2.3 Statistical analysis

2.2.3.1 Analysis of variance

Analysis of variance (ANOVA) was performed using a generalized linear model procedure (SAS 9.2 version, SAS Inst., Cary, N.C., USA) to test the significance of G×E interactions. Year by location interactions were considered as environments (i.e. nine)

and analysis was performed as described by McIntosh (1983). The percentages of G, E, and G×E sum of squares of the total variation of three sources (E + G + G×E) have been used to indicate the magnitude of variation contributed by each component (Yan, 2001; Meredith, 2012). When the data did not conform to model assumptions, Box-Cox procedure was used to determine appropriate transformation to establish an acceptable level of homogeneity of variance across main factors. Treatment differences were determined using Duncan's multiple range tests.

2.2.3.2 Biplot analysis and its interpretation

The parameters that had significant G or G×E interaction effects were analyzed with the stability analysis software called GGE Biplot (Yan, 2001). Stability and mean performance of commercial and elite TAMU breeding lines were determined. The environment centered model ($Y_{ij} - \mu - \beta_{j} = \alpha_i + \Phi_{ij}$) was used to construct GGE biplots, where the E main effect (β_j) is removed, and the biplot contains only G (α_i) and GE (Φ_{ij}), which are the two sources of variation that are most relevant for genotype by environment evaluations. The two way genotype by environment data matrix was decomposed to principle components (PC) through singular value decomposition. The singular values of PC1 and PC2 were further divided in to genotype and environment eigenvectors to construct meaningful biplots. Thus, GGE biplot graphically presents the multi-environment data in two dimensions through principal components PC1 and PC2 which, are unit-less measures and are depicted on the x- and y-axis of a biplot, respectively. The percentage of total variation explained by PC1 and PC2 was presented

on the biplot which indicates it's validity of approximation of G and G×E components for the trait investigated.

GGE biplot is a versatile software that can generate different views of biplots. The average environment coordination view is used for ranking the genotypes based on mean performance and stability (e.g. Fig. 2.1). This graph has two lines, the average environment axis (AEA) or average environment coordination (AEC) abscissa, and the AEC ordinate. AEA (in red color) is the single arrowed line, which passes through the origin of the biplot and also through the hypothetical average environment, denoted by the circle near W11. The direction of the arrow head on the AEA points to higher mean values for the measured trait; in this case total fruit yield (TFY), thus TAM1405 and Journey had the lowest and highest TFY, respectively. The second line, the AEC ordinate (in blue color) also called the stability line, has arrow heads at both ends. This line also passes through the origin of the biplot and goes perpendicular to the AEA. The arrows on both the ends of AEC ordinate point to the higher instability (or greater variability) in either direction. Thus the shorter the projection or distance from AEA, the more stable or less variable the performance of the genotype among tested environments, and vice versa, i.e. TAMU 146 and TAMU OC are the most stable and unstable genotypes for TFY, respectively (Yan and Tinker, 2006). The environments are represented in upper-case italics letters (codes are as described in Table 2.2) and the genotypes are written in lower-case letters (codes are as described in Table 2.1).

The polygon view of the biplot presents which genotypes performed the best in one or more environments (Fig. 2.2d). These the best performing genotypes in specific

environments are described as winning genotypes. The lines originating from the center of the biplot and perpendicular to the sides of the polygon divide the plot in different sectors. The winning genotypes for each sector are the ones located on the vertex of the polygon, i.e. TAMU OC was the winning genotype in W10 and W12 environments. Fig. 2.3 depicts the discriminative and representativeness ability of the GGE biplot. The environment having a smaller angle with the AEA is more representative of other test environments. The longer vector length which is proportional to standard deviation with in the respective environment indicates greater discriminating ability of the environment. Thus, environments with representativeness and discriminating ability are good for selecting generally adapted genotypes, while the environment with discriminating ability, but not representativeness is good for selecting specifically adapted genotypes. For instance U10 is the representative environment for TFY (Yan and Tinker, 2006). GGE Biplot also calculates a stability statistics (S_i), an indicator of consistent performance, for all genotypes, a greater absolute value of this statistic means a greater contribution to G×E and less stable genotypes.

2.3 Results

2.3.1 Analysis of variance of G, E and GE components

Tables 2.3 and 2.4 depict the ANOVA, t-test (*P*-values), and the relative magnitudes of G, E, and G×E variance components for nine traits. Table 2.3 consists of four yield traits and its component traits that show G, E, Y, and L components of variance and their interactions, while Table 2.4 involves five fruit quality traits. Variation attributed to G or G×E is an indicator of genotypic response across

environments or their differential response to different environments. The environmental component (E) shows how the mean performance melon genotypes differ among environments. Irrespective of trait, the genotypic (G) contribution to total variation ranged from 5 to 58%, the E ranged from 20 to 83%, and G×E ranged 8 to 48% (Table 2.3, 2.4). Overall, the environment (E) contributed more than 70% of the total variation for yield and FN, while in FW the E contribution was 24%. The contribution of G to the total sum of squares was relatively small in TFY (5%), MFY (9%), and FN (9%) (Table 2.3). The higher percentage of total variation attributed to G for FW (58%) as compared to FN (9%), suggested that G was relatively more important in FW than FN. Furthermore, G×E contribution was also higher in FW (18%) than FN (8%) which indicates that FW was more responsible for fluctuations in TFY and MFY across environments than FN.

In fruit quality traits, the E contributed less than 70% of the total variation, except for Vitamin C where the E contribution was 73% (Table 2.4). In general, the G contribution to the total variation was higher for quality traits as compared to yield traits with the highest in β-carotene (54%), suggesting that G was relatively more important in β-carotene as compared to vitamin C where G contributed only 16% to the total variation. Furthermore, G×E contribution was higher in DHA (48%) compared to other quality traits, which led to the differential response of melon genotypes across environments for vitamin C.

Overall, TFY, MFY, FN, firmness, β-carotene and vitamin C content was higher in 2012 than in 2010 and 2011, while the highest FW and the lowest SSC were recorded

Table 2.3 ANOVA of genotype (G), environment (E), and genotype × environment (G×E) and percent contribution of G, E, and G×E to total variation of yield and components in melons

Trait	Source	DF	SS	*P*-value	% of total variation
TFY	G	8	59.3	<0.0001	5
	E	8	909.8	<0.0001	83
	Y	2	45	<0.0001	4
	L	2	783.5	<0.0001	72
	Y×L	4	81.1	<0.0001	7
	G×E	64	124.9	0.0055	11
	G×Y	16	47.3	0.0019	4
	G×L	16	41.2	0.0077	4
	G×Y×L	32	36.4	0.5564	3
MFY	G	8	69.3	<0.0001	9
	E	8	557.4	<0.0001	70
	Y	2	66.9	<0.0001	8
	L	2	438.8	<0.0001	55
	Y×L	4	51.9	<0.0001	7
	G×E	64	165.8	<0.0001	21
	G×Y	16	45.6	0.0025	6
	G×L	16	51.3	0.0006	6
	G×Y×L	32	68.6	0.0077	9
FN	G	8	5.6	<0.0001	9
	E	8	49.5	<0.0001	83
	Y	2	4.5	<0.0001	8
	L	2	41.3	<0.0001	69
	Y×L	4	3.6	<0.0001	6
	G × E	64	4.7	0.0008	8
	G×Y	16	1.3	0.0129	2
	G×L	16	2.3	<0.0001	4
	G×Y×L	32	1.1	0.6548	2
FW	G	8	55.8	<0.0001	58
	E	8	22.9	<0.0001	24
	Y	2	3.5	<0.0001	4
	L	2	14.1	<0.0001	15
	Y×L	4	5.4	<0.0001	6
	G×E	64	17.3	<0.0001	18
	G×Y	16	4.3	0.0002	4
	G×L	16	4.4	0.0001	5
	G×Y×L	32	8.7	<0.0001	9

TFY = total fruit yield, MFY = marketable fruit yield, FN = fruit number per plant, FW = average fruit weight, Total variation = G + E + G×E

Table 2.4 ANOVA of genotype (G), environment (E), and genotype × environment (G×E) and percent contribution of G, E, and G×E to total variation of quality traits in melons

Trait	Source	DF	SS	*P*-value	% of total variation
Firmness	G	8	5921	<0.0001	19
	E	8	17031	<0.0001	54
	Y	2	4768	<0.0001	15
	L	2	5498	<0.0001	17
	Y×L	4	6765	<0.0001	21
	G×E	64	8548	0.2877	27
	G×Y	16	2430	0.005	8
	G×L	16	1271	0.3008	4
	G×Y×L	32	4847	0.0003	15
SSC	G	8	306	<0.0001	17
	E	8	1182	<0.0001	65
	Y	2	433	<0.0001	24
	L	2	533	<0.0001	29
	Y×L	4	216	<0.0001	12
	G×E	64	327	<0.0001	18
	G×Y	16	145	<0.0001	8
	G×L	16	73	0.006	4
	G×Y×L	32	109	0.021	6
β-Carotene	G	8	6614	<0.0001	54
	E	8	2336	<0.0001	19
	Y	2	1061	<0.0001	9
	L	2	186	0.001	2
	Y×L	4	1089	<0.0001	9
	G×E	64	3266	<0.0001	27
	G×Y	16	910	<0.0001	7
	G×L	16	542	0.001	4
	G×Y×L	32	1814	<0.0001	15

Table 2.4 Continued

Trait	Source	DF	SS	*P*-value	% of G+L+GL
DHA	G	8	45011	0.4015	6
	E	8	354138	<0.0001	46
	Y	2	141019	0.0002	18
	L	2	202451	<0.0001	26
	Y×L	4	10668	0.853	1
	G×E	64	375300	0.1647	48
	G×Y	16	51115	0.9809	7
	G×L	16	115857	0.5513	15
	G×Y×L	32	208328	0.7399	27
Vitamin C	G	8	736302	<0.0001	18
	E	8	3014529	<0.0001	72
	Y	2	726331	<0.0001	17
	L	2	1558236	<0.0001	37
	Y×L	4	729962	<0.0001	17
	G×E	64	453705	0.0216	11
	G×Y	16	118618	0.3640	3
	G×L	16	71417	0.8352	2
	G×Y×L	32	263670	0.2083	6

SSC = soluble solids content, DHA= dehydro-ascorbic acid, total variation = G + E + G×E

in 2010. Among locations, the highest values for TFY, MFY, FN, firmness, and vitamin C content were recorded at Uvalde, while the highest FW and SSC were recorded at Weslaco and College Station, respectively (Table 2.5).

For the traits in which G×E contributed significantly to the total variation, the genotypes responded differently to a stimulus (i.e. a change across environments that influences the phenotypic expression of those traits, for example soil type) in the tested environments. Thus, the specifically better performing genotypes in a particular environment and/or most suitable environments can be identified and exploited for the traits of interest. Except DHA, all variables were significant ($P \leq 0.05$) for either G and/or G×E (Table 2.3, 2.4), indicating that the analysis in GGE Biplot was appropriate for these traits (Yan and Tinker, 2006).

2.3.2 GGE biplot analysis of fruit yield and component traits

2.3.2.1 Total fruit yield

The mean TFY of all genotypes ranged from 48.0 (TAM 1405) to 69.4 $t \cdot ha^{-1}$ (Journey) and grand mean TFY was 54.8 $t \cdot ha^{-1}$. Stability statistics ranged from - 0.011 to -1.307 (Table 2.6). Fig. 2.1a indicates that TAMU breeding line 146 was most stable for TFY, but had a lower mean TFY than that of the grand mean. Orange Dew (-0.133), and Mission (-0.171) followed TAM 146 in stability. Mission also had higher TFY than the grand mean. In contrast, the longest vector length of TAMU OC from the AEA indicates this genotype having the lowest stability for TFY, thus contributing to large G×E interactions.

Table 2.5 Effect of years and locations on fruit yield and quality traits of melon genotypes

Source	TFY	MFY	FN	FW	Firmness	SSC	β-carotene	Vitamin C
	$t \cdot ha^{-1}$	$t \cdot ha^{-1}$	No.	kg	N	%	$\mu g \cdot g^{-1*}$	$\mu g \cdot g^{-1}$
Year								
2010	49.6 b[z]	32.5 c	1.6 c	4.0 a	24.6 c	8.4 b	19.9 b	185.8 c
2011	53.3 b	37.2 b	2.1 b	3.1 b	27.0 b	10.2 a	21.1 b	230.7 b
2012	62.7 a	46.1 a	2.4 a	3.7 a	31.6 a	10.4 a	23.6 a	287.8 a
Location								
College station	31.4 c	24.7 c	1.0 c	2.6 c	24.4 c	9.6 b	23.4 a	235.3 b
Uvalde	88.4 a	60.1 a	3.5 a	4.0 b	31.6 a	10.9 a	20.8 b	304.0 a
Weslaco	52.4 b	34.0 b	1.8 b	4.3 a	27.1 b	8.6 c	21.3 b	177.0 c

[*] vitamin C and β-carotene were determined on fresh weight basis

[z] Means in a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test

TFY = total fruit yield, MFY = marketable fruit yield, FN = fruit number per plant, FW = average fruit weight, SSC = soluble solids content

Table 2.6 Mean and stability statistic of total fruit yield, marketable fruit yield, fruit weight, and fruit number of melon genotypes

	TFY		MFY		FW		FN	
Genotype	Mean	S_i	Mean	S_i	Mean	S_i	Mean	S_i
Journey	69.4	0.391	49.8	0.461	2.3	0.662	2.2	-1.044
Mission	59.7	-0.171	42.7	-0.204	1.6	-0.025	2.6	0.304
Orange Dew	48.7	-0.133	38.3	-0.374	1.8	0.265	1.8	0.097
Oro Duro	63.4	0.839	42.5	1.004	1.6	-0.010	2.8	-0.720
Sol Real	59.3	0.352	41.4	0.307	1.7	-0.218	2.6	0.256
TAMU 1405	48.0	-0.309	31.5	-0.109	1.8	0.111	1.9	0.081
TAMU 146	54.3	-0.011	31.9	-0.308	1.6	-0.200	2.3	0.253
TAMU F39	56.5	0.349	37.7	0.417	1.8	0.176	2.2	0.076
TAMU OC	66.2	1.307	50.2	1.193	2.9	-0.763	1.5	0.698

S_i = Stability statistics

Discriminative and representative views of the GGE biplot showed that U10 and U12 were the most representative environments for TFY. Moreover, U10, U11 and U12 showed good discriminative ability among genotypes for TFY. Thus, overall the Uvalde location can be a good environment for selecting generally adapted genotypes for south-central Texas (Fig. 2.1b).

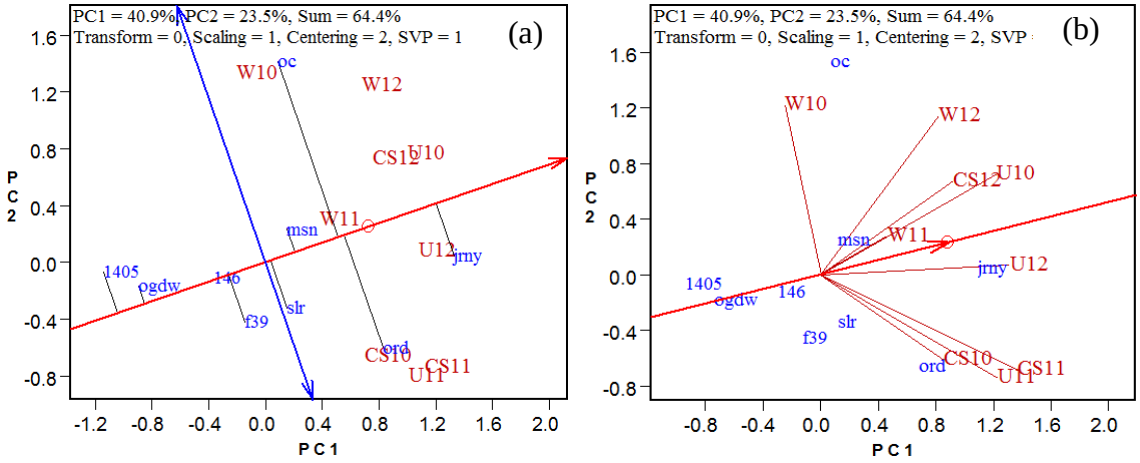

Figure 2.1 Average coordination view of biplot (a), and discrimination and representativeness view of biplot (b) for total fruit yield.

The biplot analysis for the different locations indicated a change in ranking of genotypes based mean performance and stability for TFY, with TAMU OC having the highest mean TFY at Weslaco, while Journey producing the highest TFY at College station and Uvalde (Fig. 2.2a, 2.2b, 2.2c). Furthermore, significant G×L interactions (P = 0.008), justified the use of a site regression (SREG) model for analysis of TFY (Table 2.3). The polygon view of the biplot indicated that TAMU OC was specifically adapted to W10 and W12 environments; however, W11 also occurred close to the sector line

(Fig. 2.2d). These results suggested that TAMU OC was specifically adapted to Weslaco. Similarly, Journey showed better performance at the U12 and U10 environments, and Oro Duro in CS10 and CS11. This indicates that Journey and Oro Duro were specifically suited for cultivation in Uvalde and College Station respectively. The performance varied among years, indicating non-repeatable GE interactions. Except for TAMU OC, open pollinated genotypes produced less TFY than the grand mean.

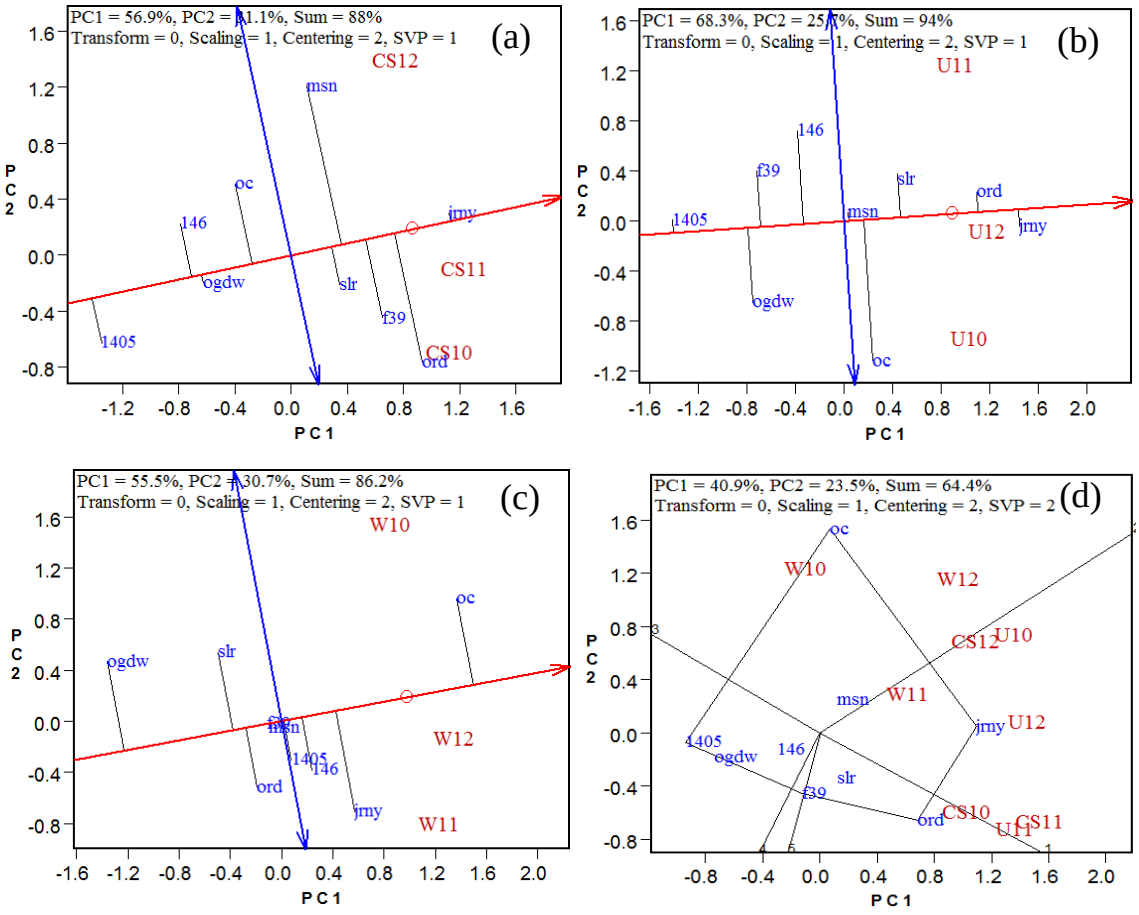

Figure 2.2 Average coordination view of biplot for College Station (a), Uvalde (b), Weslaco (c) and polygon view (d) of biplot for total fruit yield

2.3.2.2 Marketable fruit yield

Similar to TFY, mean MFY ranged from 31.5 (TAMU 1405) to 49.8 t·ha^{-1} (Journey) with a grand mean of 38.4 t·ha^{-1}. The stability statistics ranged from - 0.109 (TAMU 1405) to -1.193 (TAMU OC) (Table 2.6). Biplot analysis for MFY indicated that the trend in mean performance and stability rankings were similar to TFY with Journey ranking the highest followed by TAMU OC and Oro Duro (Fig. 2.3a). Mission was the second most stable (-0.204) genotype after TAMU 1405 for MFY, with a mean MFY (42.7 t·ha^{-1}) higher than the grand mean. Contrary to the TFY, TAMU 146 ranked lower than Orange Dew for mean MFY and stability. TAMU breeding lines TAMU 1405 and TAMU 146 had the lowest mean MFY, whereas TAMU F39 ranked equivalent to Orange Dew and 2% (38.4 vs. 37.7 t·ha^{-1}), lower than the grand mean.

Similar to TFY, TAMU OC performed better in W10 and W12, Journey in U12, and Oro Duro in CS10, and CS11 environments which indicated that TAMU OC, Journey and Oro Duro were specifically suited for cultivation in Weslaco, Uvalde and College Station, respectively.

Discriminative and representative views of the GGE biplot showed that U10, U11 and U12 were the most representative environments. Moreover, these environments showed good discriminative ability among genotypes for MFY. Thus, overall the Uvalde location can be an ideal environment for selecting generally adapted genotypes for MFY in south-central Texas (Fig. 2.3b).

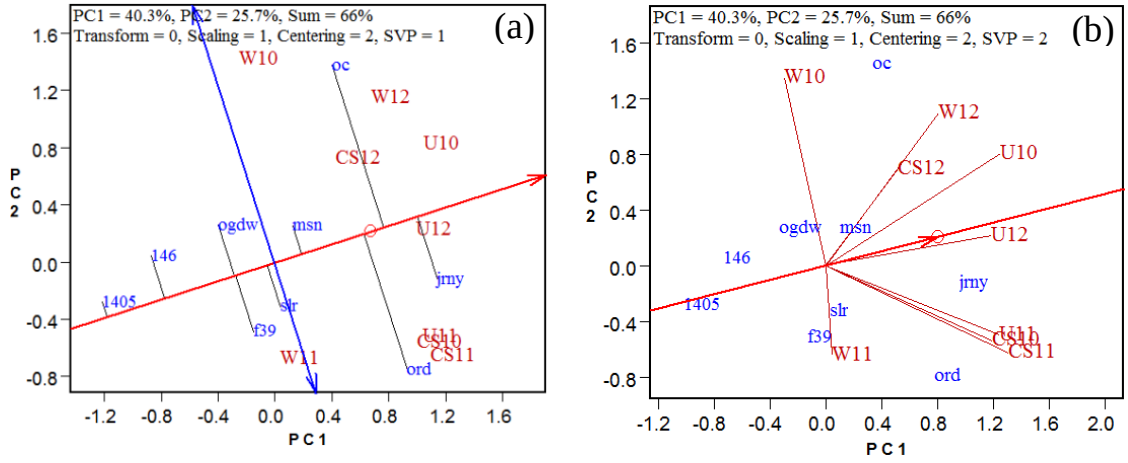

Figure 2.3 Average coordination view of biplot (a), and discrimination and representativeness view of biplot (b) for marketable fruit yield

2.3.2.3 Fruit number and fruit weight

Since the G component contributed 58% of the total variation for FW, there was no apparent specific adaption to a particular environment observed (Fig. 2.4a). Based on mean and stability, TAMU OC ranked the highest for mean FW followed by Journey. Oro Duro (-0.010) followed by Mission (-0.025) were the most stable genotypes, while TAMU OC was most variable for fruit weight (-0.763) (Table 2.6)

The mean FN ranged from 1.5 (TAMU OC) to 2.8 (Oro Duro) fruits per plant with a grand mean of 1.96 fruits per plant. Stability statistics ranged from 0.076 (TAMU F39) to -1.044 (Journey) (Table 2.6). The average coordinate view of the GGE biplot for FN indicated that the genotype Mission ranked second for mean FN with stability statistics of 0.304 followed by Sol Real. Breeding lines, TAMU F39 and 146 had above average FN values.

2.3.3 Fruit quality traits

2.3.3.1 Fruit firmness

The mean fruit firmness of all genotypes ranged from 21.5 (Oro Duro) to 33.2 N (Orange Dew) with grand mean of 27.9 N. Stability statistics ranged from 0.053 (Orange Dew) to -0.809 (TAMU OC) (Table 2.7). The average coordinates view of the GGE biplot for firmness indicated that genotype Orange Dew ranked highest for mean fruit firmness and stability statistics, followed by TAMU OC for highest mean firmness.

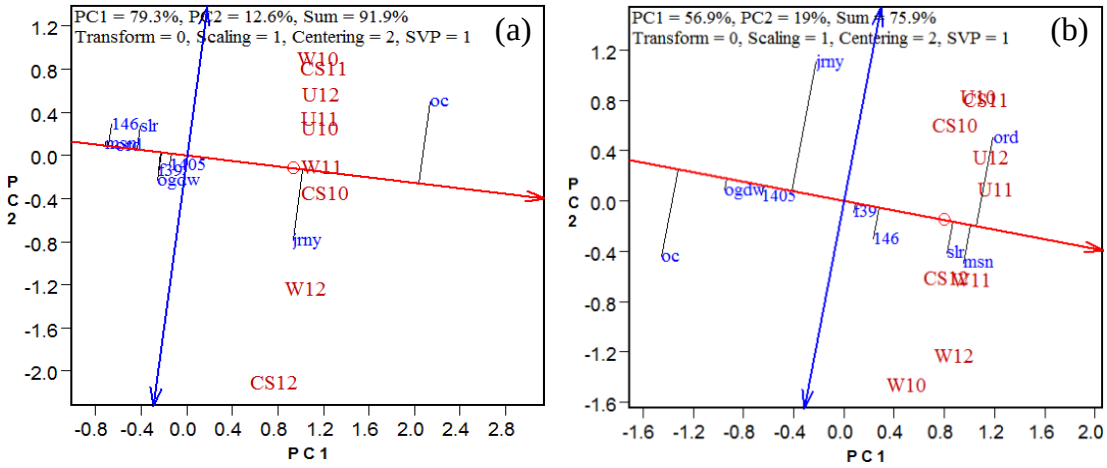

Figure 2.4 Average coordination view of biplot for fruit weight (a) and fruit number (b)

However, this was the most unstable genotype. Mission ranked second for stability having mean fruit firmness higher than the grand mean. Breeding lines, TAMU 146 and 1405 had a mean firmness higher than Sol Real and Oro Duro, as well as the grand mean. The environment U10 and U12 had the shortest projections from AEA axis, while in 2011, U11 and CS11 markers had the same projection and distance from the biplot

origin. These results indicated that overall the Uvalde location was most representative with similar discriminative ability for evaluating melon cultivars for firmness.

Table 2.7 Mean and stability statistic of firmness, soluble solids content (SSC), β-Carotene, and vitamin C of melon genotypes

	Firmness (N)		SSC (%)		β-Carotene $\mu g \cdot g^{-1}$ FW		Vitamin C $\mu g \cdot g^{-1}$ FW	
Genotype	Mean	S_i	Mean	S_i	Mean	S_i	Mean	S_i
Journey	26.5	-0.482	9.5	0.517	21.5	0.263	231	0.107
Mission	28.6	-0.084	10.0	0.561	23.9	0.033	286	0.406
Orange Dew	33.2	0.053	11.2	-0.192	19.5	-0.789	233	0.554
Oro Duro	21.5	0.141	9.7	0.225	25.8	-0.088	276	-0.159
Sol Real	26.0	-0.092	9.8	-0.156	23.1	0.454	260	-0.204
TAMU 1405	28.3	-0.766	9.1	0.091	22.0	0.118	244	-0.348
TAMU 146	28.8	-0.189	8.7	0.232	25.7	-0.299	174	0.366
TAMU F39	24.9	0.610	8.7	-0.001	21.3	0.108	253	-0.579
TAMU OC	30.6	0.809	9.9	-1.276	11.5	0.199	156	-0.142

S_i = Stability statistics

2.3.3.2 Soluble solids content

The mean SSC of all genotypes ranged from 8.7 (TAMU 146, TAMU F39) to 11.2 (Orange Dew) with grand mean of 9.7° brix. The stability statistics ranged from -0.001 (TAMU F39) to -1.276 (TAMU OC) (Table 2.7). The average coordinate view of the GGE biplot indicated that the genotype Orange Dew ranked highest followed by Mission for mean SSC (Fig. 2.5b). The polygon view of the biplot indicated that TAMU OC had specific adaptation to W11 while Orange Dew had specific adaption to U10, U11, U12, and CS11 environments (Fig 2.5c). These results suggested that TAMU OC

was specifically adapted to the Weslaco location, while Orange Dew to the Uvalde location. Environment W10 had the shortest projection from AEA axis, while in 2011 and 2012, U11 and U12 markers had the shortest projection from AEA axis and longest distance from the biplot origin. These results indicated that overall the Uvalde location was the most discriminative and representative environment for evaluating melon cultivars for SSC (Fig. 2.5d).

2.3.3.3 β-carotene

The genotypic (G) component contributed 54% to the total variation, which was higher than the G×E component (Table 2.4). Oro Duro had the highest mean β-carotene content (25.8 $\mu g \cdot g^{-1}$) of all genotypes followed by TAMU 146 (25.7 $\mu g \cdot g^{-1}$).The genotype Mission had the lowest stability statistics (0.033) with a mean β-carotene content of 23.9 $\mu g \cdot g^{-1}$, which was higher than the grand mean (Table 2.7, Fig. 2.6 a). The environment W11 had the shortest projection from AEA axis, while CS12 had the longest projection. These results indicated that, overall, the Weslaco location was the most representative and discriminative environment for evaluating melon cultivars for β-carotene (Table 2.7, Fig. 2.6a).

2.3.3.4 Vitamin C

Similar to β-carotene, the G contribution was higher than that of G×E (16 vs. 10%) to the total variation for vitamin C content (Table 2.4). The mean vitamin C of all genotypes ranged from 155.8 (TAMU OC) to 285.8 $\mu g \cdot g^{-1}$ (Mission) (Fig. 2.6b). Journey (0.107), and Orange Dew (0.554) were the most stable and variable genotypes for vitamin C content, respectively. However, Mission had an average stability (0.406) with

the highest mean vitamin C content. TAMU 1405 and TAMU F39 had a mean vitamin C contents higher than the grand mean. No systematic patterns were observed for locations or specific adaptability of melon genotypes for vitamin C content.

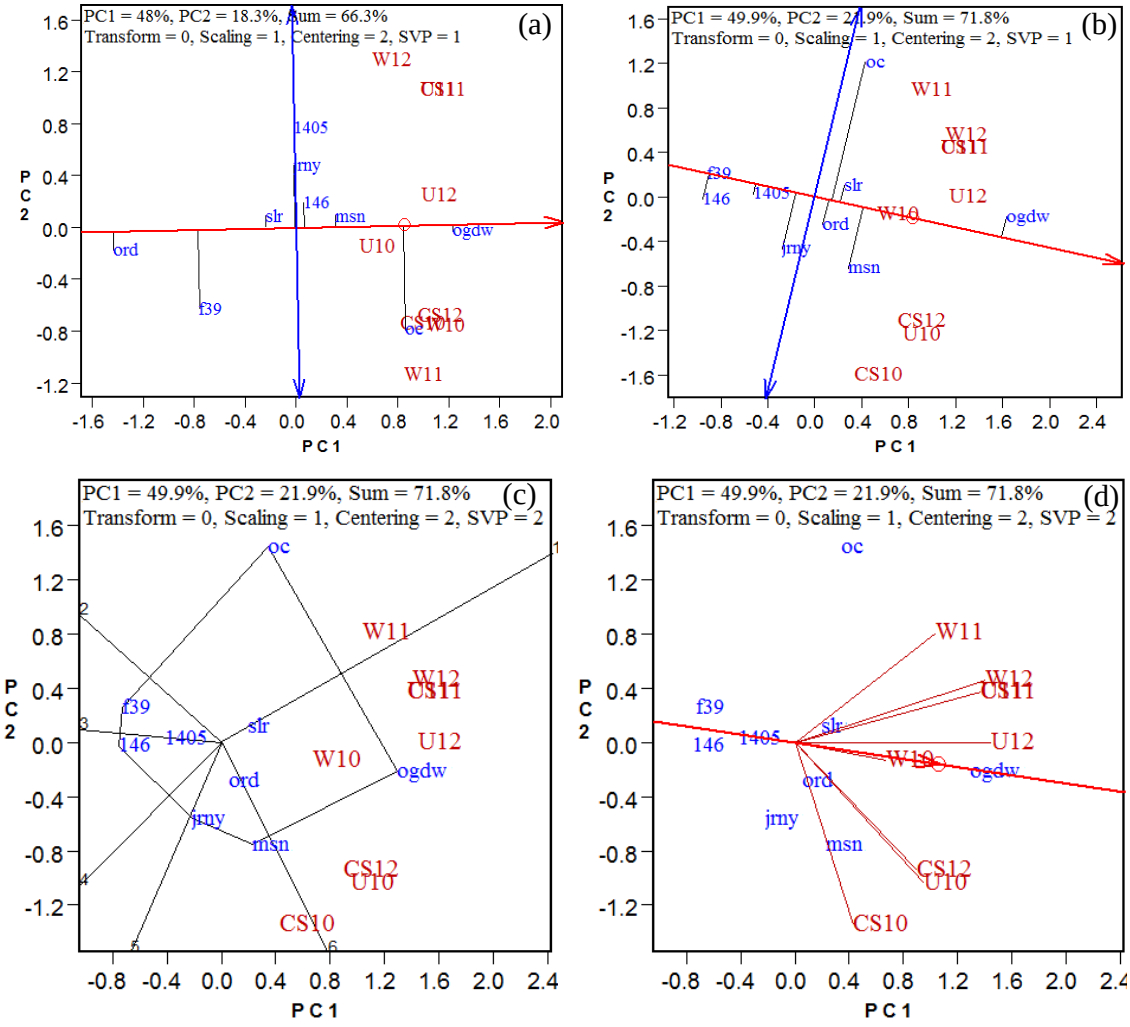

Figure 2.5 Average coordination view of biplot for fruit firmness (a), and average coordination view (b) and discrimination and representativeness view (c) and polygon view (d) of biplot for soluble solids content

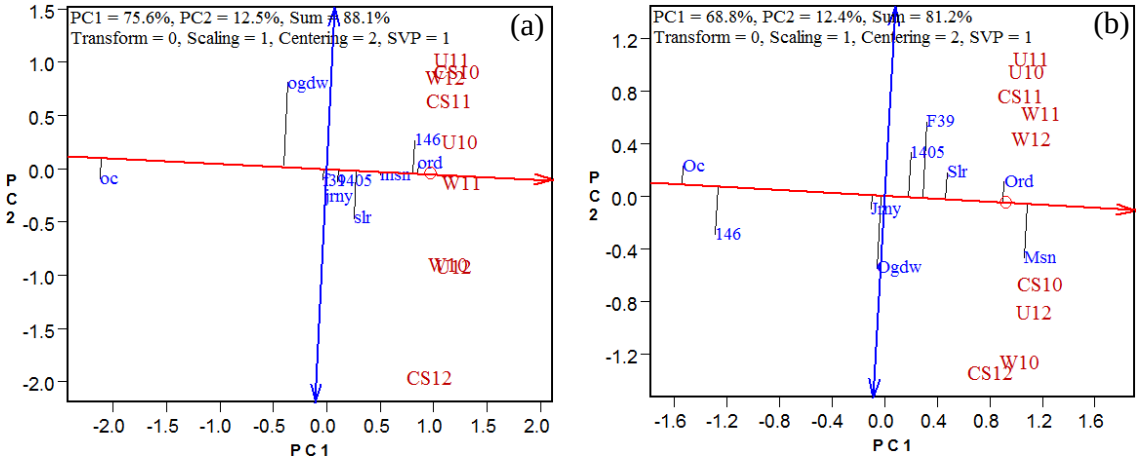

Figure 2.6 Average coordination view of biplot for β-carotene (a) and vitamin C (b)

2.4 Discussion

Selection of genotypes for high mean yield performance and stability is critical for crop production in semi-arid regions around the world. In these regions, the growing environments are usually unpredictable due to erratic rainfall distribution both in space and time, which causes genotypic responses to vary across environments (Cattivelli et al., 2008). This becomes more important in crops like melon where acceptable marketable fruit quality (i.e. firmness, level of SSC and phytonutrients) is also equally important as much as fruit yield. In a genotype by environment interaction on muskmelons, Wolf et al. (1994) emphasized the need of multiple year and location evaluations for selecting stable and high yielding cultivars.

In this experiment, fruit yield and the quality of nine melon genotypes from *reticulatus* (Mission, Oro Duro, Sol Real, Journey, TAMU 146, TAMU 1405, and

TAMU F39) and *inodorus* (TAMU Orange Casaba and Orange Dew) groups were evaluated over nine environments.

2.4.1 Fruit yield and its components

2.4.1.1 Characterization of G×E for fruit yield and its components

Environmental and G×E can have significant effects on melon fruit yield (Kultur et al., 2001; Dhakare and More, 2008). Similar to the previous studies, the E component accounted for more than 70% of the total variation in MFY, TFY and FN (Kang, 2002; Dhakare and More, 2008). Further, Meredith (2012) pointed out that traits with high heritability are typically less influenced by the environment. They reported that E contribution to boll weight was 45% as compared to 86% to cotton lint yield. Similarly in the current study, E contributed 24% in FW as compared to 83% in TFY (Table. 2.3).

Except in FW, the genotypic contribution to the total variation in TFY, MFY and FN was considerably lower than the E contribution (Table. 2.3). However, G contributions to the total variation were highly significant for all fruit yield traits. The G to G×E ratio in FW was 3.2 as compared to 1.3 in FN, indicating the high heritability of FW in melons and thus, FW was less influenced by the environment than FN.

The genotype by environment interactions ranged from 8 to 21% among the yield traits. The magnitude of G×E variance as compared to G, indicated that multi-environment cultivar evaluations are critical in muskmelon breeding programs (Meredith, 2012). Furthermore, genotype (G) by year (Y) interactions were also highly significant for yield traits, suggesting that G×Y interactions are important to consider for developing stable cultivars adapted for a specific location (Joshi et al., 2011). The

genotype (G) by location (L) interactions were also significant for these traits, indicating the need of regionalization of melon breeding programs (Meredith, 2012). In a planting density study on two locations, Kultur et al. (2001) found that G×L interactions had significant effects on FN, FW, and TFY in melons. Furthermore, Wolf et al. (1994) also reported significant G×Y×L interactions for marketable fruit yield in melons and attributed these differential responses to climate fluctuations, planting date, and stress factors.

2.4.1.2 Biplot analysis for fruit yield and its components

A genotype with mean performance and low instability or less variability in yielding ability across a set of test environments is considered a stable or ideal genotype for that mega-environment, for a particular trait (Kang, 2002; Joshi et al., 2011). Biplot analysis of TFY and MFY indicated that Mission was an ideal genotype, which had good stability along with average productivity greater than the grand mean. TAMU OC, Oro Duro and Journey were the most variable genotypes across environments, and were specifically adapted to Weslaco, College station and Uvalde locations, with yearly fluctuations. Thus, more yearly evaluations are needed to confirm these results. TAMU F39 was more stable and better performing than Mission at College Station (Fig. 2.2a) and similar to Mission at Weslaco. Overall, TAMU F39 produced almost equivalent MFY to the grand mean. TAMU 146 was most consistent for TFY across environments, but it produced comparatively lower fruit yield than the grand mean (Fig. 2.1); thus it possessed biological stability (Jamshidmoghaddam and Pourdad, 2012), which indicates genotype is less responsive to environmental variation such as level of inputs. The

Uvalde location was found to be the most suitable for melon cultivar evaluations for fruit yield.

2.4.2 Fruit quality

2.4.2.1 Characterization of G×E for fruit quality traits

The impact of environment (E) was variable on fruit quality traits with E being 72% for vitamin C content, and the lowest variance attributed to the E component was 19% for β-Carotene (Table 2.4). Both years and locations had significant impacts on all the fruit quality traits. In 2012, all the fruit quality traits had maximum values which can be attributed to the drought stress experienced during the fruit development and maturity stage explained in detail in section 3.4.1. Among the locations, Uvalde had the highest firmness, SSC and vitamin C content, while College station had highest β-Carotene.

The G×L interactions (P = 0.301) were not significant statistically, but significant G×Y (P = 0.005) and G×Y×L ($P \leq 0.001$) interactions suggested that fruit firmness is more dependent upon the unpredictable component (i.e. year to year) of environmental variation (Table. 2.4). The higher G×E contribution to the total variation than the G component indicated that SSC varied over environments. The higher variation was attributed to G×Y than to G×L (8 vs. 4%). These results indicated that SSC was also more affected by the unpredictable environmental fluctuations (G×Y). Further, Kultur et al. (2001) reported significant impact of G×L interaction on percent sugar in fruit juice. The sugar accumulation in muskmelon depends upon the translocation of photo-assimilates from the leaves during the fruit ripening (Hubbard et al., 1990). Thus, the silty clay soil with higher water holding capacity at the Uvalde location coupled with

longer cropping duration might have caused more canopy growth and higher total crop photosynthesis, which resulted in higher SSC at this location (Table 2.5).

Similar trends were observed for β-Carotene, with 27% of variation attributable to G×E. However, G contributions (54%) to the total variation were highly significant for β-carotene, suggesting high heritability of this trait in melons. Crosby et al. (2007) also reported that carotenoid content changed with the flesh color and ranged from 0 in white-fleshed to 40 μg g^{-1} in dark orange-fleshed genotypes. Cultivars 'TAM Uvalde' and 'Mission' possessed more than 36 μg g^{-1} carotenoids. Lester and Eischen (1996) reported a genotypic and environment interaction impact on β-carotene content of melon fruit. They also mentioned that β-carotene content was not significantly correlated with moisture content of the mesocarp tissue. Thus, the higher rainfall at College Station and Weslaco (Table 2.1) might have reduced SSC, but maintained higher β-Carotene at College Station (Table 2.5).

Although G×E interactions were significant (P = 0.021), G×L, G×Y, G×L×Y interactions had no effect on vitamin C content. This suggests that the vitamin C concentrations in the melon fruits were independent of genotype by location or genotype by year interactions effects. Thus, the genotypes can be selected for Vitamin C content at any of the three locations. Similarly, Lee et al. (2005) observed no G×E interactions for lutein or quercetin content in peppers. Furthermore, in general the Uvalde location can be utilized for production of melons rich in vitamin C content. Moreover, sandy loam texture of Weslaco soils promoted root growth in the deeper soil layers (refer to section 3.3.3.4) , which might have enhanced the water availability to the plants and resulted in

reduced water stress at Weslaco as compared to Uvalde (Lee et al., 2005), thus low vitamin C content.

2.4.2.2 Stability analysis for fruit quality traits

Biplot analysis of fruit firmness indicated that Orange Dew was an ideal genotype while TAMU OC was most unstable genotype for fruit firmness. Both these genotypes have been selected from crosses between orange fleshed, *reticulatus* and green or white fleshed *inodorus* type melons (Lester, 2008) thus, these genotypes inherited the higher firmness from the *inodorus* group. The instability of TAMU OC can be attributed to its specific adaptation under College station and Weslaco locations. Among the cantaloupe type genotypes, Mission followed by TAMU 146 had a good stability with an above average firmness (Fig. 2.5a). Furthermore, both TAMU 146 and 1405 were better than the commercial genotypes, Sol Real and Oro Duro. Oro Duro was the second ranking genotype for TFY and the first ranking for β-Carotene content however this genotype had low firmness as the most negative attribute of fruit qulaity.

Orange Dew was identified as the ideal genotype for SSC (Fig. 2.5b). Similar to firmness, TAMU OC showed specific adaption to the Weslaco location for SSC. The suitability of the Uvalde location for cultivar evaluations for SSC can be attributed to greater differences between day and night temperatures (i.e. 12.3, 10.3 and 9.3°C for Uvalde, Weslaco and College Station, respectively), which might have resulted in higher photosynthesis and low respiration, and thus accumulation of more sugars. Yadav and Ram (2010) also reported that three melon genotypes were specially adapted for SSC under favorable environments.

Oro Duro, followed by TAMU 146, was the ideal genotype for β-carotene content, while *inodorus* type TAMU OC followed by Orange Dew ranked the lowest for mean β-carotene content. Lester and Eischen (1996) reported that Mission had higher β-carotene content than Cristobal, Primo, Cruiser and Tasty sweet genotypes and this was considered a stable genotype for β-carotene across the years. In the current study, Mission was the most stable with β-carotene content higher than the grand mean. Thus, high and stable β-carotene contents can be attained in melons through adequate cultivar selections (Lester and Eischen, 1996). In 2010, Weslaco was the most ideal environment for β-carotene evaluation, but due to temporal fluctuations more years of testing is required to confirm these results.

Mission was identified as the ideal genotype for Vitamin C content. TAMU breeding lines TAMU 1405 and TAMU F39 also had vitamin C content higher than the grand mean. No specific genotypic adaptions were observed for vitamin C content across environments. Where G×E interactions do not follow a recognizable pattern over years or locations, then the target environment is a single mega-environment in which GEI effect cannot be predicted (Yan and Tinker, 2006). Thus, for vitamin C all the three locations can be considered as a mega-environment.

CHAPTER III

ROOT GROWTH DYNAMICS AND FRUIT YIELD OF MELON (*CUCUMIS MELO* L.) GENOTYPES AT TWO LOCATIONS WITH SANDY LOAM AND CLAY SOILS

3.1 Background

In field conditions, roots are constantly exposed to multiple interactions. Early seedling root growth patterns are first determined by the genotype, however these patterns are rapidly modified by the prevalent soil (Bhella, 1985) and environmental conditions, impacting the plant biomass allocation strategies. Thus, the genetic make-up of a cultivar interacts with temporal and spatial variations in soil conditions, having a direct on root growth and developmental patterns in the soil profile (Unger and Kaspar, 1994; Rich and Watt, 2013).

These root distribution patterns ultimately determine the plant's ability to utilize the soil resources (Robinson et al., 1991). Rich and Watt (2013) reported significant genotype × site interactions for root growth in wheat (*Triticum aestivum* L.) cultivars grown at two locations having soil types with different bulk densities and water holding capacities. Further, Andrén et al. (1993) reported that barley (*Hordeum vulgare* L.) root biomass did not differ between sandy and clay soil types, but root length was higher in sandy than clay soil. In addition, other studies indicate that genotypes can vary for rooting depth even in the same soil type (Kell, 2011).

It is well known that clay soil differs from sandy soil in texture, structure, water holding capacity, nutrient status, soil strength and even soil temperature (Jones, 1983; Andrén et al., 1993; Unger and Kaspar, 1994; Coelho and Or, 1999). About 10-20% clay content is considered ideal for root penetration (Madsen, 1985). The proportion of clay particles in a soil also decides available moisture and thus its contribution to the soil strength (Mathers et al., 1966). High bulk density in conjunction with high soil strength reduces root penetration or root elongation rates, keeping roots devoid of available water and nutrients stored beyond these high strength layers (Unger and Kaspar, 1994).

Thus, root genotypic interactions with soil types (Bengough et al., 2006), climatic conditions (Machado et al., 2003) and cultural practices (Bhella, 1985; Kirkegaard and Hunt, 2010) enhance the temporal and spatial variability of root systems under field conditions. This variation and limitations of underground observations in the rhizosphere enhances the complexity of root growth studies. Due to these implications of root growth studies, the improvement in root growth systems through breeding strategies has lagged behind the improvements in yield potentials for cultivated crops (O'Toole and Bland, 1987). Interestingly, genotypic variation in root growth responses under field conditions has been studied in only a few field crops such as maize (*Zea mays* L.) (Wiesler and Horst, 1994), wheat (Hurd, 1968), beans (*Phaseolus vulgaris* L.) (Sponchiado et al., 1989) but has not been reported in vegetable crops. This study provides new understanding on the mechanisms underlying root growth adjustments of melon genotypes grown in contrasting soil and climatic conditions.

Irrigation management over a range of soil types can have considerable impact on root growth patterns of crops and/or cultivars. In high input cropping systems, where water and nutrients are supplied directly in the root zone, roots of crop plants avoid root zone stresses and thus, root systems remain confined to the upper 15 cm soil depth, such as in semi-dwarf rice (*Oryza Sativa* L.) cultivars (O'Toole and Bland, 1987). Further, Machado et al. (2003) observed in subsurface drip irrigated tomatoes, roots were mostly concentrated at the depth of the drip tape. In such situations, root growth can be altered by plants reducing the biomass allocation to the root system, since a smaller root system can suffice to meet plant water and nutrient needs.

Root growth patterns get modified upon interaction with soil moisture characteristics (Sharp and Davies, 1985). Hunter and Kelley (1946) concluded that roots follow available water in the soil when they are in direct contact with seeping water. Light texture soils with low water holding capacity have greater downward movement of water (Andrén et al., 1993), thus there is a possibility that under sandy loam soils, roots can follow the seepage of water and increase rooting depth. These rooting depth responses may vary with genotypes and irrigation management.

Roots under field conditions encounter multiple soil conditions continuously thus, need to be observed in space and time. Minirhizotron is a non-destructive method which makes it possible to study spatial and temporal root growth patterns and their interactions with a number of soil factors (Johnson et al., 2001). The root length intensity (L_a) is considered as a good measure for characterizing root systems because fine roots get higher weightage in the L_a estimation (Coelho and Or, 1999).

The overall aim of this two year field experiment was to investigate the impact of two soil types in south Texas on root distribution patterns, yield and quality of different melon genotypes. This information will be a useful for developing resource use efficient cultivars with root systems with narrow or wider adaptation to different environments, and also for developing best irrigation and nutrient management practices for melons under variable soil types.

3.2 Materials and methods

3.2.1 Experimental site

The field experiments were conducted at the Texas A&M AgrilLife Research and Extension Centers at Uvalde (long. 29° 13” N, lat. 99° 45” W), and Weslaco; 26.12° N, 98.0° W) in Texas during 2010 and 2012. The soil at Uvalde was clay, hyperthermic Aridic Calciustolls of the Uvalde series, and at Weslaco it was sandy loam, hyperthermic Typic Calciustolls of the Hidalgo series. Monthly rainfall maximum and minimum temperature during the 2011 and 2012 seasons are given in Table 3.1. Soil samples were collected (up to 90 cm depth) before planting and analyzed for their physical and chemical properties at the Texas A&M soil testing laboratory (Table 3.2).

3.2.2 Treatments

The genotypes included were elite melon lines from the melon breeding program at Texas A&M University, which are being used for developing resource efficient cultivars for diverse eco-agriculture regions. This study evaluated seasonal root growth responses of four Texas A&M breeding lines, TAMU 146, TAMU 1405, and TAMU F39

Table 3.1 Monthly maximum and minimum temperature and rainfall during 2011 and 2012 seasons

	Max. temperature (°C)		Min. temperature (°C)		RH (%)		Rainfall (mm)	
	U	W	U	W	U	W	U	W
2011								
March	27.7	27.6	14.1	17.6	56.2	47.1	5.8	2.5
April	32.1	31.2	18.5	21.1	24.8	46.4	0.3	0.0
May	32.9	31.4	20.2	22.7	30.6	49.9	61.5	4.6
June	36.3	33.6	23.5	24.1	26.7	47.7	35.8	173.0
July	36.7	34.3	24.3	25.1	28.8	48.1	24.6	12.2
August	38.1	36.2	25.2	25.7	25.4	41.4	0.8	5.1
2012								
March	25.6	27.5	13.2	17.3	71.0	47.8	49.5	257.8
April	30.5	30.9	17.4	20.9	30.5	45.4	3.3	1.0
May	31.2	32.3	19.7	22.5	41.8	46.9	87.1	42.2
June	35.5	34.8	23.6	24.5	31.2	43.3	0	35.3
July	35.0	34.9	23.6	25.1	34.8	42.9	67.6	55.1
August	36.4	36.2	24.3	25.5	28.2	37.7	8.9	7.6

Uvalde, TX. U = Uvalde, W = Weslaco

Table 3.2 Pre-plant soil physical and chemical properties in 2011 and 2012 seasons, Uvalde and Weslaco, TX

Depth	Soil	Sand	Silt	Clay	pH	EC	OM	NO_3-N	NH_3-N	P	K
(cm)	texture	%	%	%		µmhos·cm^{-1}	%		mg·kg^{-1}		
Uvalde (2011)											
0-15	CL	31	27	42	7.7	324	2.6	10	-	73	714
15-30	CL	27	28	45	7.9	307	2.7	6	-	65	684
30-45	CL	29	23	48	7.8	329	2.6	7	-	28	509
45-60	CL	27	24	49	7.9	373	2.6	13	-	11	438
60-90	CL	27	24	49	7.9	476	2.3	9	-	7	385
Uvalde (2012)											
0-15	CL	22	27	51	8.1	340	2.4	32	2.6	64	864
15-30	CL	20	31	49	8.1	320	2.6	11	2.5	59	727
30-45	CL	21	27	51	8.1	360	2.5	6	2.4	40	646
45-60	CL	13	31	56	8.1	359	2.3	11	2.6	8	463
60-90	CL	22	24	54	8.2	350	2.1	10	3.1	6	398
Weslaco (2011)											
0-15	SL	59	18	23	7.7	503	0.9	42	-	51	457
15-30	SL	69	9	22	7.9	238	0.6	7	-	34	381
30-45	SL	65	9	26	7.9	189	0.8	9	-	30	346
45-60	SL	59	13	28	8.0	185	0.8	9	-	25	334
60-90	SL	53	14	33	8.1	198	0.9	7	-	23	216
Weslaco (2012)											
0-15	SL	68	14	18	8.0	230	0.8	19	2.5	82	490
15-30	SL	68	14	18	7.9	156	0.7	17	2.0	121	488
30-45	SL	68	14	18	8.0	188	0.7	37	2.7	135	483
45-60	SL	64	10	26	7.7	296	0.5	44	2.0	58	317
60-90	SL	58	12	30	7.6	317	0.4	29	2.1	9	260

CL = Clay, SL = Sandy loam, EC = Electrical conductivity; OM = Organic matter; N = Nitrogen; P = Phosphorus; K = Potassium

Soil samples (0 to 90 cm depth) were collected on 1 April, 2011 and 15 April, 2012 (at Uvalde); 3 March, 2011 and 18 March, 2012 (at Weslaco)

and TAMU Orange Casaba along with two commercial hybrids, Mission and Journey. The melons were grown in clay (Uvalde) and sandy loam (Weslaco) soils using subsurface drip irrigation and black plastic mulch. Seeds of six melon genotypes were planted in a single row on raised beds (2.03 m between, 0.30 m with in row spacing) covered with black plastic mulch on 1 April 2011 and 15 April 2012 at Uvalde and on 3 March 2011 and 21 March 2012 at Weslaco. Irrigation management was followed as described in (Sharma et al., 2014). Fertigation, pest control and other field practices were consistent with those recommended for melon production in the region. The experiment was designed as randomized complete block design with four replications.

3.2.3 Root measurements

At planting, minirhizotron observation tubes, clear, cellulose acetate butyrate with 5.08 cm inside diameter, 5.7 cm outside diameter and 182 cm in length (Bartz technology Corporation, Carpentaria, CA, USA) were installed. These were placed parallel to and 10 cm away from the planting row at a 45° angle to the vertical using a trailer mounted Giddings hydraulic probe (Giddings Machine Co., Windsor CO, USA). A spiral auger with 57 mm diameter was used to dig the holes (Box et al., 1989; Machado et al., 2003). This installation procedure minimizes compaction and facilitates good contact between the tube and soil (Upchurch and Ritchie, 1983) and reduces the chances of roots following the preferential path of soil-tube interface ((Johnson et al., 2001). To exclude light and minimize the heat transfer to the soil near the surface, a 30 cm above ground portion of the minirhizotrons was painted with black plastic enamel paint and repainted with a coat of white enamel paint (McLean et al., 1992; Kage et al.,

2000). The length of the painted portion also served as a guide to install all the tubes at the same depth. Soil around the tubes was tightly covered with plastic sheet to preserve soil moisture and control weed around the tube (McMichael and Taylor, 1987). To prevent temperature fluctuation through heat convection, foam (camping pad) rolls were inserted inside the above ground 30 cm portion the tubes, and the top end of each minirhizotron was covered with a PVC end cap (57 cm internal diameter).

Minirhizotron images were collected approximately at two week interval (depending upon weather) till the end of the growing season. Dates of root image collection for each location and year are given in Table 3.3. Two images were taken every 10 cm interval using an indexing handle set for seven depths *viz*. 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, and 60-70 cm (given the tubes were installed at 45° angle to the vertical). Root length from two images for each depth was used as sub-sample in the statistical analysis. Images were recorded using a Bartz BTC-2 Minirhizotron Video Microscope camera system and BTC I-CAP image capture system (Bartz technology Corporation, Carpinteria, CA, USA). The total area represented in each image was 3.24 cm^2. Before every measurement, the minirhizotron tubes were cleaned with an absorbent swab to wipe out any condensed moisture along the inner tube walls.

Images were analyzed using the WinRHIZO Tron 2009a (Régent Instruments Inc., Quebec, Canada), which provided root length (L_a, mm cm^{-2}) for each depth and treatment combination at all sampling dates (Johnson et al., 2001). Total standing root length was measured seven (Uvalde) and six (Weslaco) times in 2011 and six (Uvalde) and five (Weslaco) times in 2012 respectively. After reviewing all measurements, data

for L_a is presented only for sampling dates corresponding to the four most important phenological stages *viz*. pre-flowering (28 and 28 DAP), fruit setting (56 and 56 DAP),

Table 3.3 Planting and measurements dates in 2011 and 2012 at Uvalde and Weslaco, TX

Location	Year	Date of planting	Minirhizotron measurements duration		Total No.	Harvest duration		Total No.	Crop duration
			Start date	Last date		Start date	Last date		(Days)
Uvalde	2011	1-Apr	29-Apr	10-Aug	7	15-Jun	5-Aug	14	126
	2012	15-Apr	11-May	1-Aug	6	25-Jun	30-Jul	9	106
Weslaco	2011	3-Mar	22-Mar	14-Jun	6	16-May	5-Jul	8	119
	2012	18-Mar	18-Apr	13-Jun	5	30-May	20-Jun	4	91

fruit maturity (70 and 72 DAP) and fruit ripening (90 and 84 DAP) for Uvalde and Weslaco in 2011 and pre-flowering (26 and 28 DAP), fruit setting (60 and 55 DAP), fruit maturity (79 and 70 DAP) and fruit ripening (95 and 84 DAP) for Uvalde and Weslaco in 2012 seasons respectively.

3.2.4 Soil bulk density

After the last harvest, soil cores were collected to determine soil bulk density for the different depths. To minimize compaction effects, the soil corer (4.01 cm inside diameter, ST-062, Giddings Machine Co., Windsor, CO) was gently inserted after spraying with cooking oil. The samples were collected in plastic bags and immediately placed in an ice chest. After recording fresh weights, soil samples were oven dried at

65°C for 72 hours. Bulk density (g cm^{-3}) was calculated by dividing the dry weight by the sample volume (Blake and Hartge, 1986) (Table 3.4).

Table 3.4 Bulk density of Uvalde and Weslaco soils, season, 2012

	Bulk density ($g \cdot cm^{-3}$)	
Depth (cm)	Uvalde	Weslaco
0-10	1.07	1.40
10-20	1.22	1.69
20-30	1.42	1.93
30-40	1.23	1.98
40-50	1.06	1.79
50-60	1.15	1.75
60-70	1.32	1.67

3.2.5 Fruit yield and quality

Fruits were harvested at half to full slip stage, 14 and 8 times in 2011 and 9 and 4 times in 2012 at Uvalde and Weslaco respectively (Table 3.3). At each harvest, TFY, MFY, FN and FW were recorded as detailed in section 2.2.1. Fruit quality parameters, SSC and fruit firmness were determined as described in section 2.2.2.

3.2.6 Statistical analysis

All statistical data analyses were performed using a generalized linear model procedure of SAS 9.2 version (SAS Inst., Cary, N.C., USA). A combined analysis over year, growth stage, and locations for L_a, Marketable Fruit Yield (MFY), Total Fruit Yield (TFY), Fruit Number (FN), Fruit Weight (FW), fruit firmness, and soluble solids content (SSC) was performed as described by McIntosh (1983). The L_a was log transformed to establish an acceptable level of homogeneity of variance across main

factors. Samson and Sinclair (1994) also used the same transformation to resolve the statistical problems in root length intensity. Treatment differences were determined using Duncan's multiple range tests. Significant interactions among all factors were explored. Sigma plot software (Systat Software, Inc., San Jose, California USA) was used for plotting graphs.

3.3 Results

3.3.1 Weather conditions

The Weslaco location received 53% (197 vs. 129 mm) and 84% (399 vs. 258 mm) higher total seasonal rainfall than the Uvalde location in 2011 and 2012 respectively. Temporal rainfall distribution patterns also varied between locations. In 2011, March to April at Uvalde and March to May months at Weslaco were drier than these in 2012 (Table 3.1). However, rainfall received in June 2012 at Uvalde and May-June at Weslaco was less than the corresponding months in 2011. Overall, rainfall received in 2012 was 68% (216 vs. 129 mm) higher at Uvalde and 102% (399 vs. 197 mm) higher at Weslaco than in 2011. Although, 2011 was overall drier than 2012, but over time 2011 was drier in the beginning, while 2012 was drier later in the season (Table 3.1).

Seasonal mean maximum temperature was higher at Uvalde by 2°C than at Weslaco in 2011, whereas the seasonal mean minimum temperature was lower at Uvalde by 2 and 3°C in in 2011 and 2012 respectively. Relative humidity was higher at Weslaco (47 and 44%) as compared to Uvalde (32 and 40%) in (2011 and 2012) respectively.

3.3.2 Soil conditions

The Uvalde and Weslaco soils were clay and sandy loam in both the years, with 50% and 63% of clay and sand content respectively (Table 3.2). The Uvalde soil was higher in organic matter and potassium (K) content as compared to the Weslaco soil. However, NO_3-N content was higher at Weslaco than Uvalde at 0-15 cm soil depth in 2011 and 30-90 cm soil depth in 2012. Similarly, Phosphorus (P) concentration was also higher at all depths in Weslaco in 2012. In general, concentration of all nutrients, except N decreased with soil depth.

The bulk density of the Weslaco soil was higher than the Uvalde soil. In both soils, bulk density increased up to 20-30 cm of soil depth and then declined, but in Uvalde soil it again increased at 50 - 70 cm of soil depth. The Uvalde soil below 25 cm depth contains a hard pan due to presence of considerable amount of caliche coated limestone (20 - 40%) which becomes very hard under dry conditions (USDA, 1969). The ideal soil bulk density for root growth is less than 1.40 g cm^{-3} in clay and 1.6 g cm^{-3} in sandy soils (Brady and Weil, 2002).

3.3.3 Root length intensity

3.3.3.1 Year and growth stage effects

Tables 3.5 and 3.6 show ANOVA means for root length intensity (L_a) as affected by year, growth stage, location, genotype, and soil depth. Years were significantly different ($P \leq 0.001$) for L_a (Table 3.5). Overall, L_a was higher in 2012 (2.0 vs. 0.5 cm cm^{-2}) as compared to 2011. This trend was the same at both locations, with seven (0.22 vs. 1.66 cm cm^{-2}) and three times (0.91 vs. 2.27 cm cm^{-2}) greater L_a in 2012 than in 2011

Table 3.5 Analysis of variance of root length intensity (L_a) as influenced by year, growth stage, location, cultivar, and soil depth during 2011 and 2012 seasons. Data were collected using minirhizotron

Source	d.f.	L_a
Year (Y)	1	***
Growth stage (S)	3	***
Y × S	3	***
Location (L)	1	***
L × Y	1	**
L × S	3	*
L × Y × S	3	†
Error a	20	
Genotype (G)	5	†
G × Y	5	†
G × S	15	NS
G × L	5	NS
G × Y × S	15	NS
G × S × L	15	NS
G × Y × L	5	NS
G × Y × S × L	15	NS
Error b	200	
Soil depth (D)	6	***
D × Y	6	***
D × S	18	***
D × L	6	***
D × G	30	***
D × Y × S	18	***
D × L × Y	6	***
D × L × S	18	NS
D × G × Y	30	***
D × G × S	90	NS
D × G × L	30	*
D × L × Y × S	18	***
D × G × Y × S	90	NS
D × G × S × L	90	NS
D × G × Y × L	30	***
D × G × Y × S × L	90	NS
Experimental error	1438	

†, *, **, *** show significant difference at P ≤ 0.1, 0.05, 0.01 and 0.001 respectively
NS, not significant at P ≤ 0.1

at Uvalde and Weslaco, respectively (Table 3.7). Growth stage also had a significant effect ($P \leq 0.001$) on L_a. Combining both years, the L_a increased significantly up to fruit setting stage (1.5 cm cm^{-2}) and attained maximum at the fruit ripening stage (1.8 cm cm^{-2}) and decreased by 11% between fruit ripening and harvest stage. Trends in L_a increase among growth stages varied significantly ($P \leq 0.001$) between years (Table 3.5). In general, L_a reached a maximum at the fruit setting (FS) stage and remained unchanged thereafter, however, in 2012 at Uvalde location L_a increased up to fruit ripening stage (FR) and decreased at harvesting (HS) (Fig. 3.1).

3.3.3.2 Location effects

Location (soil type) had a significant effect ($P \leq 0.001$) on L_a. Weslaco (sandy loam soil) had 77% (1.6 vs. 0.9 cm cm^{-2}) higher L_a than Uvalde (clay soil) (Table 3.5 and 3.6). These trends were similar in both years, in spite of significant ($P = 0.005$) location × year interaction effects. Weslaco had almost four times higher L_a (0.91 vs. 0.22 cm cm^{-2}; $P \leq 0.001$) in 2011, and 37% numerically higher *L*a in 2012 as compared to Uvalde. Location × growth stage ($P = 0.035$) and location × year × growth stage ($P = 0.071$) interactions were also significant for L_a. Numerically, Weslaco had higher *L*a at all the growth stages compared to Uvalde after pre-flowering (setting, ripening and harvest) in 2011 and at fruit setting stag e in 2012 (Table 3.7).

3.3.3.3 Genotype effects

Genotypes had numerical differences ($P \leq 0.074$) for L_a (Table 3.6). Overall, Journey had the lowest L_a as compared to Mission, TAMU 146 and TAMU 1405.

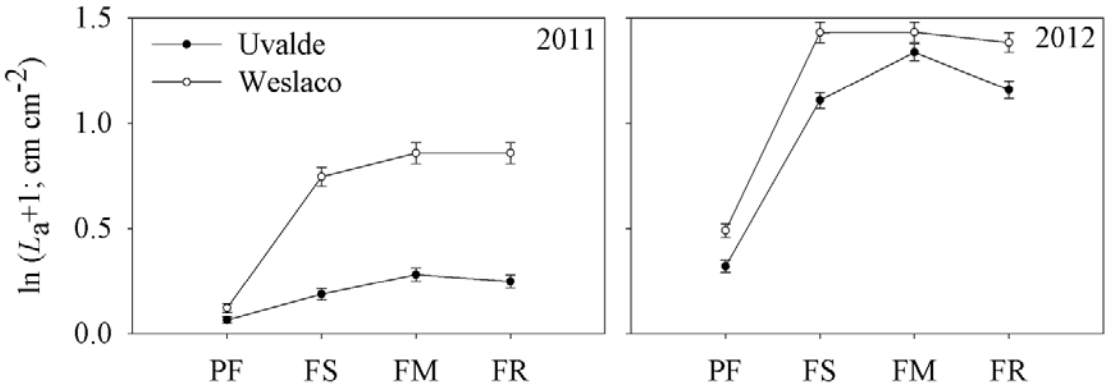

Figure 3.1 Trends in root length intensity (La) over different growth stages in 2011 and 2012. Data presented as mean values ± 1 SE for locations within growth stages (n= 252 in 2011, 336 in 2012). Data were collected using minirhizotron. PF = Pre-flowering, FS = Fruit setting, FR = Fruit ripening, HS = Harvesting

3.3.3.4 Root growth patterns along soil depth

Across year, growth stage, location and genotypes, soil depths had significant ($P \leq 0.0001$) effects on L_a with the highest L_a (1.4 cm cm^{-2}) recorded at 10 - 20 cm soil depth and the lowest (1.0 cm cm^{-2}) at 0 - 10 cm of soil depth (Table 3.5, 3.6). However, significant interactions among year × soil depth ($P \leq 0.001$) and soil depth × year × location ($P \leq 0.001$) for L_a showed that root growth distribution patterns along the soil depth differed between years and locations. In 2011, Weslaco had significantly higher L_a than Uvalde throughout the soil profile except at 50 - 60 cm soil depth while, in 2012 Uvalde had significantly higher L_a than Weslaco at shallower depth (<30 cm) but lower in the deeper soil depth (>30 cm) (Fig. 3.2).

Table 3.6 Mean root length intensity (L_a) as influenced by year, sampling date, location, genotype, and soil depth during 2011 and 2012 seasons. Data were collected using minirhizotron

Main effect		L_a (cm cm^{-2})
Year		
	2011	0.5 b[z]
	2012	2.0 a
Sampling date		
	Pre-flowering	0.3 b
	Fruit setting	1.5 a
	Fruit ripening	1.8 a
	Harvesting	1.6 a
Location		
	Uvalde	0.9 b
	Weslaco	1.6 a
Genotype		
	Mission	1.4 a
	Journey	1.0 b
	TAMU F39	1.2 ab
	TAMU 146	1.3 a
	TAMU 1405	1.4 a
	TAMU OC	1.2 ab
Soil depth		
	0-10	1.0 d
	10-20	1.4 a
	20-30	1.3 ab
	30-40	1.3 ab
	40-50	1.2 abc
	50-60	1.2 bcd
	60-70	1.1 cd

[z]Means of main factor followed by different letters are significantly different at $P \leq 0.05$ according to the Duncan's multiple range test

Pre-flowering (28, 32), Fruit setting (42, 46), Fruit ripening (90, 80), Final harvest (131, 107) days after planting in (2011, 2012) respectively

There were also significant depth × genotype ($P \leq 0.001$), depth × genotype × year ($P \leq 0.001$), depth × genotype × location ($P \leq 0.030$), and depth × genotype × year × location ($P \leq 0.001$) interactions for L_a which indicates that the root distribution of genotypes with respect to locations varied over years along the soil depth (Table 3.5).

3.3.3.5 Location, genotype and depth interactions by year and growth stage

The ANOVA of L_a as affected by location, genotype, and soil depth over growth stages in 2011 and 2012 is presented in Table 3.7. In 2011, location × depth and genotype × depth interactions had significant effect ($P \leq 0.01$) on L_a at all the growth stages. Similarly, in 2012 these interactions were also significant except at pre-flowering ($P \leq 0.1$). However, location × genotype × soil depth interactions were significant ($P \leq 0.05$) at all stages in both years except pre-flowering and fruit setting in 2012. These significant interactive effects indicated that seasonal L_a distribution patterns between locations and genotypes differed over soil depth.

Figure 3.3 shows L_a of six genotypes in the soil profile at four growth stages in 2011. In all the genotypes at fruit setting, L_a was higher in Weslaco (sandy loam soil) as compared to Uvalde (clay soil). At fruit setting and fruit maturity stage, TAMU 146 showed significantly higher L_a at Weslaco as compared to Uvalde location at 10 - 30 cm soil depth, although not significant but trends reversed in deeper soil layers (50 - 70 cm). TAMU 1405 had higher L_a at Weslaco at fruit setting stage between 20 - 40 cm depth, these trends were more pronounced at all depths at fruit maturity, and were maintained at fruit ripening stage. TAMU OC had higher L_a at 20 - 50 cm soil depth at all the growth stages. Overall, TAMU 1405 had uniformly distributed root system except a slight

Table 3.7 ANOVA and mean root length intensity (L_a) as influenced by location, genotype, and soil depth at different growth stages during 2011 and 2012 seasons. Data were collected using minirhizotron

	L_a (cm cm^{-2})									
	2011					2012				
Main effect	PF	FS	FR	HS	Mean	PF	FS	FR	HS	Mean
Location (L)										
Uvalde	0.07 a	0.21 b	0.32 b	0.28 b	0.22 b	0.38 a	2.03 b	2.81 a	2.18 a	1.66 b
Weslaco	0.13 a	1.11 a	1.36 a	1.36 a	0.91 a	0.63 a	3.18 a	3.19 a	2.99 a	2.27 a
Genotype (G)										
Mission	0.15 a	0.45 a	0.58 a	0.55 b	0.42 cd	0.55 a	3.44 a	3.82 a	3.26 a	2.45 a
Journey	0.02 a	0.49 a	0.55 a	0.40 b	0.35 d	0.31 a	2.22 a	2.21 a	2.46 a	1.61 b
TAMU F39	0.12 a	0.63 a	0.97 a	0.82 ab	0.6 abc	0.51 a	2.42 a	2.67 a	2.39 a	1.83 ab
TAMU 146	0.13 a	0.91 a	1.07 a	0.86 ab	0.70 a	0.46 a	2.33 a	3.33 a	2.35 a	1.89 ab
TAMU 1405	0.10 a	0.63 a	0.83 a	1.22 a	0.65 ab	0.57 a	2.90 a	3.38 a	2.30 a	2.07 ab
TAMU OC	0.06 a	0.51 a	0.67 a	0.69 ab	0.46 bcd	0.62 a	2.21 a	2.77 a	2.72 a	1.92 ab
Soil depth (D)										
0-10	0.18 a	0.56 abc	0.81 ab	0.71 ab	0.54 ab	0.78 ab	1.52 c	2.03 b	1.79 a	1.48 b
10-20	0.20 a	0.62 abc	1.02 a	1.02 a	0.68 a	1.04 a	2.29 b	3.20 a	2.49 ab	2.15 a
20-30	0.17 a	0.89 a	0.88 ab	1.08 a	0.71 a	0.83 a	2.20 b	2.72 ab	2.27 ab	1.91 a
30-40	0.04 b	0.76 ab	0.99 a	0.98 a	0.64 a	0.56 b	2.65 ab	3.01 a	2.71 a	2.03 a
40-50	0.08 ab	0.56 abc	0.66 ab	0.63 ab	0.46 bc	0.24 c	3.41 a	3.31 a	2.84 a	2.09 a
50-60	0.02 b	0.35 c	0.49 b	0.44 b	0.31 d	0.26 c	3.41 a	3.62 a	3.00 a	2.18 a
60-70	0.01 b	0.48 bc	0.59 ab	0.44 b	0.36 cd	0.05 d	2.88 ab	3.29 a	3.01 a	1.88 a

Table 3.7 Continued

	L_a (cm cm^{-2})									
	2011					2012				
Main effect	PF	FS	FR	HS	Mean	PF	FS	FR	HS	Mean
ANOVA										
L	NS	*	†	*	***	†	*	NS	NS	**
G	NS	NS	NS	†	**	NS	NS	NS	NS	NS
D	***	***	***	***	***	*******	*******	*******	*******	*******
L × G	NS	***	NS	NS	**	***	***	***	***	NS
L × D	***	***	***	***	***	*******	*******	*******	*******	***
G × D	***	***	**	***	***	†	**	***	***	*******
L × G × D	***	***	*	*	**	**NS**	NS	***	**	*

[z]Means of main factor followed by different letters are significantly different at P ≤ 0.05 according to the Duncan's multiple range test

†, *, **, *** show significant difference at P ≤ 0.1, 0.05, 0.01 and 0.001 respectively

NS, not significant at P ≤ 0.1

PF = Pre-flowering, FS = Fruit setting, FR = Fruit ripening, HS = Harvesting

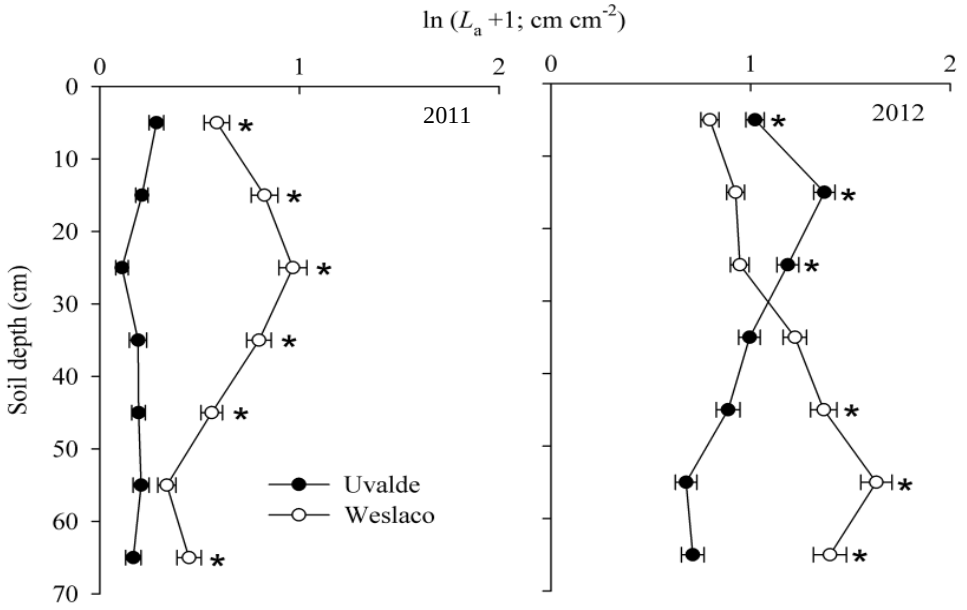

Figure 3.2 Effect of locations on root length intensity (L_a) distribution along different soil depths in 2011 and 2012. Data presented as mean values ± 1 SE for soil depths within locations (n= 144 in 2011, 192 in 2012). Asterisk (*) represents significant differences between locations at $P \leq 0.05$. Data were collected using minirhizotron

increase in L_a at 20 - 30 cm depth in both soils. TAMU 146 showed potential of deep root growth in Uvalde clay soil. TAMU F39 showed more root growth concentrated in 10 - 50 cm soil, but also showed potential of increased growth at 70 cm depth under Weslaco soils. TAMU OC showed enhanced root growth under sandy loam soils in the sub soil (20 - 50 cm) depth.

Similarly, in 2012 (Fig. 3.4) at the pre-flowering stage L_a was observed up to 70 cm depth in Weslaco in all genotypes except in Journey and TAMU 146, but at Uvalde none of the genotypes recorded L_a beyond 40 cm depth at this stage. In general, after flowering in all genotypes, L_a was higher in the upper soil depth (0- 30 cm) at the Uvalde location than at Weslaco, while, a reverse trend was observed in the deeper soil

layers (40 - 70 cm). In the upper soil layers, Mission had similar root growth at both locations, but in deeper soil layers (> 40 cm), L_a was significantly higher at Weslaco location. Breeding lines TAMU F39 and TAMU 1405 showed similar L_a distribution patterns to Mission. Interestingly, TAMU 1405 also showed higher L_a at Uvalde in the upper layers (< 30 cm) as compared to Weslaco, particularly at fruit maturity, conversely in the

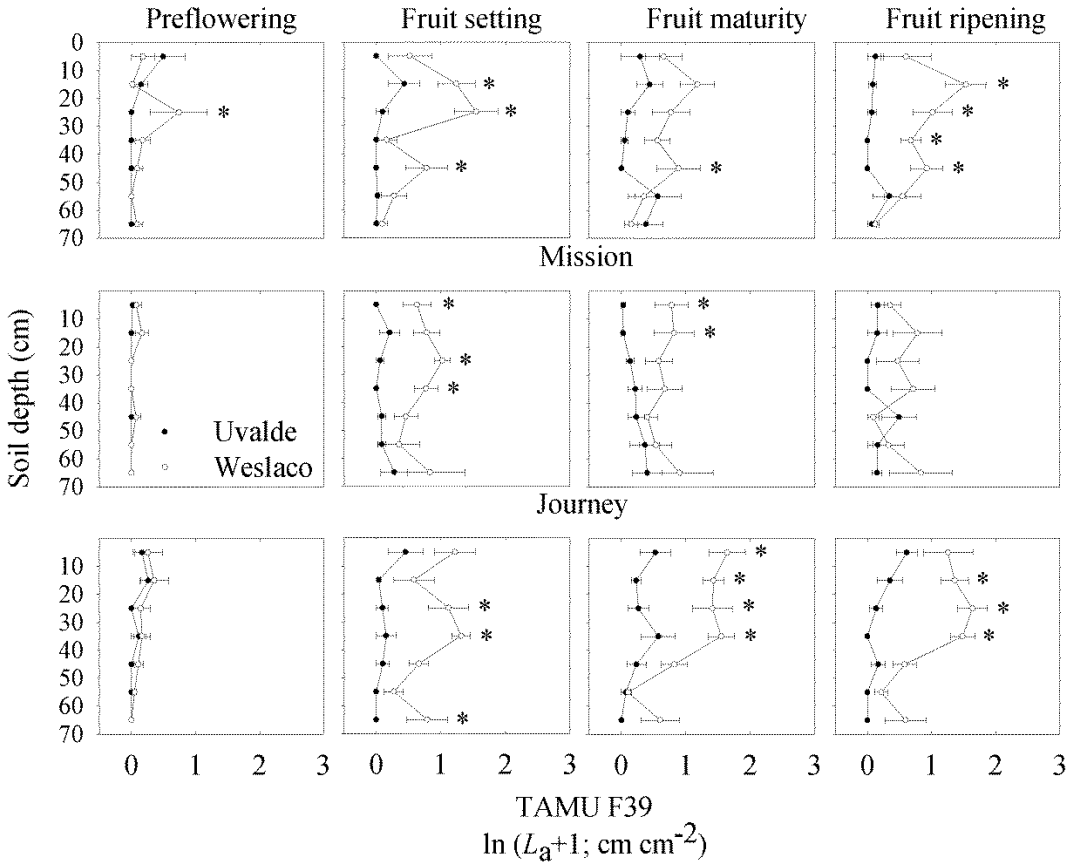

Figure 3.3 Effect of location and cultivars on root length intensity (L_a) for different soil depths in 2011. Data presented as mean values for location within cultivars for different growth stages (n=6). Asterisk (*) represents significant differences between locations rates at $P \leq 0.05$. Data were collected using minirhizotron

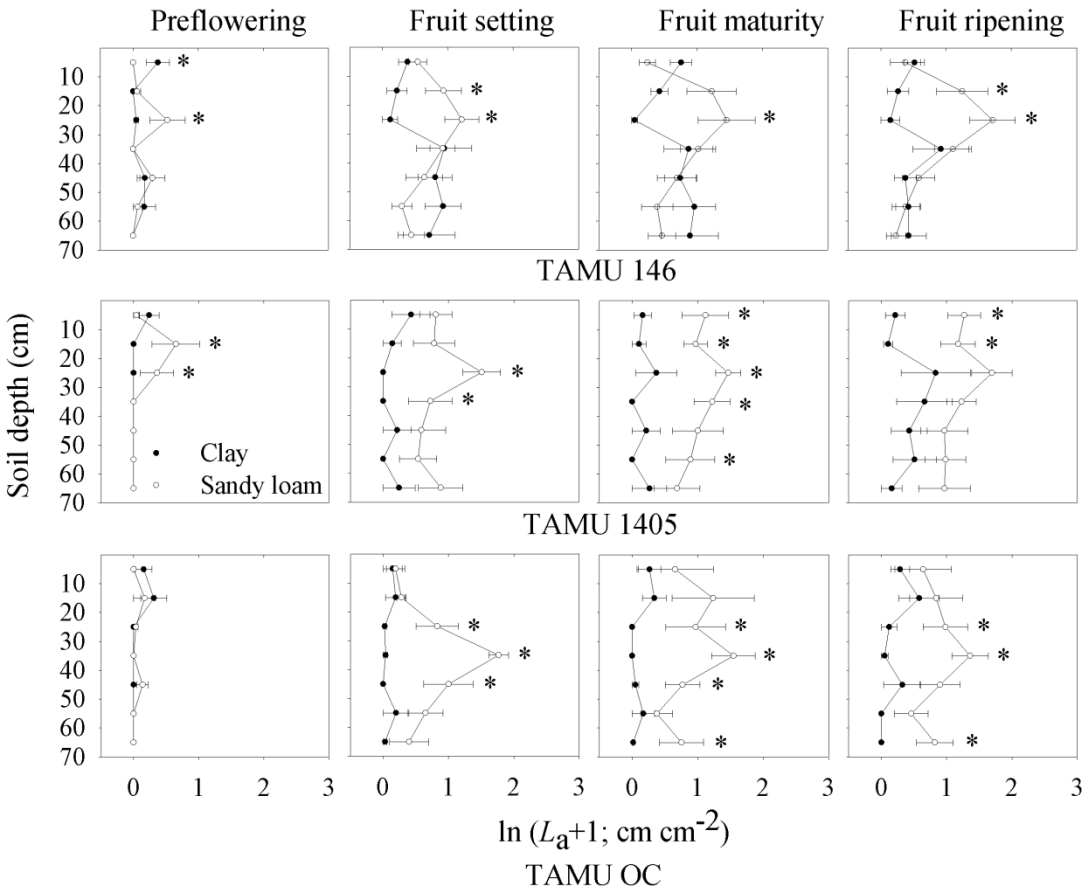

Figure 3.3 Continued

deeper layers (>50 cm) L_a at Weslaco was lower than Uvalde particularly, at fruit setting and fruit ripening. This indicates a potential for deeper root growth in this genotype under sandy loam soil (Weslaco) as compared to other genotypes. In TAMU OC, L_a was higher at Weslaco in the deeper layers (> 40 cm) at the pre-flowering and fruit setting stages, but at fruit maturity and ripening stages, differences between locations were minimal.

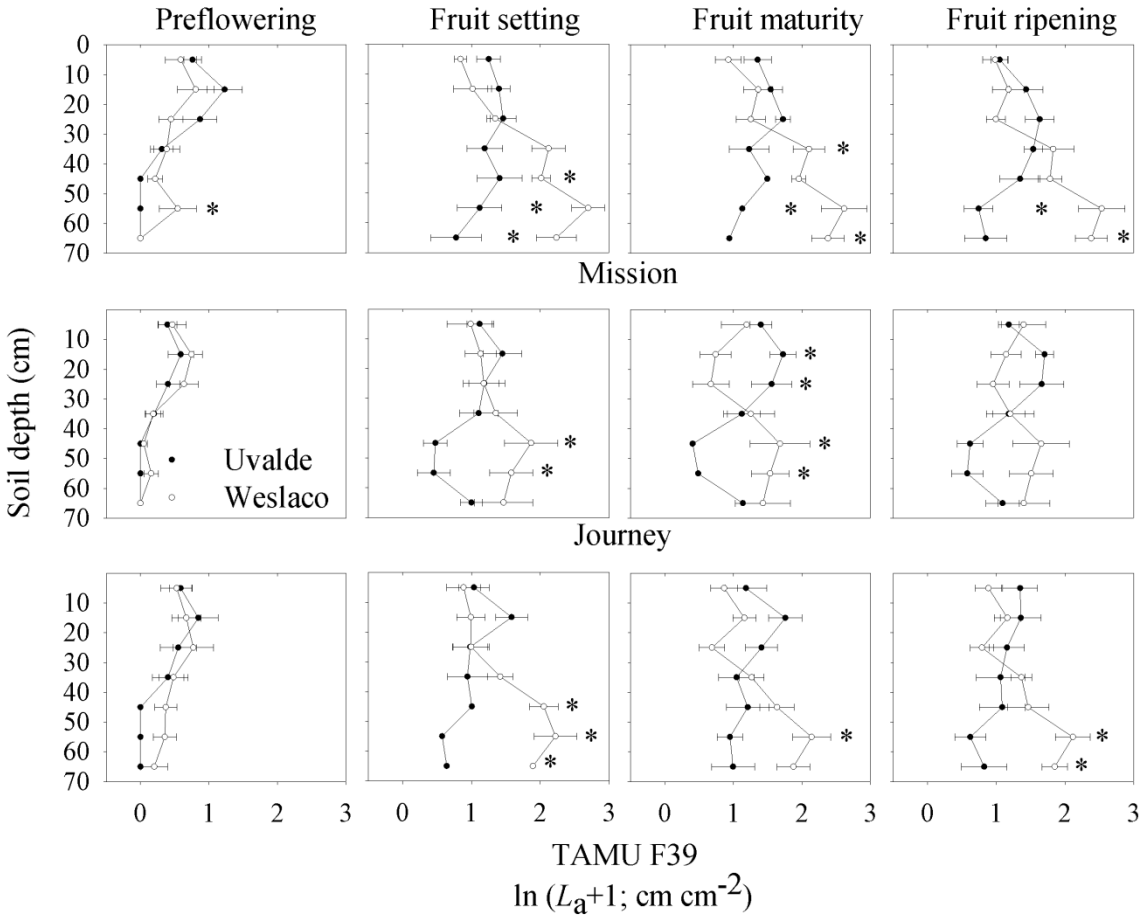

Figure 3.4 Effect of location and cultivars on root length intensity (L_a) for different soil depths in 2012. Data presented as mean values for location within cultivars for different growth stages (n=6). Asterisk (*) represents significant differences between locations rates at $P \leq 0.05$. Data were collected using minirhizotron

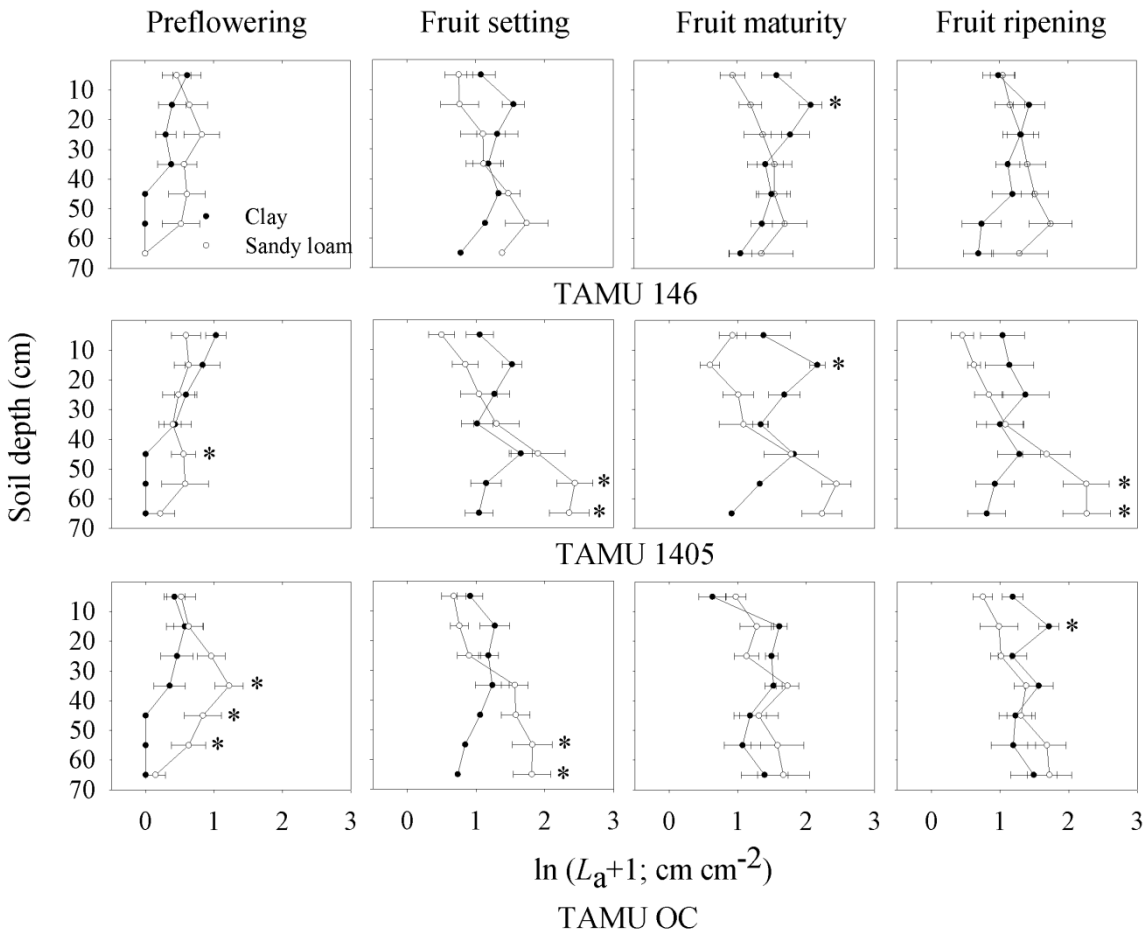

Figure 3.4 continued

3.3.4 Fruit yield and component traits

Year and location had significant effect on marketable (MFY) and total fruit yield (TFY) (Table 3.8). In 2012, MFY and TFY were higher by 34% (P = 0.004) and 17% (P = 0.008) than in 2012. Yield trait components, fruit number per plant (FN) and fruit weight (FW) were also higher in 2012 (19%; P = 0.004) than in 2011(8%; P = 0.090). Between locations, Uvalde had higher MFY (40%; P = 0.002) and TFY (24%; P = 0.038) as compared to Weslaco. Among genotypes, Mission had highest FN (3.6) and

lowest FW (1.62 kg), while, TAMU OC recorded the lowest FN (2.0) and highest FW (3.08 kg), indicated that FW and FN had negative association.

The year × location interaction effects were significant for MFY (P = 0.026), while year × genotype (P = 0.024), and location × genotype (P = 0.044) interactions had a significant effect on TFY. Further, interactions location × genotype (P = 0.027) for FN and year × location × genotype (P = 0.013) for FW were significant. Within locations, higher TFY and FN were recorded in 2012, while FW was higher in 2012 only at Uvalde location. However, between locations Uvalde had higher TFY (31% in 2011 and 18% in 2012) and FN (68% in 2011 and 35% in 2012). These results suggest that fruit number was the major component that contributed to higher yield at Uvalde (Table 3.9).

3.3.5 Fruit quality

In 2012, both SSC and fruit firmness were significantly higher (8%, P = 0.021; 39%, P≤ 0.001, respectively) than in 2011 (Table 3.8). Overall, both locations had no significant differences for SSC and fruit firmness; however a numerical increase of 21% (11.0 vs. 9.1 °brix) in SSC was recorded at Uvalde. All genotypes had a SSC content higher than the USDA established minimum standard (9% soluble solids) for high-quality muskmelon fruit (Lester, 2008). Among the genotypes, TAMU OC had the highest and TAMU F39 the lowest SSC and firmness, while both fruit quality components were similar for Mission, Journey, TAMU 146, and TAMU 1405. Moreover, all the genotypes except TAMU F39 did not show any significant differences for fruit firmness.

Table 3.8 ANOVA and means marketable fruit yield (MFY), total fruit yield (TFY), fruit number (FN), fruit weight (FW), soluble solids content (SSC) and fruit firmness as influenced by year, location, and genotype during 2011 and 2012 seasons

Main effect	MFY $t \cdot ha^{-1}$	TFY $t \cdot ha^{-1}$	FN (No.)	FW (kg)	SSC °brix	Firmness N
Year (Y)						
2011	45.5 b[z]	69.2 b	2.6 b	2.05 a	9.6 b	26.3 b
2012	61.0 a	81.1 a	3.1 b	2.21 b	10.4 a	36.5 a
Location (L)						
Uvalde	62.1 a	83.2 a	3.4 a	2.14 a	11.0 b	32.6 a
Weslaco	44.3 b	67.1 b	2.3 b	2.13 a	9.1 b	30.4 a
Genotype (G)						
Mission	53.0 a	73.7 a	3.6 a	1.62 d	10.3 b	33.7 a
Journey	63.4 a	87.7 a	2.8 b	2.52 b	10.0 b	31.6 ab
TAMU F39	51.4 a	70.0 a	2.8 b	1.86 cd	9.1 b	25.6 b
TAMU 146	45.3 a	76.2 a	3.1 ab	1.72 cd	9.2 b	30.4 ab
TAMU 1405	46.5 a	66.5 a	2.6 b	2.00 c	9.6 b	33.8 a
TAMU OC	59.7 a	76.9 a	2.0 c	3.08 a	11.7 a	33.9 a
ANOVA						
Y	0.0049	0.0084	0.0035	0.0903	0.0209	0.0001
L	0.0020	0.0384	0.0001	0.9091	0.0001	0.2624
Y × L	0.0262	0.2153	0.1358	0.0546	0.2168	0.0577
G	0.2136	0.3131	0.0007	0.0001	0.0001	0.0335
Y × G	0.2364	0.0236	0.3202	0.9734	0.6322	0.4309
L × G	0.3706	0.0443	0.0271	0.4532	0.4145	0.8431
Y × L × G	0.1429	0.8250	0.1319	0.0128	0.3635	0.1823

[z]Means in a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test

Table 3.9 Total fruit yield (TFY), fruit number (FN), and fruit weight (FW) as influenced location, and genotype during 2011 and 2012

Source	TFY ($t \cdot ha^{-1}$)		FN (No.)		FW (kg)	
	Uvalde	Weslaco	Uvalde	Weslaco	Uvalde	Weslaco
Genotypes						
Mission	80.3 ab[x] A[y]	53.3 a B	4.1 a A	2.1a B	1.6 c A	1.6 c A
Journey	95.2 a A	61.3 a B	3.3 ab A	1.6 a B	2.1 b A	2.7 b B
TAMU F39	85.2 ab A	59.6 a B	3.6 ab A	2.0 a B	1.7 bc A	2.0 c A
TAMU 146	84.8 ab A	63.4 a B	3.9 a A	2.3 a B	1.5 c A	2.0 c B
TAMU 1405	63.3 b A	60.2 a A	3.0 b A	2.0 a B	1.9 bc A	2.0 c A
TAMU OC	62.7 b A	61.4 a A	1.8 c A	1.5 a A	2.7 a A	3.2 a B
Overall mean	78.5 b A[z]	59.8 b A	3.2 b A	1.9 b B	1.9 b A	2.2 a A
			2012			
Genotypes						
Mission	90.2 abc A	71.0 b B	5.2 a A	3.1 a B	1.8 c A	1.6 c A
Journey	104.6 a A	89.8 a B	4.2 b A	2.2 b B	2.4 b A	3.0 b B
TAMU F39	76.1 c A	59.2 b B	3.1 c A	2.6 ab B	2.2 bc A	1.7 bc B
TAMU 146	89.5 bc A	67.4 b B	3.8 b A	2.8 ab B	1.8 c A	1.7 c A
TAMU 1405	75.9 c A	66.7 b A	3.1 c A	2.5 ab B	2.3 b A	1.9 b A
TAMU OC	91.6 ab A	91.9 a A	1.9 d A	2.8 ab B	4.0 a A	2.6 a B
Overall mean	87.9 a A	74.3 a B	3.5 a A	2.6 a B	2.4 a A	2.0 b B

[x]With in year and locations means followed by the same lower case letters are not significantly different
[y]Across locations means followed by the same upper case letters are not significantly different
[z]Overall means are compared with overall means

3.4 Discussion

3.4.1 Impact of weather on root growth

Overall, L_a was four time higher in 2012 as compared to in 2011. Similar, temporal trends in L_a were observed at both locations, with a 7-fold and 3-fold increase in L_a in 2012 than in 2011 at Uvalde and Weslaco. The experimental sites experienced severe drought during both years of the study, but the timing and duration varied between locations. The year 2011 was drier during the pre-plant and establishment period (March - June), while 2012 was drier later in the season i.e. during fruit setting and developmental stage (May-June). This temporal climatic variability is not unusual in the drought-prone environments like southwest Texas. Transient drought events can have variable impact on different growth stages of crop plants, and consequently the genotypic responses can vary among years (Cattivelli et al., 2008). It is well known that subsurface drip irrigation system in this study delivered precise amount of water directly into the root zone, keeping the soil moisture at adequate levels for optimum water uptake (Leskovar et al., 2001). However, the higher evaporative demands under drought conditions usually create an imbalance between water absorption and water losses through transpiration, impacting leaf gas exchange of melon plants (Chapter VI) and biomass allocation strategies, affecting the portioning of shoot and root growth patterns.

Another possibility that can also be ascribed to the lower L_a values in 2011 is that the soil dryness, (due to less rainfall received during the pre-plant and establishment period), might have resulted in poor soil-tube interface contact as compared to 2012 (Rytter and Rytter, 2012). Similarly, Muñoz-Romero et al. (2012) reported that

minirhizotrons recorded less RLD in a drier year as compared to a wet year in chickpea (*Cicer arietinum* L.). Sandy soils such as in Weslaco location, settle fast and more smoothly than clay soils around the tubes after installation, particularly when soils are low in moisture. Thus, year to year L_a differences were less pronounced at Weslaco than at the Uvalde location.

3.4.2 Impact of growth stages on root growth

Melons is a fast growing crop, with roots attaining the highest L_a at the fruit setting stage (42-46 DAP) (Table 3.6) and thereafter, remaining stable across years and locations, except for an increase at fruit maturity at Uvalde location (Fig. 3.1). This response can be attributed to the continued increase in L_a of all genotypes except Mission in the upper soil layers (< 30 cm). All genotypes recorded L_a at or below 60 cm of soil depth at Weslaco, while root growth was not observed at Uvalde below 40 cm of soil depth, indicating that root growth proliferation was faster in the sandy loam soil of Weslaco (Fig. 3.5). It is clear that genotypic differences for root distribution across soil types in the two locations were maintained over different growth stages, pre-flowering to fruit ripening (Fig. 3.4, 3.5).

3.4.3 Impact of soil type on root growth

Further, L_a was 77% higher at Weslaco than at Uvalde location. This variation in L_a can be attributed to the differences in soil types among locations. In 2011, L_a at Weslaco was higher than at Uvalde throughout the soil profile, while in 2012 it was higher at Uvalde in the shallow layers (<30 cm), but the trends reversed in the deeper soil depths (>30 cm) (Fig. 3.2). Similarly, Andrén et al. (1993) also reported higher root

distribution in the deeper layers in the sandy soils as compared to clay soil. They attributed deeper root growth distribution to the greater downward seepage of excess rainfall or irrigation water in sandy soils, due to lower field capacity of these soils than that of clay soils, which resulted in higher concentration of nutrients in deeper soil layer. In 2012, at Weslaco higher rainfall (Table 3.1) might have resulted in higher NO_3-N in the deeper layers (Table 3.2) and thus, promoted greater deep root distribution at this location (Fig. 3.2). Further, Hodge (2004) argued that roots have tendency to proliferate more in N rich soil layers.

Conversely, (Madsen, 1985) reported that roots penetrate deeper in clay soils than sandy soils. There may be several reasons for lower L_a in clay soil of Uvalde in this study, for example the irrigation system used, clay content, soil structure, possibility of mineralization in the upper layers, and soil-tube interface artifacts. The subsurface drip irrigation system and presence of hard pan below 25 cm of soil depth might have caused the roots to proliferate around the emitter areas. Similarly, Kirkham et al. (1998) reported that the presence of a hard clay pan at 25 cm prevented maize root growth. Another possibility is higher mineralization of nutrients in the clay soils due to higher organic matter content as compared to sandy soils particularly in the presence of adequate soil moisture (Andrén et al., 1993), might have promoted preferential root growth in the shallow layers (< 30 cm) at Uvalde location. Ability of sandy soils to settle more smoothly than clay soils around tube, might also have contributed to higher L_a estimates at Weslaco than at Uvalde. However, (Madsen, 1985) also described that 10-20% clay content is most ideal for root penetration. The clay content of sandy loam soil

of Weslaco ranged between 18-26% up to 60 cm of soil depth (Table 3.2), which coupled downward movement of soil water might had facilitated deep root distribution through lubricating effect at this location.

3.4.4 Impact of genotypes on root growth

Root growth patterns are genetically programmed, but these are altered when roots interact with variable soil environments (Coelho and Or, 1999). TAMU breeding lines TAMU 146 and TAMU 1405 recorded L_a equivalent to most popular commercial cultivar Mission and higher than another commercial cultivar Journey (Table 3.6). TAMU 146 showed more stability for root growth, with similar L_a at both the locations over years (data not shown). The highest root growth estimates of Mission in 2012 (Table 3.7) also confirmed the adaptability of this cultivar under south Texas conditions. Crosby et al. (2008) also reported that melon genotypes belonging to *cantalupensis, inodorus,* and *momordica* groups showed significant variability for total root length, fine root length, root area and root disease tolerance at seedling stage. Genotypic variability in root have also been previously reported in melons (Sharma et al., 2014), maize (Wiesler and Horst, 1994), wheat (Hurd, 1968; Mian et al., 1994), beans (Sponchiado et al., 1989). Further, the ability of melons to adjust root growth distributions across soil depths in response to soil types appears to be genotype dependent. Mission, TAMU 39, TAMU 1405 and TAMU OC showed tendency of deep (> 50 cm) root distribution in sandy loam soil of Weslaco location whereas, TAMU 146 showed tendency of deep root growth at Uvalde. Genotypic differences for root length distribution have been

previously reported in melons in response to deficit irrigation (Sharma et al., 2014), and in wheat in response to soil aeration (Box and Johnson, 1987).

3.4.5 Root growth patterns along soil depth

Root growth of melons was distributed over the entire 70 cm soil profile (Table 3.6). The lower L_a below 30 cm of soil depth in clay soil (Uvalde) than sandy loam soil (Weslaco) (Fig. 3.2), was probably due to higher mechanical resistance in the clay soil below this layer due to higher clay and lower downward movement of water. Similar a report of less root penetration in a loamy sand with a 22% clay content as compared in a sandy loam soil with a 10-15% clay content confirms the results of this study (Ahmadi et al., 2011) . Further, Madsen (1985) reviewed that in clayey soils, soil structure and bulk density have strong impact on root penetration, as higher clay content (> 20%) increases cohesion of the soil. While, around 50% clay content specifically below 30 cm of depth coupled with a hard pan at 25 cm of depth might have prevented a deep root growth in clay soil of Uvalde as compared to sandy loam soil of Weslaco. Furthermore, some of the roots were able to cross this layer proliferated in deeper soil layers (> 40 cm).

Contrary to the findings of this study, Machado et al. (2003) found that the roots of subsurface drip irrigated tomatoes were mostly concentrated at the depth of the drip tape. Similarly, Bhella (1985) reported a decrease in depth of root penetration in a sandy loam or silt loam soil under trickle irrigated muskmelon as compared to non-irrigated. These discrepancies in results can be due to the difference of crop species in case of tomato and destructive method used to examine the muskmelon roots visually but, no data on root growth was presented.

3.4.6 Impact of soil type and genotypes on yield and quality

Although the growing season in 2012 was 15 days shorter as compared to in 2011 due to late planting, but still both fruit yield and quality were better in 2012 than in 2011. This improvement in yield and quality can be attributed to favorable environmental condition which might have enhanced nutrient and water uptake through improved root growth. Contrary to the root growth patterns, the higher fruit yield at Uvalde as compared to at Weslaco can be attributed to the longer duration of growing season which resulted in higher number of harvests at Uvalde (Table 3.3). As mentioned above, higher amount of mineralized nutrients in clay soil of Uvalde might have resulted in enhanced uptake and growth (Andrén et al., 1993). Further, the cultivar Journey which had the lowest L_a (Table 3.6, 3.7) had the higher fruit yield (Table 3.8, 3.9). Further, Coelho and Or (1999) argued that in frequently irrigated crops (such as this melon study) with highly active root systems, root distribution in the soil profile may not represent root effectiveness. According to Robinson et al. (1991), only a part of the total root length is physically and physiologically active in water and nutrient uptake, thus a small root system may be enough in a highly efficient production system (Blum, 2005), such as the subsurface drip irrigation system used in this study. Moreover, if enhanced root growth under limited resources does not lead to sufficient nutrient and water uptake improvement, the diversion of carbon to the root system may decrease the yield (Blum, 2005; Herrera et al., 2012).

Yield is a complex trait which involves increased allocation of total crop biomass to the economically harvested product (Richards, 2000), for example higher root growth

in some genotypes might enhance total biomass, but not improve the fruit yield. However, TAMU breeding lines produced equivalent fruit yield of same quality to the most popular hybrid Mission (Table 3.9). Thus, the great rooting ability of TAMU breeding lines and equivalent yield under contrasting soil types compared to commercial hybrids confirms the suitability of these breeding lines as a potential parent for developing genetically improved and stable cultivars for wide range of environments.

CHAPTER IV

ROOT GROWTH, YIELD, AND FRUIT QUALITY RESPONSES OF *RETICULATUS* AND *INODORUS* MELONS (*CUCUMIS MELO* L.) TO DEFICIT SUBSURFACE DRIP IRRIGATION[1]

4.1 Background

Among the seven horticultural melon groups, *reticulatus* and *inodorus* are the most important for commercial cultivation. Tuscan type, and netted muskmelons commonly known as 'Cantaloupes' in the U.S. belong to the *reticulatus* group whereas, honeydews, are included under the *inodorus* group (Munger and Robinson, 1991). Usually all melon types are cultivated with similar cultural practices particularly irrigation, but the acclimation response to deficit irrigation varies among the cultivars or genetic make-up (Leskovar et al., 2004; Leskovar and Piccinni, 2005). Thus, the genetic diversity and morphological dissimilarities among different melon groups suggest the need to consider water requirements by cultivar.

Melon plants are highly productive under adequate irrigation conditions, but water scarcity is a major constraint to horticultural production in arid and semiarid regions around the world. In 2011, the southern US experienced the most severe drought in 50 years (USDA, 2012). Groundwater supplies have declined severely, and in the

[1] Part of this chapter is reprinted with permission from "Root growth, yield, and fruit quality responses of *reticulatus* and *inodorus* melons (*Cucumis melo* L) to deficit subsurface drip irrigation" by Sharma, S.P., Leskovar, D.I., Crosby, K., Volder, A. and Ibrahim, A.M.H. (2014) Agricultural Water Management 136: 75-85, Copyright 2014 by Elsevier.

future the region is likely to face more strict water regulations (Leskovar et al., 2004; Leskovar and Piccinni, 2005). High energy costs, falling water tables, and increased demand from competing urban, municipal, and rural sectors are dictating the need to implement water saving practices which can optimize water productivity rather than maximizing crop yields (Pereira et al., 2002).

Deficit irrigation, a practice that supplies water below evapotranspiration (ET) demands, deliberately exposes plants to a certain level of moisture stress (Fereres and Soriano, 2007). Although deficit irrigation can save a significant amount of irrigation water, there is also a risk of yield reductions in some crops and cultivars.

The feasibility of applying deficit irrigation to vegetable crops has been previously reported in the literature. In watermelons [*Citrullus lanatus* (Thunb) Matsum & Nakai], deficit irrigation (75% ETc) saved 25% of irrigation water with a 34% reduction in yield (Leskovar et al., 2004). Reduced irrigation volumes also caused a reduction in fruit size and yield in muskmelon cvs. Piel de sapo and Sancho (Fabeiro et al., 2002; Cabello et al., 2009). In contrast, studies by Patanè et al. (2011) in tomato (*Lycopersicon esculentum* Mill.), Enciso et al. (2009) in onion (*Allium cepa* L) and Jovanovic et al. (2010) in potato (*Solanum tuberosum* L.) reported 46%, 10% and 38% water saving respectively, without any negative impact on yield.

Besides water savings, deficit irrigation may also have positive effects on fruit quality. Larger irrigation volumes have been reported to decrease melon fruit quality, especially soluble solids content (SSC) (Fabeiro et al., 2002; Sensoy et al., 2007). Water deficit before or at the ripening stage increased (Lester et al., 1994), decreased (Long et

al., 2006), or had no effect (Hartz, 1997) on SSC of melon fruits. Moisture stress can induce changes in secondary metabolism of plants (Gill and Tuteja, 2010), which may enhance the levels of health promoting bioactive compounds in fruits. For example, deficit irrigation (75% ETc) caused a 7% increase in lycopene content with no impact on vitamin C content of watermelons (Leskovar et al., 2004). Most of the irrigation studies in muskmelon quality are related to its effects on SSC, but no information is available on its effect on vitamin C and β-carotene levels.

Subsurface drip irrigation ensures precise application of water directly into the root zone through emitters that are placed beneath the soil surface (Leskovar et al., 2001). Roots generally follow the wetting patterns around emitters (Oliveira et al., 1996); however, deficit moisture supply may cause plants to allocate more resources to roots promoting deeper penetration in the soil profile (Sharp and Davies, 1985) and thus, changing root growth patterns. Although root biomass may decrease or remain unchanged, total root length and growing depth can increase under water deficit conditions (Blum, 2005). Root growth responses also vary among cultivars. Sponchiado et al. (1989) reported that drought resistant cultivars of common beans (*Phaseolus vulgaris* L.) produced higher root length at deeper layers (1.3 m), while drought sensitive cultivars at shallow or intermediate layers (0.8 m). Therefore, knowledge of root growth patterns of melon cultivars under water deficit is not only critical for understanding drought tolerance mechanisms but also in achieving efficient crop management and breeding strategies (Chaves et al., 2003; Machado et al., 2003). There is no guarantee that root traits selected on nursery seedlings will translate into a stronger root system

under field conditions (Franco and Leskovar, 2002), which further necessitates *in situ* field evaluations of root growth of muskmelon cultivars under deficit irrigation.

In this study, we evaluated three melon cultivars namely Mission (*reticulatus*; muskmelon type), Da Vinci (*reticulatus*; tuscan type) and Super Nectar (*inodorus*; honeydew type) under two irrigation rates (50% and 100% ETc). Since each cultivar belongs to a distinct horticultural group, these differ widely in morphological traits. For example, Mission has a yellow flesh and netted skin, Da Vinci has an orange yellow flesh and sutured-netted skin and Super Nectar has a greenish white flesh and smooth creamy white skin fruits. . Owing to these differences, we expected that deficit irrigation may enhance root growth and fruit quality through elevated levels of vitamin C and β-carotene, responses that may be cultivar dependent. Thus, the overall aim of this two-year study was to determine the impact of deficit irrigation on root growth, fruit yield and quality, and efficiency in water use of melon cultivars from diverse horticultural groups grown under subsurface drip irrigation. We expect this information will be useful for developing water saving and eco-friendly irrigation technologies for melons in southern regions of the U.S., such as in southwest Texas. Further, Da Vinci is a specialty melon cultivar which can provide a new market opportunity to growers in the region.

4.2 Materials and methods

4.2.1 Experimental site

The field experiment was conducted at the Texas A&M AgriLife Research and Extension Center at Uvalde, TX (long. 29° 13” N, lat. 99° 45” W; msl 283) on a clay soil (Hyperthermic Aridic Calciustolls) of the Uvalde series during the 2011 and 2012

seasons. The site has a semi-arid climate with a long term average annual rainfall of 663 mm, average annual high temperature of 27.4°C and average annual low temperature of 13.6°C. The mean annual evapotranspiration is 1506 mm which is 2.3 times higher than the average annual precipitation, making supplemental irrigation necessary for crop production. Rainfall and maximum and minimum temperature during the 2011 and 2012 seasons are provided in Fig. 4.1.

The precipitation received was only 250 mm in 2011 and 349 mm in 2012 which represented 37% and 52% of the total annual average, respectively. Soil samples were collected (up to 15 cm soil depth) before planting and analyzed for soil physical and chemical properties at the Texas A&M soil testing laboratory. Soil data for 2011 and 2012 are provided in Table 4.1.

4.2.2 Experimental treatments and procedures

The crop was direct-seeded on high-rise beds (2.03 m between, 0.30 m with in row spacing) covered with black plastic mulch on 1 and 15 April 2011 and 2012 respectively. The experiment was laid out in a split plot arrangement with irrigation rates *viz.* 50% ETc and 100% ETc assigned to the main plots and cultivars to the sub plots with three replications. Each sub plot had an area of 18.55 m^2 (9.14 m × 2.03 m). To avoid the impact of irrigation through lateral movement from the neighboring plots a 2.03 m (one bed) bare space was left between the beds. Irrigation was applied with a subsurface drip system based on the daily ETc, which was calculated as a product of the reference evapotranspiration (ETo) obtained from the grass lysimeter facility located at the Texas A&M Center (Ko et al., 2009) and the stage specific crop coefficients (Kc).

Kc values were used as; Kc ini = 0.5, Kc mid = 0.85 and Kc end = 0.60 (Allen et al., 1998). The water requirement was calculated with adjustments for effective rainfall

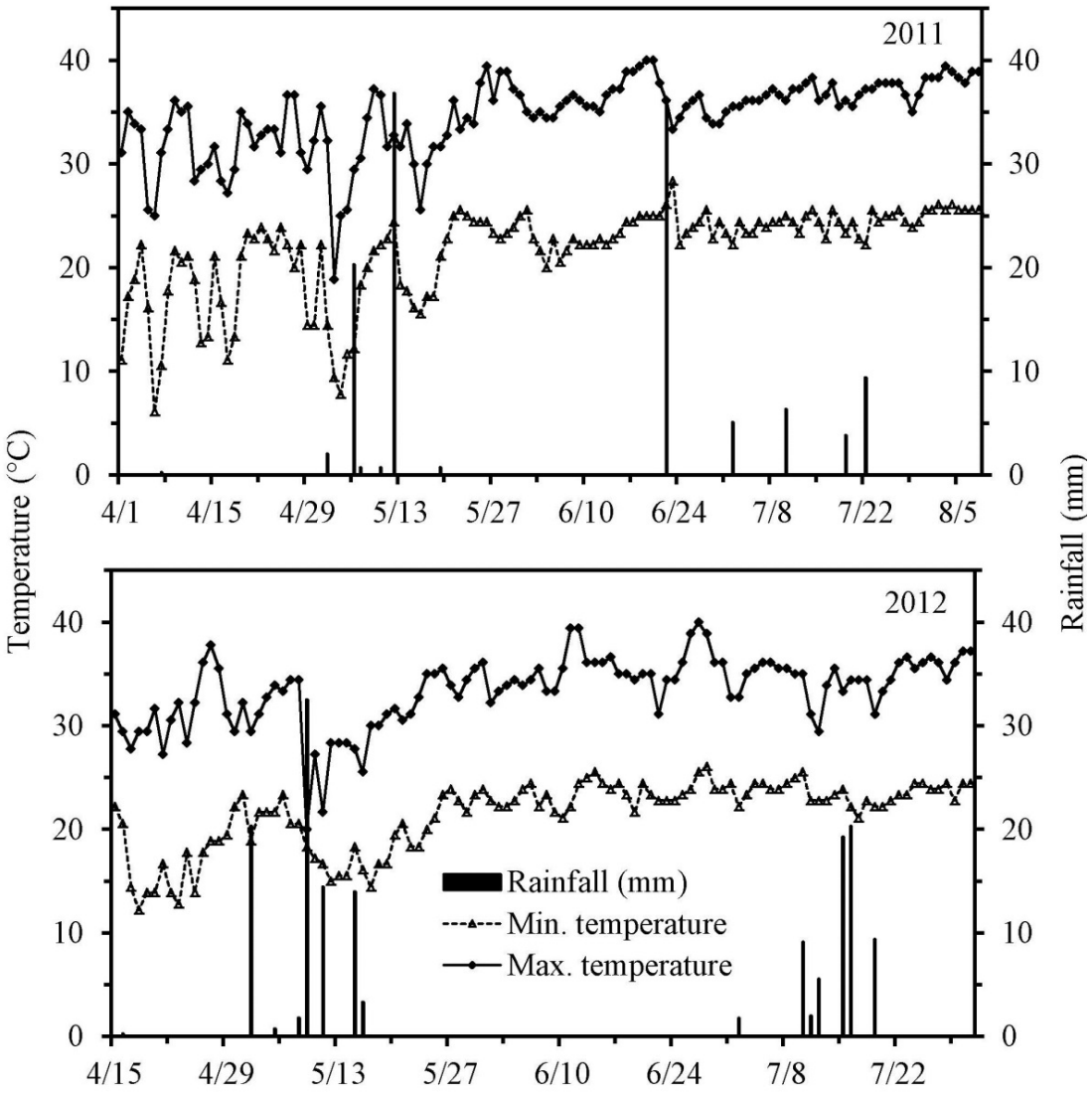

Figure 4.1 Rainfall, minimum and maximum temperature during 2011 and 2012 seasons, Uvalde, TX

Table 4.1 Pre-plant physical and chemical properties in 2011 and 2012 seasons, Uvalde, TX

		Year	
	Unit	2011	2012
Soil texture		clay	clay
Sand	%	31	22
Silt	%	27	27
Clay	%	42	51
pH	-	7.7	8.1
EC	dS m^{-1}	324	340
Organic carbon	%	1.5	-
Organic matter	%	2.6	2.4
NO_3^--N	mg kg^{-1}	10	32
NH_4^+-N	mg kg^{-1}	-	2.6
P	mg kg^{-1}	73	64
K	mg kg^{-1}	714	864
Ca	g kg^{-1}	13.4	17.1
Mg	mg kg^{-1}	332	395
S	mg kg^{-1}	23	26
Na	mg kg^{-1}	106	142
Fe	mg kg^{-1}	-	6.54
Zn	mg kg^{-1}	-	1.32
Mn	mg kg^{-1}	-	8.12
Cu	mg kg^{-1}	-	0.74

Soil samples (0 to 15 cm depth) were collected on 1 April, 2011 and 15 April, 2012

(50%), black plastic mulch (bare soil Kc = 0.2) (Shinohara et al., 2011), effective irrigation wetting bed width (estimated at 70%) and canopy growth. The rainfall was measured at Uvalde Research Weather Station at the Texas A&M Center. Irrigation was triggered twice a week when cumulative irrigation requirement reached at 10 mm

approximately. The drip tape (T-Tape, John Deere, Moline, IL) with 1.02 liter h^{-1} flow rate at 55 kPa was buried in the middle of each bed at a 15-cm depth with drippers spaced at 30.48 cm. Irrigation amount applied was calculated from drip tape flow rate, duration of irrigation applied (hours) and the linear length irrigated. Total fertilizers 90N-42P-30K kg ha^{-1} and 73N-30P-36K kg ha^{-1} were applied through fertigation during 2011 and 2012 seasons, respectively. Differential irrigation started after the seedlings were fully established on 5 May (2011 season) and 23 May (2012 season). Irrigation frequency and total amount of water applied (irrigation + rainfall) to each treatment is given in Table 4.2.

Table 4.2 Rainfall and irrigation applied during 2011 and 2012 seasons

Season	Irrigation rate (% ETc)	Rainfall (mm)	Irrigation			Rainfall and irrigation (mm)
			Initial	Differential[y]	Total	
2011						
	50	123	78 (9)[z]	184 (27)	261 (36)	383
	100	123	78 (9)	335 (27)	413 (36)	535
2012						
	50	155	45(6)	182(32)	227 (38)	382
	100	155	45 (6)	364(32)	409 (38)	564

[y]Differential irrigation started on 5 May and 23 May (34 and 48 days after sowing) in 2011 and 2012 season, respectively
[z]Values in parentheses are the number of irrigation events
ETc = Crop evapotranspiration

4.2.3 Root core sampling

Root core samples were collected at the end of growing season in both years using a hydraulic soil coring and drilling machine (Giddings Machine Co., Windsor CO, USA). Since the subsurface drip tape was located in the center of the bed, sampling was done at 10 cm from the middle of the planting row (Machado et al., 2003). The soil core was cut into 10 cm increments up to a 70-cm depth. Samples were placed in plastic bags and stored in a cold room at 4°C until washing was completed within one week (Kage et al., 2000). Root washing and extraction from soil cores was done using a hydropneumatic elutriation root washer (Gillison's Variety Fabrication Inc., Benzonia, MI, USA) (Smucker et al., 1982). Soil cores were soaked for 15 minutes in water before transferring to the root washer. The soaked samples were washed for 10 minutes using No. 350 sieve size while maintaining the air pressure at 7 psi and water pressure at 50 psi (Gillison's Variety Fabrication Inc., Benzonia, MI). Due to a large amount of organic debris, roots were manually picked from the sieve with tweezers after washing and stored in 20 ml plastic scintillation vials at room temperature in a 20% (v/v) ethanol solution (Wang et al., 2004) for later analysis. Washed root samples were scanned on a flatbed scanner (Reagent Instruments Inc.; STD 4800, Epson Perfection V700 Photo) using 450 dpi resolution. Root length density (RLD; cm cm^{-3}), root surface area (RSA; cm^2), and average diameter (AVD; mm) were determined using WinRhizo software ver. 2003b (Reagent Instruments Inc., Quebec, Canada). Roots were classified by diameter using the Böhm (1979) classification procedure. Roots were grouped into 0-0.5 mm (fine), 0.5-1 mm (coarse) and > 2 mm (very coarse) and presented as per cent of the total

root length (Table 4.3). After analysis, root samples were dried at 65°C for 3 days to measure root dry mass (Leskovar and Cantliffe, 1991). Specific root length (SRL; cm g^{-1}) and specific root area (SPRA; cm^2 g^{-1}) were calculated by dividing the respective root length and surface area by root dry mass. SRL and SPRA were calculated for two depth intervals viz. 0-30 cm and 40-70 cm.

Table 4.3 Effect of deficit irrigation and melon cultivars on root length density (RLD), root surface area (RSA), average diameter (AVD) and root classification (fine, coarse and very coarse)

	RLD		AVD		RSA	
	($cm\ cm^{-3}$)		(mm)		($cm^2\ cm^{-3}$)	
Treatment	2011	2012	2011	2012	2011	2012
Irrigation (IR, ETc)						
50%	0.68	0.99 a	0.21	0.19	0.055	0.074 a
100%	0.62	0.77 b	0.21	0.21	0.049	0.062 b
Cultivar (CV)						
Mission	0.60 b[z]	1.08 a	0.24 a	0.2	0.050 b	0.079 a
Da Vinci	0.52 c	0.75 b	0.18 b	0.21	0.036 c	0.063 a
Super Nectar	0.86 a	0.84 ab	0.21 a	0.19	0.070 a	0.062 a
Depth (D)						
0-10	2.23 a	1.14 bc	0.18 c	0.21	0.134 a	0.091 b
10-20	2.22 a	2.46 a	0.20 bc	0.2	0.143 a	0.174 a
20-30	0.77 b	1.66 b	0.19 c	0.19	0.046 b	0.105 b
30-40	0.36 c	0.97 c	0.25 ab	0.19	0.031 b	0.060 bc
40-50	0.11 d	0.32 d	0.22 bc	0.18	0.007 c	0.020 c
50-60	0.09 d	0.30 d	0.17 c	0.18	0.006 c	0.018 c
60-70	0.09 d	0.26 d	0.26 a	0.21	0.006 c	0.019 c
IR	0.130	0.036	0.801	0.146	0.343	0.069
CV	0.001	0.034	0.027	0.164	0.001	0.148
D	0.001	0.001	0.005	0.213	0.001	0.001
IR × CV	0.001	0.072	0.147	0.680	0.025	0.836
IR × D	0.001	0.195	0.001	0.775	0.039	0.519
CV × D	0.001	0.211	0.018	0.150	0.001	0.625
IR× CV × D	0.001	0.252	0.001	0.015	0.008	0.317

Table 4.3 Continued

	Root classification[y] (% length per diameter class)					
	Fine (<0.5 mm)		Coarse (0.5-2 mm)		V. Coarse (>2.0 mm)	
Treatment	2011	2012	2011	2012	2011	2012
Irrigation (IR, ETc)						
50%	90.6	97.8	9.4	2.1	0.1 b	0.1
100%	93.8	97.2	5.9	2.7	0.3 a	0.1
Cultivar (CV)						
Mission	86.7 b	96.7	13.1 a	3.2	0.3 a	0.1
Da Vinci	95.9 a	97.1	4.0 b	2.8	0.1 b	0.1
Super Nectar	93.9 a	98.7	6.0 b	1.2	0.2 b	0.1
Depth (D)						
0-10	95.8 ab	96.7 ab	3.5 bc	3.0 ab	0.7 a	0.4 a
10-20	94.0 ab	97.0 ab	5.5 bc	2.8 ab	0.5 b	0.2 ab
20-30	91.0 bc	97.9 ab	8.9 ab	1.8 ab	0.2 c	0.3 ab
30-40	89.0 bc	98.3 ab	11.0 ab	1.7 ab	0.0 d	0.0 b
40-50	91.7 abc	98.3 ab	8.3 abc	1.7 ab	0.0 d	0.0 b
50-60	99.0 a	99.6 a	1.0 c	0.4 b	0.0 d	0.0 b
60-70	85.7 c	94.8 b	14.3 a	5.2 a	0.0 d	0.0 b
ANOVA			*P*-value			
IR	0.619	0.801	0.588	0.800	0.031	0.873
CV	0.010	0.261	0.012	0.303	0.002	0.777
D	0.008	0.137	0.006	0.154	0.001	0.088
IR × CV	0.841	0.808	0.874	0.830	0.001	0.532
IR × D	0.023	0.920	0.030	0.930	0.001	0.982
CV × D	0.014	0.199	0.012	0.219	0.001	0.250
IR× CV × D	0.387	0.535	0.411	0.683	0.001	0.243

[y]Roots classified according to diameter; fine (0-0.5 mm), coarse (0.5-2 mm) and very coarse (> 2 mm)

[z]Means in a column followed by the same letter are not significantly different at $P \leq 0.10$ according to the Duncan's multiple range test

ETc = Crop evapotranspiration

4.2.4 Fruit yield and quality

Fruits were harvested at half to full slip stage, fourteen times between 18 June (78 DAP, day after planting) to 5 August 2011 (126 DAP) and ten times between 25 June (71 DAP) and 24 July 2012 (100 DAP). MY, FN and FW were recoded as detailed in section 2.2.1.

Fruit quality parameters were determined on three class 9-count fruits from each plot. Fruit diameter, seed cavity diameter ratio and flesh and rind thickness were measured transversely with a digital caliper on half cut fruits. Soluble solid content and fruit firmness were measured as described in section 2.2.2. Mesocarp tissue flesh color indices L* (Lightness; -100 = black, +100 = white), C* (Chroma = color saturation $=a^{*2}+b^{*2}$), h° (hue angle (0° = red-purple, 90° = yellow, 180° = bluish-green, 270° = blue) = arctangent b*/a*) were determined with a Minolta chromameter (CR-400: Minolta Corp. Ramsey, NJ), calibrated with a white porcelain reference plate (McGuire, 1992).

4.2.5 Vitamin analysis

A flesh sample (~100 g fresh wt.) devoid of seeds and integument tissue was sampled in three random slices from each fruit and stored at -80°C until used for vitamin C and β-Carotene analysis. β-carotene was measured using the procedure described by Sadler et al. (1990) with some modifications. Free ascorbic acid (AA) and total ascorbic acid/vitamin C (TA) were extracted by homogenizing 10 g of frozen tissue in 10 ml of 3 g/100 mL meta-phosphoric acid (Sigma, St Luis, Mo) using a polytron homogenizer (Brinkman Instruments, Westbury, New York, USA) at a medium speed for 5 s and

vortexed for an additional 5 s. The homogenate was then filtered through a filter paper (Whatman No. 4, Whatman International, Ltd., Maidstone, England) and 2.0 ml of the filtrate centrifuged at 3000× g (Micro 12 Centrifuge, Fisher Scientific, Hanover Park, IL, USA) for 15 min. Ascorbic acid was determined using a Waters Alliance 2695 HPLC system equipped with photodiode array (PDA) detector (Model 2996, Waters Corp., Milford, MA, USA) set at 254 nm (Wimalasiri and Wills, 1983). Dehydroascorbic acid was determined using the procedure described by Chebrolu et al. (2012). A 500 µL sample of the supernatant was reduced with 500 µL of tris (2-carboxy ethyl) phosphine hydrochloride (TCEP) for 30 min before injecting to the HPLC for determination of TA. Dehydro-ascorbic acid (DHA) was calculated as the difference between TA and AA (Sharma et al., 2014).

4.2.6 Water use efficiency

The total water use for each irrigation rate was determined as the sum total of irrigation water applied and rainfall received during the cropping season. Agronomic water use efficiency (WUE) was calculated as marketable fruit yield (kg ha^{-1}) per millimeter of total water use (Table 4.5).

4.2.7 Statistical analysis

Data for each variable were subjected to analysis of variance (ANOVA) with a split split plot design using generalized linear model procedures of (SAS 9.1, SAS Inst., Cary, N.C., USA). Irrigation regime (50% ETc and 100% ETc) was the main plot, cultivar (Mission, Da Vinci and Super Nectar) was the subplot, and root sampling depth (10-cm to 70-cm) was the sub-sub plot factor (McIntosh, 1983; Box and Johnson, 1987).

The data were tested for homogeneity of variance with Levene's test and normality with the Shapiro-Wilk test. In root data, the problem of heteroscedasticity and non-normality is not unusual (Samson and Sinclair, 1994). Data on non-conforming variables was log transformed to achieve acceptable level of homogeneity of variance. This transformation has been previously used by Samson and Sinclair (1994) to resolve statistical problems in root length data. Differences among treatments were determined according to Duncan's multiple-range test.

4.3 Results

4.3.1 Rainfall and irrigation

Total rainfall received was 123 mm in 2011 and 155 mm in 2012 (Table 4.2). The differences (32 mm) were mainly due to higher rainfall events received during May and July in the 2012 season; otherwise, climatic conditions were similar for each growing season (Fig. 4.1). Rainfall contributed 23% and 28% of 100% ETc in the 2011 and 2012 seasons, respectively. A total of 36 irrigation events were applied in 2011. The first nine events applied the same total amount (78 mm) to both treatments to ensure adequate germination and stand establishment. After May 5, 27 different irrigation events were applied totalling 184 and 335 mm in the 50% and 100% ETc treatments, respectively. In 2012, 38 irrigation events were applied, with the first 6 applying the same total amount (45mm) followed by 32 additional applications after May 23, totalling 227 and 409 mm for 50% and 100% ETc respectively. Rainfall events during May 2012 reduced the water requirement for the establishment period by 42% (45 vs. 78 mm)

compared with 2011. Deficit irrigation (50% ETc) resulted in 37% (2011) and 44% (2012) savings of irrigation water.

4.3.2 Root growth

4.3.2.1 Root length density

Overall, deficit irrigation (50% ETc) had a significant effect ($P = 0.036$) on RLD in the 2012 season. Averaged across all cultivars, deficit irrigation increased RLD to 0.99 cm cm^{-3} compared to 0.77 cm cm^{-3} under 100% ETc in 2012. Data for 2011 showed a similar, but not statistically significant ($P = 0.130$) trend (Table 4.3). Cultivars also showed significant differences for RLD in both seasons, with Super Nectar and Mission having the highest RLD in 2011 and 2012 respectively. RLD also varied significantly with soil depth ($P \leq 0.001$), in spite of some inconsistency in the shallow layers (0 - 30 cm), it decreased with increasing soil depth (Table 4.3 and Fig. 4.2) in both seasons. The proportion of the RLD in the upper soil layer (0- 30 cm) was slightly higher in 2011 (78%) as compared to the one in 2012 (74%), whereas the trend was reversed in the deeper soil layer (40-70 cm) (Table 4.3; Fig. 4.2). The proportion of total RLD in the deeper soil layers (40-70 cm) was 26% in 2012 as compared to 22% in 2011.

Irrigation × cultivar interactions were significant for RLD in both seasons ($P = 0.10$); however, irrigation × depth, cultivar × depth, irrigation × cultivar × depth interactions were only significant in 2011 (Table 4.3), indicating that RLD response to deficit irrigation varied among the cultivars and soil depth (Fig. 4.2). Deficit irrigation significantly enhanced RLD in cv. Mission at 10-20 cm soil depth in season 2011 and at

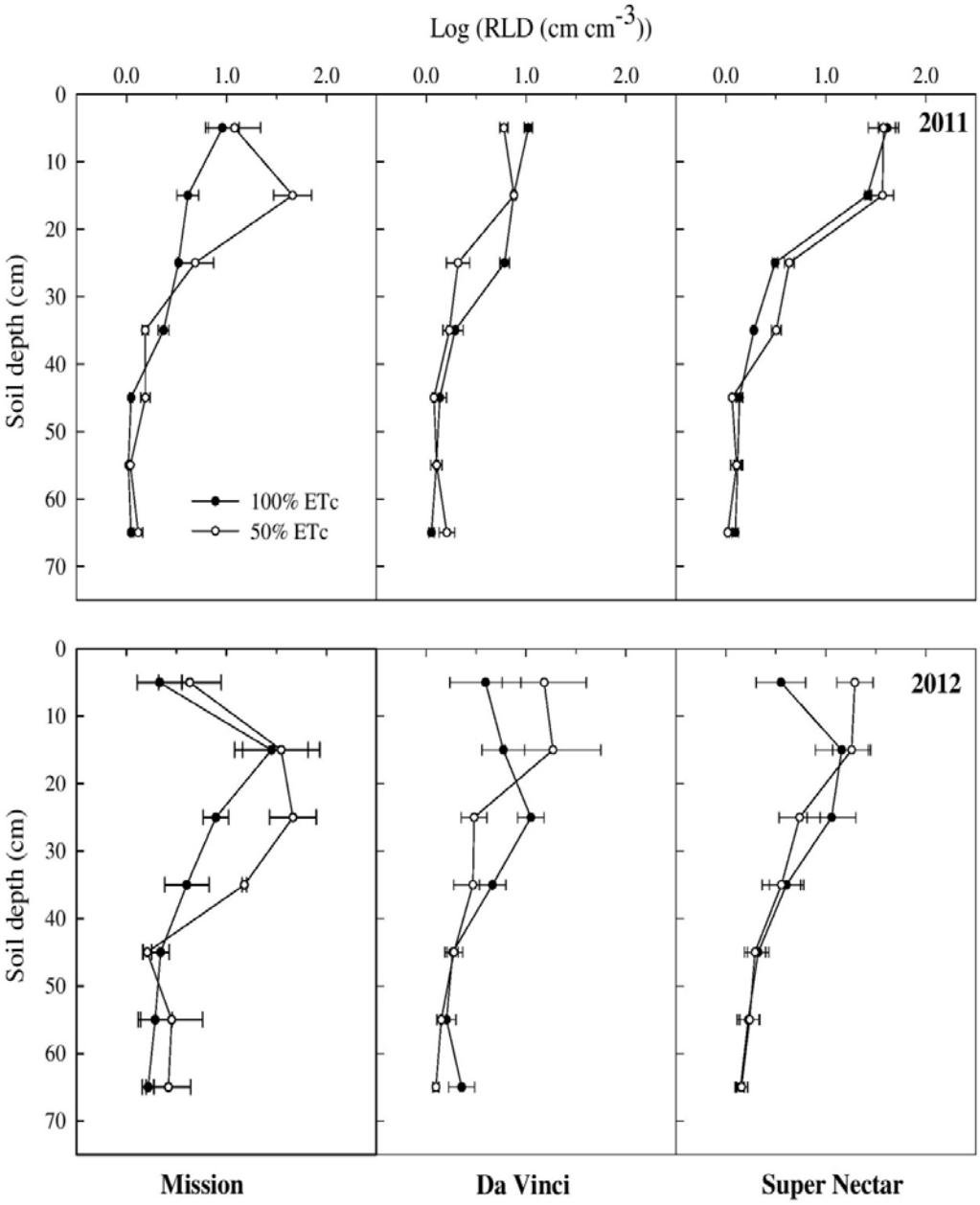

Figure 4.2 Interaction effects of irrigation rates and melon cultivars on root length density (RLD) in 2011 and 2012 seasons. Horizontal bars indicate mean ± SE

20 to 40 cm in 2012. In cv. Da Vinci RLD was reduced in 20-30 cm soil depth in both seasons (Fig. 4.2). However, in cv. Super Nectar RLD was unaffected by irrigation treatments in both seasons except a significant increase with deficit irrigation at 20-40 cm and 0-10 cm depth in 2011 and 2012 respectively (Fig. 4.2).

4.3.2.2 Average root diameter

The average root diameter (AVD) was unaffected by the irrigation rates in both seasons. However, AVD varied among the cultivars and depths in 2011. Mission (0.24 mm) had the largest AVD as compared to cv. Da Vinci (0.18 mm). Soil depth also had a significant effect on AVD with significant increase at 30-40 cm (0.25 mm) and 60-70 cm depth (0.26 mm) (Table 4.3). Irrigation × depth, cultivar × depth, irrigation × cultivar × depth interactions for AVD were significant in 2011 (Table 4.3), but no consistent patterns were observed (data not presented).

4.3.2.3 Root surface area

Since root surface area (RSA) is the function of root length and root diameter, the trends observed in RSA among the cultivars across irrigation rates and depths were very similar to RLD (Table 4.3). Overall, deficit irrigation increased RSA in 2012 (P = 0.069). The highest RSA was recorded for cv. Super Nectar (0.070 cm^2 cm^{-3}) in season 2011 and for cv. Mission (0.079 cm^2 cm^{-3}) in 2012. More than 70% of the total RSA was concentrated in the upper soil depth (0-30 cm). Irrigation × cultivar, irrigation × depth, cultivar × depth, irrigation × cultivar × depth interactions for RSA were significant in 2011 (Table 4.3), and the trends were similar to RLD (data not presented)

4.3.2.4 Root length classification

Cultivar Da Vinci had the highest allocation of root length to the fine root fraction (95.9%), while cv. Mission had the highest length allocation to coarse (13.1%) and very coarse (0.3%) roots (Table 4.3) in the 2011 season. In 2012, there were no differences (P = 0.261) in length allocation to the three root fractions between cultivars (Table 4.3). The percentage of fine roots varied with depth (P = 0.008 and P = 0.137 in 2011 and 2012 respectively) with a higher proportion at shallow depths and at 50-60 cm. A small proportion (< 2% of total length in 2011 and < 1.0% in 2012), of very coarse roots was distributed in the shallow soil depth (0-30 cm) in both seasons, but not beyond 30 cm depth.

4.3.2.5 Specific root length

Specific root length (SRL) was determined only in the 2012 season (Table 4.4). Irrigation rates or cultivars had no significant impact on SRL, both in shallow (0-30 cm) or deeper (40-70 cm) soil layers; however, a numerical decrease (9%) in SRL was observed under deficit irrigation in deeper soil layer. Irrigation and cultivar interaction had a significant effect (P = 0.006) on SRL in the shallow layer (Table 4.4). In cv. Mission deficit irrigation significantly increased SRL (410 m g^{-1}) as compared to 199 m g^{-1} at 100% ETc. Conversely, there was a decrease in SRL in cvs. Da Vinci and Super Nectar in response to deficit irrigation (Fig. 4.3).

4.3.2.6 Specific root area

Overall, deficit irrigation decreased specific root area (SRA) by 17% in shallow soil depth (P = 0.016) and 15% (P = 0.228) in deeper soil depth (Table 4.4). The highest

SRA occurred at shallow soil depth for cv. Mission (17.9 m^2 g^{-1}) and at deeper soil layers for Super Nectar (31.85 m^2 g^{-1}). However, the significant irrigation and cultivar interaction for SRA at shallow depth (Table 4.4) indicated that SRA increased (30%) by deficit irrigation in Mission but decreased in cvs. Da Vinci (43%) and Super Nectar (27%) (Fig. 4.3).

Table 4.4 Effect of deficit irrigation and melon cultivars on specific root length (SRL) and specific root area (SRA) for two soil depth intervals in 2012 season.

	SRL (m g^{-1} dw)		SRA (m^2 g^{-1} dw)	
	Depth		Depth	
Treatment	0-30 cm	40-70 cm	0-30 cm	40-70 cm
Irrigation rate (IR, ETc)				
50%	279.2	421.5	15.0 b	24.1
100%	276.2	464.6	17.3 a[z]	28.5
Cultivars (CV)				
Mission	304.6	384.6	17.9 a	21.8 b
Da Vinci	238.9	400.0	14.9 b	25.4 b
Super Nectar	290.1	544.5	15.6 b	31.9 a
ANOVA		*P*-value		
IR	0.943	0.544	0.016	0.228
CV	0.316	0.162	0.028	0.099
IR × CV	0.006	0.879	0.000	0.949

[z]Means in a column followed by the same letter are significantly different at P≤ 0.05 according to the Duncan's multiple range test
ETc = Crop evapotranspiration
dw = dry weight

4.3.3 Fruit yield and component traits

Exceptionally high marketable yields (t ha^{-1}) were obtained in both seasons (range, 54.1 to 106.5 t ha^{-1}). Overall, deficit irrigation caused a significant reduction in marketable yield (MY) (Table 5) of 30% (P = 0.045) in 2011 and 31% (P = 0.046) in

2012. Deficit irrigation significantly reduced marketable fruit number per vine (FN) by 20% (P = 0.007) in 2011 while, average fruit weight (FW) was decreased by 16% (P = 0.002) in 2012.

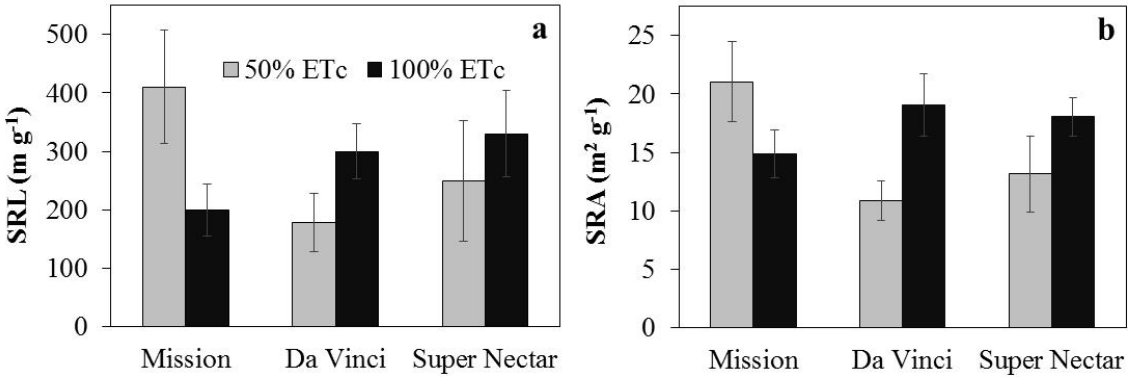

Figure 4.3 Interaction effects of irrigation rates and melon cultivars on specific root length (SRL; a) and specific root area (SRA; b) in 0-30 cm soil depth. Vertical bars indicate mean ± SE

Among the cultivars, Super Nectar produced the highest MY and FW while, cv. Da Vinci had the highest (FN) in both seasons. There was an irrigation rate × cultivar interaction for MY both in 2011 (P = 0.030) and 2012 (P = 0.001) seasons and on FN (P = 0.002) in 2012. Deficit irrigation caused the highest reduction in MY in cultivar Super Nectar, 43% (P = 0.001) in 2011 and 36% (P = 0.001) in 2012. Similarly, cvs. Mission and Da Vinci recorded a 23% and 30% reduction in MY in 2012, with a similar trend in 2011. The irrigation rate × cultivar interactions had a significant effect on FN during 2012 resulting in 19% ($P \leq 0.001$) and 26% ($P \leq 0.001$) reduction in Da Vinci and Super

Nectar respectively. The cultivar Mission and Super Nectar recorded a 25% (P = 0.001) and 12% (P = 0.019) reduction in FW in 2012 season (Table 4.5).

The correlation between fruit yield and average fruit weight (r = 0.61) was stronger than the correlation between fruit yield and fruit number per plant (r = 0.11) which indicates that the increase in fruit yield in the different treatment combinations was attributable mainly to the change in average fruit weight (Fig. 4.4a and 4.4b). Similarly, fruit number and fruit weight had a negative correlation (r = -0.64) (Fig. 4.4c). Reduction in fruit size with deficit irrigation was also evident from the significant decrease in fruit yield of 9-count class size (P = 0.013; 30%) and a corresponding increase (P = 0.073; 65%) in 12-count class size fruit yield in the season 2012 (Table 4.6). A similar trend was observed in 2011 with 12% numerical reduction in class 9-count size fruit yield and 16% increase in class 15-count (P = 0.008). Comparing cultivars, Super Nectar had 84.3% of class 9-count size fruit yield followed by Mission (43.1%); while, cv. Da Vinci had highest percentage (41.2% in 2011 and 53.5% in 2012) of class 15-count size fruit yield. Irrigation rate and cultivar interactions were significant in 2012 for cv. Mission only in class 9, - 12 and - 15-count and for Super Nectar in class-9 size fruit yield. In cultivar Mission deficit irrigation caused a 48% reduction in class 9-count, while 53% and 19% increase in class 12-count and 15-count size fruit yield respectively; whereas, cultivar Super Nectar recorded 19% reduction in percentage of class-9 size fruit yield under deficit irrigation (Table 4.6).

Table 4.5 Effect of deficit irrigation and melon cultivar on average fruit weight (FW), marketable number of fruits per vine (FN), marketable yield (MY), and water use efficiency (WUE) in 2011 and 2012 seasons

Treatment		2011				2012			
		FW (kg)	FN (No.)	MY (t ha^{-1})	WUE (kg ha^{-1} mm^{-1})	FW (kg)	FN (No.)	MY (t ha^{-1})	WUE (kg ha^{-1} mm^{-1})
Irrigation rate (IR, ETc)									
50%		1.50	2.4 b[z]	54.2 b	141.6	1.6 b	2.1	54.5 b	142.3
100%		1.60	3.0 a	77.1 a	144.1	1.9 a	2.6	78.7 a	139.5
Cultivar (CV)									
Mission		1.5 b	2.4 ab	59.4 b	131.3	1.7 b	2.1 b	58.6 ab	125.3 b
Da Vinci		1.1 c	3.1 a	54.1 b	118.9	1.2 c	2.8 a	55.1 b	116.9 b
Super Nectar		2.2 a	2.4 b	83.5 a	178.5	2.4 a	2.2 b	86.1 a	188.1 a
Interaction (IR × CV)									
Mission	50%	1.4	2.3	54.1	141.3	1.5 b	2.1	50.9 b	133.2 a
	100%	1.5	2.6	64.9	121.3	2.0 a	2.1	66.2 a	117.4 b
Da Vinci	50%	1.0	2.9	48.2	125.9	1.1	2.5 b	45.4 b	118.8
	100%	1.1	3.4	59.9	112.0	1.3	3.1 a	64.9 a	115.0
Super Nectar	50%	2.1	1.9	60.4 b[y]	157.8 b	2.2 b	1.9 b	70.4 b	191.1
	100%	2.3	2.8	106.5 a	199.2 a	2.5 a	2.6 a	104.9 a	186.1

[z]Means in a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test

[y]For interaction effects significant mean differences at $P \leq 0.05$ are indicated within cultivars. ETc = Evapotranspiration

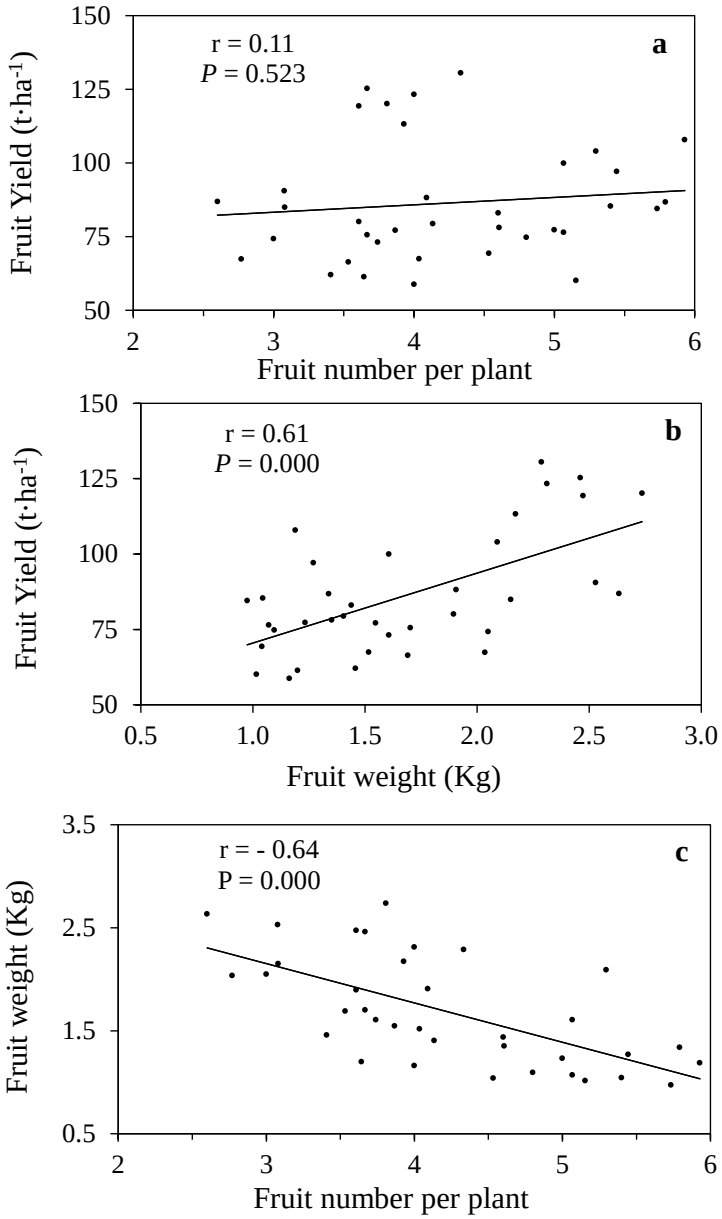

Figure 4.4 Relationship between fruit yield and fruit number (a), fruit yield and fruit weight (b) and fruit number and fruit weight (c) as influenced by irrigation rates and melon cultivars

Table 4.6 Effect of deficit irrigation and melon cultivars on fruit size distribution in 2011 and 2012 seasons

		Fruit size distribution[x] (% marketable yield, wt/wt)									
		2011					2012				
Treatments		9	12	15	18	23	9	12	15	18	23
Irrigation rate (IR, ETc)											
50%		45.3	21.4	23.6 b[y]	8.7	1.0	43.0 b	29.0 a	22.6	4.4	1.0
100%		51.7	19.3	20.4 a	7.6	1.0	61.6 a	17.6 b	19.0	1.8	0.1
Cultivar (CV)											
Mission		43.1 b	27.7 a	21.8 b	6.6 b	0.9	64.7 b	26.5 a	7.4 b	1.3 b	0.1 b
Da Vinci		18.2 c	21.8 ab	41.2 a	16.8 a	2.0	6.4 c	30.5 a	53.5 a	8.1 a	1.5 a
Super Nectar		84.3 a	11.5 b	3.04 c	1.1 b	0.0	85.7 a	12.9 b	1.4 b	0.0 b	0.0 b
Interaction (CV × IR)											
Mission	50%	42.0	24.7	25.6	5.9	1.8	44.3 b[z]	40.0 a	13.2 a	2.2	0.2
	100%	44.1	30.7	18.0	7.2	0.0	85.2 a	13.0 b	1.6 b	0.3	0.0
Da Vinci	50%	17.1	22.7	40.5	18.7	1.1	7.9	26.6	51.7	11.1	2.7
	100%	19.3	20.9	41.0	14.9	3.0	4.9	34.4	55.4	5.1	0.2
Super Nectar	50%	76.9	16.8	4.8	1.5	0.0	76.8 b	20.4	2.8	0.0	0.0
	100%	91.8	6.2	1.3	0.7	0.0	94.6 a	5.4	0.0	0.0	0.0

[x]Marketable fruits were classed according to the U.S. commercial trade standards (9-. 12-, 15-, 18- and 23-count per 18 kg carton)

[y]Means in a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test

Table 4.7 Effect of deficit irrigation and melon cultivar on fruit diameter, fruit firmness, rind thickness, and seed cavity:diameter ratio (SC:D) in 2011 and 2012 seasons

Treatment	2011				2012			
	Fruit diameter (cm)	Fruit firmness (N)	Rind thickness (mm)	SC:D ratio	Fruit diameter (cm)	Fruit firmness (N)	Rind thickness (mm)	SC:D ratio
Irrigation rate (IR, ETc)								
50%	14.3	25.9	0.4	0.3	15.0 b	25.7	0.7	0.4
100%	14.7	26.0	0.3	0.3	16.1 a	26.9	0.7	0.4
Cultivar (CV)								
Mission	13.2 b[y]	23.4 b	0.2 b	0.4 a	15.9 b	23.9 b	0.3 c	0.4 a
Da Vinci	13.2 b	24.5 b	0.4 a	0.2 b	13.3 c	27.1 a	0.5 b	0.3 b
Super Nectar	17.2 a	29.9 a	0.4 a	0.3 b	17.4 a	27.9 a	1.2 a	0.4 a
				P-value				
Interaction (IR × CV)	0.491	0.711	0.793	0.336	0.120	0.208	0.537	0.335

[y]Means in a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

4.3.4 Fruit quality components

Physical fruit quality characteristics were consistent over both seasons. Deficit irrigation reduced fruit diameter in 2012, but did not affect rind thickness (mm) and seed cavity: fruit diameter (SC:D) ratio. Among cultivars, Super Nectar recorded the highest fruit diameter, fruit firmness and rind thickness and Da Vinci had the lowest SC: D ratio in both seasons (Table 4.7).

Overall deficit irrigation had no significant effect on soluble solid content (%, SSC); except for cultivar Mission which recorded a 23% increase in SSC in response to deficit irrigation in 2011 (Fig. 4.5). Cultivar Super Nectar recorded higher SSC (13.3%) as compared to Mission (9.7%) and Da Vinci (11.9%) (Table 4.8). β-carotene is the main carotenoid present in yellow fleshed *reticulatus* melon cultivars (Mission and Da Vinci), but not in the white flesh *inodorus* melons (Super Nectar). Deficit irrigation had no significant effect on β-carotene content in cultivar Mission but had a significant increase (25%) in Da Vinci in 2011 (Fig. 4.5).

Overall deficit irrigation caused a numerical increase in AA (18%) in 2011, with a significant increase (42%) in 2012. Cultivar Mission recorded the highest AA and vitamin C compared to cvs. Da Vinci and Super Nectar in both seasons. Irrigation × cultivar interactions had no effect on AA, DHA and Vitamin C content (Table 4.8). Neither deficit irrigation nor cultivars had significant impact on color indices; L*, C* and hue° (data not presented).

Table 4.8 Effect of deficit irrigation and melon cultivar on soluble solids content (SSC), free ascorbic acid (AA), dehydroascorbic acid (DHA), vitamin C and β-carotene on fresh weight basis in 2011 and 2012 seasons

Treatment	SSC (%)	AA ($\mu g\ g^{-1}$)	DHA ($\mu g\ g^{-1}$)	Vitamin C ($\mu g\ g^{-1}$)	β-Carotene ($\mu g\ g^{-1}$)
			2011		
Irrigation rate (IR, ETc)					
50%	12.3	141.5	154.8	290.2	24.7
100%	11.3	123.6	162.8	284.2	21.4
Cultivar (CV)					
Mission	9.7 c[z]	196.2 a	180.3	366.3 a	22.8
Da Vinci	11.9 b	171.2 a	150.7	321.9 a	23.2
Super Nectar	13.3 a	26.8 b	146.6	173.4 b	-
Interaction (IR × CV)	0.102	0.306	0.187	0.927	0.032
			2012		
Irrigation rate (IR, ETc)					
50%	12.3	88.4 a	198.1	245.1	21.5
100%	12.3	46.4 b	229.3	276.6	21.3
Cultivar (CV)					
Mission	11.9	125.8 a	224.8	325.6 a	20.5
Da Vinci	12.7	65.8 b	227.2	281.9 b	22.3
Super Nectar	12.3	12.8 b	190.6	179.6 c	-
Interaction (IR × CV)	0.718	0.306	0.216	0.674	0.762

[z]Means in a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test
ETc = Evapotranspiration

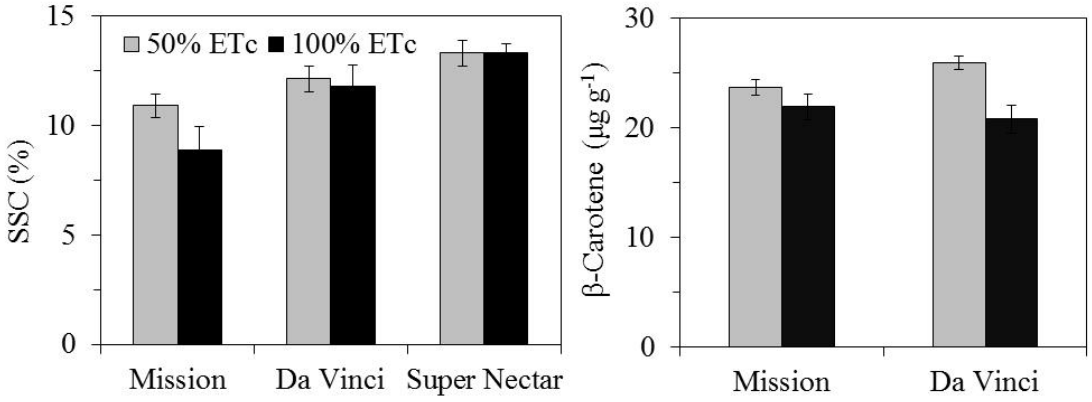

Figure 4.5 Interaction effects of irrigation rates and melon cultivars on soluble solids content (SSC; %) (left) and β-carotene (µg g^{-1}) (right) in 2011 season. Vertical bars indicate mean ± SE

4.3.5 Water use efficiency

Cultivars Mission and Da Vinci exhibited an increasing trend in WUE in response to deficit irrigation, but the difference was statistically significant only in cv. Mission (P = 0.017) in 2012 (Table 4.5). In cultivar Super Nectar WUE was decreased (P = 0.065) under deficit irrigation in the 2011 season. The percent reduction in marketable yield was also higher in Super Nectar (43.3% in 2011) which resulted in a decrease in WUE in this cultivar.

4.4 Discussion

In melons, the early phase of crop development requires constant maintenance of optimum soil moisture to assure high germination and successful seedling establishment. The cumulative rainfall was similar in both seasons, but the rainfall received during the seedling establishment period (before starting the differential irrigation) was higher in 2012 (87.4 mm) as compared to 2011 (2.3 mm) (Fig. 4.1). Therefore, 78 mm in 2011

and 45 mm in 2012 of irrigation water was applied for crop establishment (Table 4.1). As a result, the difference in initial irrigation was reflected in slightly lower volumetric soil water content values in 2012 than in 2011 season (data not presented). The significant reduction in class 9-count size fruit yield under deficit irrigation in 2012 (30%) compared to 2011 (12%) also indicates more stringent water stress during 2012. These differences in soil water content might have stimulated more root growth in the initial growth period and resulted in a higher RLD in 2012 as compared to 2011 (Table 4.3; Fig. 4.2).

Overall, deficit irrigation increased root length density by 22% and 12% in 2012 and 2011, respectively (Table 4.3). These differences can potentially be attributed to an altered source-sink relationship under deficit water supply causing more biomass allocation to roots (Kage et al., 2004). For example, in maize (*Zea mays* L.) mild water stress resulted in increased root growth compared to well-watered conditions (Sharp and Davies, 1985).

Root plasticity or the ability of melons to adjust root length distributions across soil depths in response to irrigation rates appears to be cultivar dependent. Deficit irrigation increased the RLD in cv. Mission, decreased in cv. Da Vinci and had no effect (except 0-10 cm soil depth, 2012) in cv. Super Nectar (Fig 4.2). Similarly, in a root trait genotypic variability study at seedling stage, (Crosby et al., 2008) found that melon genotypes belonging to *cantalupensis, inodorus* and *momordica* groups had differences for total and, fine root length, root area and root disease tolerance. Cultivar differences for root length distribution in response to soil aeration conditions have also been

reported in wheat (*Triticum aestivum* L.) (Box and Johnson, 1987). Thus, the genetic differences among melon cultivars may affect adaptation to moisture deficit conditions.

In our study, root length differences were observed only in shallow (10- to 40-cm) layers. Under water deficit, increased soil strength in clay soils might have prevented deep penetration. The soil depth that contains 90% of the roots, with maximum root activity and water uptake, is known as effective rooting depth (Atkinson, 2000). We found 74-78% of the total RLD was distributed in the top 30 cm layer (Table 3; Fig. 2). Similarly, in tomato Zotarelli et al. (2009) reported that 51-78% RLD in tomato was found in the top 0 to 15 cm of soil depth and substantially decreased with increasing soil depth, with 4-10% present at 60 to 90 cm. We also found, 3% (2011 season) and 8% (2012 season) of total melon RLD distributed in deeper layers (50- to 70 cm) (Table 4.3). (Sponchiado et al., 1989) indicated that drought tolerant bean cultivars had a deep root system as compared to drought sensitive cultivars. In winter wheat only 3% of the roots (dry weight basis) accounted for 20% of evapotranspiration requirements during dry periods (Gregory et al., 1978). Therefore, in our case cv. Mission shows potential for drought tolerance having increased root length in deeper layers under deficit moisture supply. Moreover, yield reduction in Mission was also less than cvs. Da Vinci and Super Nectar under deficit irrigation in both seasons (Table 4.5).

In cv. Mission, deficit irrigation also enhanced SRL and SRA by 51% and 30% respectively, as compared to 100% ETc irrigation rate. However, both parameters were depressed with deficit irrigation in cultivar Da Vinci and Super Nectar. The average root diameter and diameter based RL classification results also showed that cultivar Mission

had higher average diameter and higher proportion of coarse and very coarse roots, indicating that cv. Mission had a better root skeleton to support fine roots and root hairs than other cultivars. These results suggest that cultivar Mission was more resource efficient at deficit irrigation conditions. Some increase in diameter at deeper layers can be explained by the physical limitation created by the slightly higher bulk density (data not presented) which might have increased soil strength (Unger and Kaspar, 1994).

Deficit irrigation decreased marketable fruit yield; however, the response varied among cultivars. Mission (muskmelon) and Da Vinci (tuscan type) showed less sensitivity to water deficit than cv. Super Nectar (honeydew). Less reduction in fruit yield can be attributed to their shorter growing season as reported by Stewart and Musick (1982), ability to adapt to low moisture through enhanced root growth (e.g. Mission) and other physiological adjustments (e.g. Da Vinci) as indicated by enhanced β-carotene levels (Fig. 4.5). However, under conventional cultivation practices all melon cultivars, even from diverse groups, are treated alike for their irrigation water requirement. Thus, varying cultivar responses to deficit irrigation indicate the need for cultivar and region specific irrigation recommendations in melons.

The reduction in fruit yield in response to deficit irrigation was mainly due to decreased fruit weight and diameter (Fig.4.4; Table 4.7). Cabello et al. (2009) also observed reduction in fruit size in melons under deficit irrigation. The decrease in fruit size with deficit irrigation was mostly associated with a decrease in class-9 size fruits and increase in the proportion of class-12 or lower classes. Irrigation water supplied during the establishment period can also be responsible for less reduction in fruit number

as compared to fruit weight. Before starting the differential irrigation at 23 DAP and 32 DAP in 2011 and 2012 seasons respectively, both treatments (50% ETc and 100 ETc) were supplied with similar amount of water to maximize stands and uniform crop establishment. By the time deficit irrigation was imposed plants were already programmed for fruit number; therefore the fruit enlargement stage was more affected by water stress, resulting in reduction of fruit size. In this study the combination of silty clay soil having higher moisture conserving capacity with SDI plus plastic mulching kept soil moisture at adequate levels during the flowering and fruit setting period. Similar observations have also been reported by Hartz (1997) who found differences in fruit yield among irrigation treatments (deficit vs. well watered) are less prevalent in heavy soils that have high moisture holding capacity.

Similar to Hartz (1997) findings, variable irrigation rates did not affect physical fruit quality characteristics. No treatments differences for SC: D ratio and rind thickness (Table 4.7) indicated that deficit irrigation had on adverse impact on seed cavity and flesh thickness. Compact and smaller seed cavity in Da Vinci resulted in lower SC: D ratio among the cultivars. In our study subsurface drip irrigation never allowed the root zone to be over saturated which could have had an adverse impact on fruit quality as previously reported (Lester et al., 1994). However, a 25% increase in β-carotene (Fig. 4.5b) and 23% increase in SSC (Fig. 4.5) for cv. Da Vinci and Mission respectively in season 2011, and overall 42% increase in ascorbic acid in season 2012 suggested a positive impact of deficit irrigation on fruit quality (Fig. 4.5b). In cv. Super Nectar (*inodorus* type) even though the yield reductions were up to 43%; no adverse impact on

fruit quality was measured. Cultivar dependent responses to deficit irrigation have also been observed in other vegetable crops such as spinach (*Spinacia oleracea* L.) (Leskovar and Piccinni, 2005) and watermelon (Leskovar et al., 2004).

Overall, deficit irrigation resulted in 37% and 45% water savings in 2011 and 2012 respectively. Improved WUE can be achieved either by achieving the same yield with less water or less water use resulting in proportionally lower reduction in yield as compared with corresponding reduction in water used. WUE increased in cv. Mission as the quantity of water applied decreased by 45% (382 mm in 50% ETc as compared to 464 mm in 100% ETc) and with a relative yield reduction of 30% (Table 4.7). Higher WUE has also been achieved with deficit irrigation in watermelon (Leskovar et al., 2004).

CHAPTER V

ROOT GROWTH DISTRIBUTION PATTERNS OF *RETICULATUS* AND *INODORUS* MELON (*CUCUMIS MELO* L.) UNDER SUBSURFACE DEFICIT IRRIGATION

5.1 Background

Root growth distribution pattern in the soil profile is an adaptive plant response to spatial and temporal constraints to resource availability. Root growth maintenance under water deficit is therefore critical to attain and maintain adequate nutrient and water uptake (Fageria and Moreira, 2011). Plant breeders have recognized the importance of genetics on maintaining root growth for optimum crop yield under water deficit conditions (O'Toole and Bland, 1987; Gewin, 2010; Liu et al., 2011), however complex drought tolerance mechanisms and low heritability have limited the progress in developing water deficit adapted cultivars particularly in vegetable crops. To some extent, the cultivars developed under optimal inputs also have shown potential to perform well under water stress (Cattivelli et al., 2008) . Cultivars differ in root growth adjustments to deficit soil moisture (Wasson et al., 2012), depending upon their interactions with soil type (Bengough et al., 2006), crop management (Kirkegaard and Hunt, 2010) and climatic conditions (Machado et al., 2003). Favorable cultivar and management (i.e. irrigation) interactions can be exploited for selecting cultivars adapted to water limited environments.

Due to recurrent droughts and competition from industry and urban sectors, the share of underground water supplies to agriculture has rapidly declined in the southern US (Leskovar and Piccinni, 2005). In the future, inevitable water restrictions can lead to a major shift in the prevalent cropping systems and areas selected for intensive vegetable production in the southern semiarid regions of the U.S., such as the Wintergarden of Texas. Therefore, in order to adopt water saving practices to preserve cropping system diversity under such environments, it is very important to better understand the factors affecting root growth and plant water use (Bengough et al., 2011).

Sustained water deficit may change root distribution patterns and root traits, such as diameter and specific root length (length per mass), as an adaptation strategy to decreasing soil moisture and the impact of decreasing soil moisture on soil physical properties, i.e. increased soil strength (Sharp and Davies, 1985; Unger and Kaspar, 1994). Understanding root growth adaptation dynamics of cultivars to prolonged stress can help in allocation of available water resources for maximizing returns.

Deficit irrigation combined with subsurface drip irrigation offers a suitable alternative system for melon cultivation in arid and semiarid environments, which are characterized by high evaporative demands during hot summers. However, the tendency of root system to preferentially grow around the emitter area along the drip tape (Oliveira et al., 1996) can adversely affect the utilization of water stored in deeper soil profile. Therefore cultivars having the ability to extend deep root growth under water deficit can be useful to overcome this limitation of subsurface irrigation.

Above-ground adaptations to water deficit have been reported in melon (Fabeiro et al., 2002; Cabello et al., 2009), but research on root growth maintenance under sustained soil water deficits in the field has been lacking. Most of the irrigation studies on root growth have been conducted in tomato (*Lycopersicon esculentum* Mill.) (Oliveira et al., 1996; Machado et al., 2003; Machado and Oliveira, 2005; Zotarelli et al., 2009), cauliflower (*Brassica oleracea* L. var. *botrytis*) (Kage et al., 2000), and lettuce (*Lactuca sativa* L.) (Jackson and Stivers, 1993). Franco and Leskovar (2002) studied the effect of nursery irrigation on melon transplants, however drought adaptation responses at the seedling stage are different from the ones experienced in the field (Blum, 2005).

There is an urgent need to develop a reliable and efficient method for estimating root growth under water stress in the field. Minirhizotron is a non-destructive method for observing and monitoring live roots *in situ* on transparent interfaces, which provide images on root production over time and space (Johnson et al., 2001). However, due to tube installation artifacts, minirhizotron has been reported to underestimate root growth in upper soil layers (< 30 cm) and over-estimate in deeper layers (> 30 cm) in crops such as fababean (*Vicia faba* L.) (Heeraman and Juma, 1993), sorghum [(*Sorghum bicolor* (L.) Moench] and maize (*Zea mays* L.) (Upchurch and Ritchie, 1983; Samson and Sinclair, 1994). Heeraman and Juma (1993) reported that RLD estimates obtained from minirhizotron and soil core methods were significantly correlated for barley (*Hordeum vulgare* L.), but not for fababean. Hence, Box and Ramsuer (1993) emphasized the need for calibration of minirhizotron estimates with destructive methods for each soil, climate and crop or in some cases cultivar. Another consideration is that under water deficit,

shrinking of soil can create voids on soil-tube interface and modify root growth responses (Rytter and Rytter, 2012), which further justifies the need to confirm the reliability of minirhizotrons to screen for drought tolerance.

Root growth distribution is an important indicator of soil water uptake (Sharp and Davies, 1985). However, the water uptake patterns are not simply controlled by L_a, rather it depends upon the complex interactions among L_a and soil factors (Coelho and Or, 1999) . For implementing precise and cultivar specific irrigation strategies, a real time monitoring of spatial and temporal water uptake patterns is also critical along with monitoring root growth patterns (Zotarelli et al., 2009).

The purpose of this study was to compare the effect of sustained deficit irrigation (50% ETc) vs. full irrigation (100% ETc) on root distribution patterns of three diverse melon cultivars namely Mission (*reticulatus*; muskmelon type), Da Vinci (*reticulatus*; tuscan type) and Super Nectar (*inodorus*; honeydew type) as described in section 4.1. We expected that the morpho-physiological differences in fruit characteristics would also be exhibited in root growth adaptations to deficit soil moisture. The overall aim of this two year study was to determine the impact of deficit irrigation on seasonal root growth patterns of these three diverse melon cultivars under subsurface irrigation using minirhizotron. We expect, this information will be a useful benchmark in screening drought tolerant cultivars to sustain melon productivity in the semiarid regions around the world.

5.2 Materials and methods

5.2.1 Experimental details

The experimental details are as described in sections 4.2.1 and 4.2.2. Monthly rainfall and maximum and minimum temperature during the 2011 and 2012 seasons are given in Table 5.1. Soil samples (up to 90 cm depth) were collected before planting and analyzed for soil physical and chemical properties at the Texas A&M soil testing laboratory (Table 5.2).

5.2.2 Treatments

The experiment was designed as a split plot with irrigation rates *viz*. 50% ETc and 100% ETc assigned to main plots and cultivars to sub plots. Monthly irrigation frequency and total amount of water applied (irrigation and rainfall) to each treatment is given in Table 5.3.

5.2.3 Root measurements

5.2.3.1 Minirhizotron

Seasonal root growth patterns were measured using the minirhizotron technique. All procedures and measurement methods were as described in section 3.2.3.Root growth was measured seven and six times in 2011 and 2012 respectively, but for clarity data has been presented only for sampling dates corresponding to important phenological stages *viz*. at flowering (28 and 32 DAP), fruit setting (42 and 46 DAP), fruit ripening period (90 and 80 DAP) and after final harvest (131 and 107 DAP) for 2011 and 2012 seasons respectively (Fig. 5.3 and 5.4).

Table 5.1 Monthly maximum and minimum temperature and rainfall during 2011 and 2012 seasons, Uvalde, TX

Year		Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)
2011				
	March	27.7	14.1	5.8
	April	32.1	18.5	0.3
	May	32.9	20.2	61.5
	June	36.3	23.5	35.8
	July	36.7	24.3	24.6
	August	38.1	25.2	0.8
2012				
	March	25.6	13.2	49.5
	April	30.5	17.4	3.3
	May	31.2	19.7	87.1
	June	35.5	23.6	0
	July	35.0	23.6	67.6
	August	36.4	24.3	8.9

Table 5.2 Pre-plant soil physical and chemical properties in 2011 and 2012 seasons, Uvalde, TX

Soil depth (cm)	Texture	Sand %	Silt %	Clay %	pH	OM %	NO_3-N	NH_4-N	P	K	Na	Mg	S	Ca
							----------			mg kg^{-1}	----------			g kg^{-1}
						2011								
0-15	Clay	31	27	42	7.7	2.60	10	-	73	714	106	332	23	13.4
15-30	Clay	27	28	45	7.9	2.67	6	-	65	684	87	315	20	13.3
30-45	Clay	29	23	48	7.8	2.59	7	-	28	509	108	298	22	14.8
45-60	Clay	27	24	49	7.9	2.55	13	-	11	438	125	270	25	18.1
60-90	Clay	27	24	49	7.9	2.27	9	-	7	385	111	251	29	19.5
						2012								
0-15	Clay	22	27	51	8.1	2.37	32	2.6	64	864	142.0	395	26	17
15-30	Clay	20	31	49	8.1	2.56	11	2.5	59	727	149.0	357	21	16
30-45	Clay	21	27	51	8.1	2.47	6	2.4	40	646	164.0	336	20	17
45-60	Clay	13	31	56	8.1	2.34	11	2.6	8	463	153.0	248	20	22
60-90	Clay	22	24	54	8.2	2.12	10	3.1	6	398	157.0	201	22	22

EC = Electrical conductivity; OM = Organic matter; N = Nitrogen; P = Phosphorus; K = Potassium; Na = Sodium; Mg = Magnesium; S = Sulfur; Ca = Calcium

Soil samples (0 to 90 cm depth) were collected on 1 April, 2011 and 15 April, 2012

Table 5.3 Frequency (No.) and amount (mm) of irrigation applied and rainfall received during 2011 and 2012 seasons, Uvalde, TX

Irrigation rate	April		May		June		July		Aug.		Total	Total
(ETc)	No.	mm	No.	mm	No.	mm	No.	mm	No.	mm	No.	mm
					2011							
50%	9	78	5	28	12	67	8	74	2	14	36	261
100%	9	78	5	59	12	132	8	117	2	27	36	413
Rainfall	0	0	6	62	1	36	4	25	0	0	11	123
					2012							
50%	4	37	5	21	13	73	10	69	6	27	38	227
100%	4	37	5	33	13	144	10	140	6	55	38	409
Rainfall	0	0	7	87	0	0	7	68	0	0	14	155

ETc = Crop evapotranspiration
Crop was planted on 1 April 2011 and 15 April in 2012
Differential irrigation started on 5 May 2011 and 23 May 2012 (34 and 38 days after planting, respectively)

5.2.3.2 Soil core

Root core samples were collected after final harvest in both years using a hydraulic soil coring and drilling machine (Giddings Machine Co., Windsor CO, USA). Sampling was done at 10 cm from the middle of the planting row at the plant next to the minirhizotron tube (Machado et al., 2003). Root length density (RLD; cm cm^{-3}) was determined as described in section 4.2.3. For comparing soil core and minirhizotron techniques RLD and L_a (after final harvest) at each depth were converted to percentage of total RLD and L_a in the soil profile of 0 - 70 cm (Fig. 5.6).

5.2.4 Soil moisture status

Volumetric soil moisture content was monitored with ECH_2O soil moisture probes (EC-5; Decagon Devices Inc., Pullman, WA). The sensor probes were installed in the middle of the bed at 15, 30 and 60 cm depths for each treatment as previously described by Leskovar et al. (2012). Data were recorded at every 30 min with data loggers but, for clarity averages of 24 hour are presented.

5.2.5 Bulk density

After the last harvest, soil cores were collected to determine bulk density for the different depths as detailed in section 3.2.4.

5.2.6 Statistical analysis

All statistical analyses were performed using a generalized linear model procedure of SAS 9.2 version (SAS Inst., Cary, N.C., USA). The L_a, ARD and RLD were analyzed according to a split plot design with sub-sampling with year, growth stage, and irrigation rate as the main plots, cultivars as the subplots, and soil depth as the

sub-sub plots (McIntosh, 1983). Significant interactions among all factors were explored. The L_a, ARD and RLD were log transformed to establish an acceptable level of homogeneity of variance across main factors. Samson and Sinclair (1994) also used the same transformation to resolve the statistical problems in root length intensity. Treatment differences were determined using Duncan's multiple range tests at $P \leq 0.05$. Sigma plot software (Systat Software, Inc., San Jose, California USA) was used for plotting graphs.

5.3 Results

5.3.1 Rainfall and irrigation

To the total amount of irrigation water applied, rainfall contribution was 23% (123 mm) and 28% (155 mm) of 100% ETc in 2011 and 2012 respectively (Table 5.3). Although the amount of rainfall received during both cropping seasons was almost similar, the distribution patterns were quite different (Table 5.1 and 5.3). Cumulative rainfall received during the pre-plant time (March) and seedling establishment (before starting differential irrigation) was higher in 2012 as compared to 2011 (140 vs. 6.1 mm), but later in the season, no rainfall was received after the third week of May (30 DAP) to the first week of July (84 DAP) in the 2012 season. This period corresponds to the growth stages of fruit setting to ripening (Table 5.1 and Fig.5.1). During the crop establishment period (seeding to the start of the differential irrigation) both 50% and 100% ETc irrigation treatments received a similar amount of irrigation water i.e. 78 mm in 2011 and 45 mm in 2012 through 9 and 6 irrigation events, respectively.

After the differential irrigation was established, 50% and 100% ETc irrigation rates received a total of 184 and 335 mm in 2011 and 182 and 364 mm in 2012, respectively. Considering the seasonal water application deficit irrigation (50% ETc) resulted in 37% (2011) and 44% (2012) savings of irrigation water.

5.3.2 Soil conditions

The clay content and soil pH of the experimental site were slightly higher in 2012 as compared to 2011 (Table 5.2). Except for phosphorus (P), concentration of all other nutrients was also higher in 2012 as compared to 2011. NO_3-N content at 0-15 cm soil depth was 69% higher in 2012 than in 2011. In general, concentration of all nutrients, except N, decreased with soil depth. For example in 2012, N content first decreased (32 to 6 mg kg^{-1}) up to 30-45 cm depth and again increased (6 to 11 mg kg^{-1}) in deeper layers. The ideal soil bulk density for root growth in clay soils is less than 1.40 g cm^{-3} (Brady and Weil, 2002). The bulk density of the experimental site was 1.07 (0 - 10 cm), 1.22 (10 - 20 cm), 1.42 (20 - 30 cm), 1.23 (30 - 40 cm), 1.06 (40 - 50 cm), 1.15 (50 - 60 cm) and 1.32 (60 - 70 cm) g cm^{-3} for their respective soil depths. The soil below 25 cm depth contains a hard pan due to presence of considerable amount of caliche coated limestone (20 - 40%) which becomes very hard under dry condition (USDA, 1969).

5.3.3 Soil moisture

The real time trends in volumetric soil water content for Mission, Da Vinci and Super Nectar cultivars at 50% and 100% ETc irrigation rates monitored at 15, 30 and 60 cm soil depths are shown in Fig. 5.1. Overall, water content fluctuations observed at

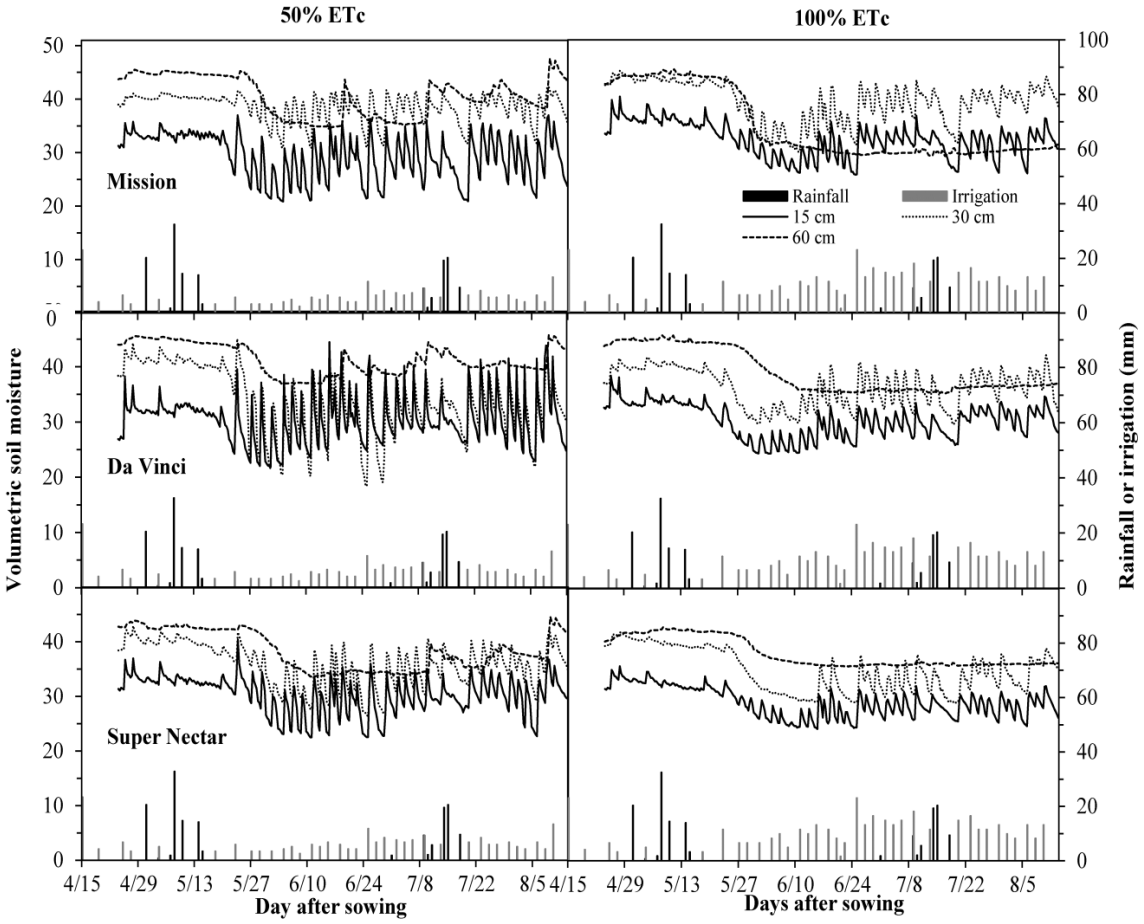

Figure 5.1 Volumetric soil moisture (%) at 15, 30 and 60 cm soil depths, rainfall, and irrigation events during 2012 season, Uvalde, TX

50% ETc irrigation rate were higher as compared to 100% ETc at 15 and 30 cm depths. This may be due to the readjustments in hydraulic conductivity and growth activity of roots (very fine roots and root hairs) between irrigation/rainfall events (Coelho and Or, 1999) .

The cultivars varied in their water uptake within each irrigation rate. At 100% ETc, cv. Mission showed more water absorption at 60 cm soil depth as compared to Da Vinci and Super Nectar. Further, during the dry period (May 27 to July 8) in cv. Da Vinci at 50% ETc soil moisture content was occasionally less at 30 cm soil depth than at 15 cm soil depth, which also corresponds to enhanced root growth in 10-30 cm of soil depth zone at fruit setting stage (Fig. 5.4). This indicates that Da Vinci absorbed more water at 30 cm soil depth. During the same dry period, lower water content was observed at 60 cm soil depth at 50% ETc in cv. Super Nectar which appears to be associated with enhanced root growth in the 60-70 cm soil depth (Fig. 5.4).

5.3.4 Root length intensity

5.3.4.1 Year and growth stage effects

Table 5.4, and 5.5 show means, and ANOVA for root length intensity (L_a) as affected by year, growth stage, irrigation rate, cultivar, and soil depth. Year had a significant ($P \leq 0.001$) impact on L_a (Table 5.4.). Overall, significantly higher L_a was recorded in 2012 (3.7 mm cm^{-2}) as compared to 2011 (0.5 mm cm^{-2}). Growth stage also had a significant effect ($P = 0.014$) on L_a. The maximum L_a (2.3 mm cm^{-2}) was attained at the fruit ripening stage and decreased by 13% between fruit ripening and final harvest.

5.3.4.2. Irrigation rate effects

Overall, irrigation rates had significant differences (P = 0.055) for L_a with a 39% (1.8 vs. 1.3 mm cm^{-2}) increase in L_a under deficit irrigation (50% ETc) as compared to 100% ETc. Irrigation × year interaction also affected (P = 0.086) L_a. In 2012, deficit irrigation caused a 70% increase (4.25 vs. 2.50 mm cm^{-2}; P = 0.026) in La as compared to 100% ETc, while it was the same (0.53 vs. 0.49 mm cm^{-2}; P = 0.812) in 2011 (data not shown).

5.3.4.3 Cultivar effects

Although L_a was not affected by cultivar, yet there were significant depth × cultivar (P = 0.025) and depth × cultivar × year ($P \leq 0.074$) interactions on L_a which indicates that root distribution of cultivars in response to irrigation rates varied at different soil depth and years.

5.3.4.4 Root growth patterns along soil depth

Across year, growth stage, irrigation rate and cultivars, soil depths had significant ($P \leq 0.001$) effects on L_a with the highest L_a (3.0 mm cm^{-2}) recorded at 0 - 10 cm soil depth. However, significant interactions among year × soil depth ($P \leq 0.001$) for L_a showed that root growth distribution patterns along the soil depth varied among years. In 2011, 11% of the total profile L_a was concentrated in the deeper soil layers (30-70 cm), while in 2012, 55% was observed in the deeper layer (data not shown). Depth × irrigation × years interaction also had significant effect (P = 0.002) on L_a. In 2012, deficit irrigation (50% ETc) significantly improved L_a at 40-70 cm of soil depth as compared to 100% ETc irrigation rate (Fig. 5.2).

Table 5.4 Analysis of variance of root length intensity (L_a) as influenced by year, growth stage, irrigation rate, cultivar, and soil depth during 2011 and 2012 seasons, Uvalde, TX. Data were collected using minirhizotron

Source	d.f.	L_a
Year (Y)	1	***
Growth stage (S)	3	**
Y × S	3	NS
Irrigation rate (IR)	1	*
IR × Y	1	†
IR × S	3	NS
IR × Y × S	3	NS
Error a	16	
Cultivar (C)	2	NS
C × Y	2	NS
C × S	6	NS
C × IR	2	NS
C × Y × S	6	NS
C × S × IR	6	NS
C × Y × IR	2	NS
C × Y × S × IR	6	NS
Error b	59	
Soil depth (D)	6	***
D × Y	6	***
D × S	18	NS
D × IR	6	***
D × C	12	*
D × Y × S	15	NS
D × IR × Y	6	NS
D × IR × S	18	NS
D × C × Y	12	†
D × C × S	36	NS
D × C × IR	12	NS
D × IR × Y × S	15	NS
D × C × Y × S	30	NS
D × C × S × IR	36	NS
D × C × Y × IR	12	NS
D × C × Y × S × IR	30	NS
Experimental error	509	

†, *, **, *** show significant difference at P ≤ 0.1, 0.05, 0.01 and 0.001 respectively
NS, not significant at P ≤ 0.1

Table 5.5 Mean root length intensity (L_a) as influenced by year, sampling date, irrigation rate, cultivar, and soil depth during 2011 and 2012 seasons, Uvalde, TX. Data were collected using minirhizotron

Main effect	L_a (mm cm^{-2})
Year	
2011	0.5[b]
2012	3.7[a]
Growth stage	
Pre-flowering	0.6[c]
Fruit setting	1.3[b]
Fruit ripening	2.3[a]
Final harvest	2.0[ab]
Irrigation rate (ETc)	
50%	1.8[a]
100%	1.3[b]
Cultivar	
Mission	1.4
Da Vinci	1.7
Super Nectar	1.4
Soil depth (cm)	
0-10	3.0[a]
10-20	2.2[b]
20-30	1.6[c]
30-40	1.0[de]
40-50	1.3[cd]
50-60	1.2[d]
60-70	0.8[e]

ETc = Crop evapotranspiration

[z]Means of main factor followed by different letters are significantly different at $P \leq 0.05$ according to the Duncan's multiple range test

Pre-flowering (28, 32), Fruit setting (42, 46), Fruit ripening (90, 80), Final harvest (131, 107) days after planting in (2011, 2012) respectively

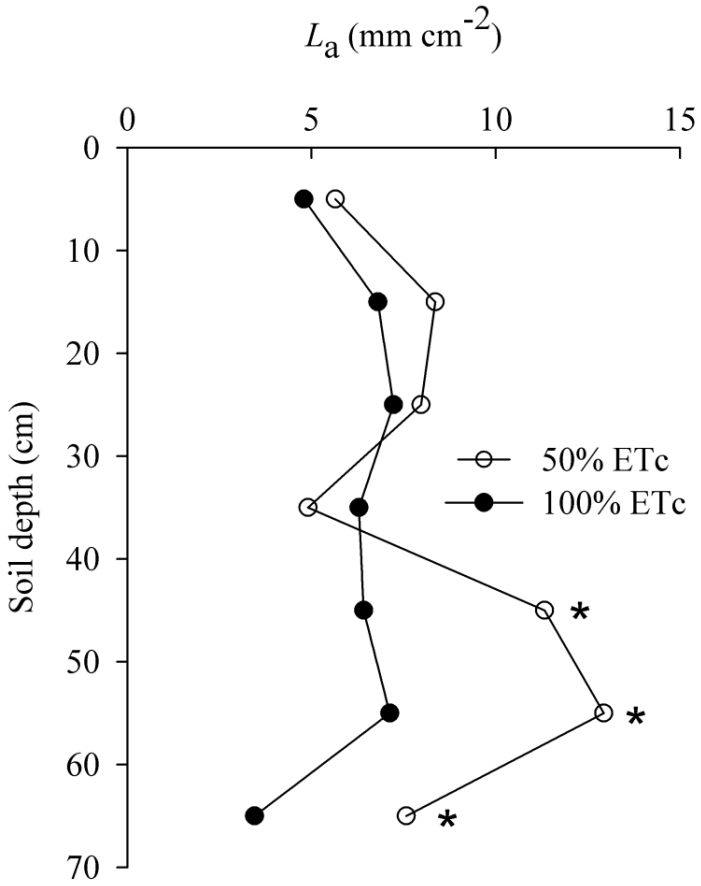

Figure 5.2 Effect of irrigation rates (50% and 100% ETc) on root length intensity (L_a) for different soil depths. Data presented as mean values for irrigation rates across cultivars and sampling dates (n=108). Asterisk (*) represents significant differences between irrigation rates at $P \leq 0.05$. Data were collected using minirhizotron

5.3.4.5 Main factor interactions by year and growth stage

Table 5.6 shows ANOVA and means of L_a as affected by irrigation rate, cultivar, and soil depth over growth stages in 2011 and 2012. Irrigation × cultivar × depth interaction had significant effect ($P \leq 0.1$) on L_a at all the growth stages except at fruit setting and final harvest in 2011. However cultivar × soil depth interactions were significant ($P \leq 0.1$) at all stages in both years. These significant interactive effects indicated that L_a distribution patterns among irrigation rates and cultivars vary over soil depth.

Fig.5.3 depicts L_a in the soil profile at four growth stages in 2011. L_a decreased at all growth stages with increasing soil depth and most of the L_a was concentrated in the 0-20 cm soil depth. At fruit setting and fruit ripening stage deficit irrigation enhanced L_a in all three cultivars between 0 - 30 cm soil depth. After final harvest, L_a decreased under deficit irrigation as compared to 100% ETc, except in cv. Mission at 0 - 10 cm soil depth. Similarly, in 2012 at fruit setting stage deficit irrigation promoted deep root growth (> 40 cm) in cv. Mission, which was maintained throughout the season except for a general inhibition at 20 - 40 cm soil depth (Fig. 5.4). A similar trend was observed in cv. Da Vinci though the differences were less pronounced at later growth stages. In cv. Super Nectar deficit irrigation resulted in a decreasing trend in L_a in the upper soil layers (0 - 30 cm) at fruit setting stage however, an increase in L_a was observed in deeper soil layer (40 - 70 cm). This increase diminished at subsequent growth stages.

Table 5.6 ANOVA and mean root length intensity (L_a) as influenced by irrigation rate, cultivar, and soil depth at different growth stages during 2011 and 2012 seasons, Uvalde, TX. Data were collected using minirhizotron

	L_a (mm cm^{-2}) day after planting							
	2011				2012			
Main effect	PF	FS	FR	FH	PF	FS	FR	FH
Irrigation rate (IR, ETc)								
50%	0.4	0.6^{a}	0.6	0.5^{b}	2.9	4.4	7.0	6.6
100%	0.2	0.2^{b}	0.5	0.8^{a}	1.8	2.8	5.0	4.5
Cultivars (C)								
Mission	0.4	0.6	0.7	0.9	3.3	2.9	5.7	5.4
Da Vinci	0.3	0.3	0.6	0.3	2.1	4.5	5.7	5.5
Super Nectar	0.3	0.3	0.7	0.5	1.8	3.3	6.4	5.5
Soil Depth (D, cm)								
0-10	2.0^{a}	2.0^{a}	3.0^{a}	4.0^{a}	2.8^{a}	4.3^{ab}	4.6^{ab}	5.1^{ab}
10-20	0.5^{b}	0.7^{b}	0.9^{b}	1.5^{b}	2.8^{a}	5.0^{a}	7.9^{a}	6.7^{a}
20-30	0.2^{bc}	0.3^{c}	0.8^{b}	0.7^{c}	2.2^{a}	3.9^{ab}	6.0^{ab}	6.5^{a}
30-40	0.2^{bc}	0.2^{c}	0.1^{c}	0.2^{c}	1.6^{b}	3.2^{ab}	4.7^{ab}	4.7^{ab}
40-50	0.1^{bc}	0.1^{c}	0.1^{c}	0.1^{c}	0^{c}	3.2^{ab}	7.7^{a}	5.9^{ab}
50-60	0^{c}	0.1^{c}	0.1^{c}	0.1^{c}	0^{c}	2.8^{ab}	7.9^{a}	6.6^{ab}
60-70	0^{c}	0.1^{c}	0.3^{bc}	0.0^{c}	0^{c}	2.5^{b}	4.1^{b}	3.4^{b}
ANOVA								
IR	NS	*	NS	*	NS	NS	NS	NS
C	NS	NS	NS	NS	NS	NS	NS	NS
D	***	***	***	***	*******	*******	*******	*******
IR X C	†	NS	*	*	NS	NS	NS	NS
IR X D	NS	***	NS	NS	*******	*******	NS	†
C X D	*	**	†	***	†	†	******	*******
IR X C X D	*	NS	†	NS	*****	†	†	†

ETc = Crop evapotranspiration

[z]Means of main factor followed by different letters are significantly different at $P \leq 0.05$ according to the Duncan's multiple range test

†, *, **, *** show significant difference at $P \leq 0.1$, 0.05, 0.01 and 0.001 respectively

NS, not significant at $P \leq 0.1$

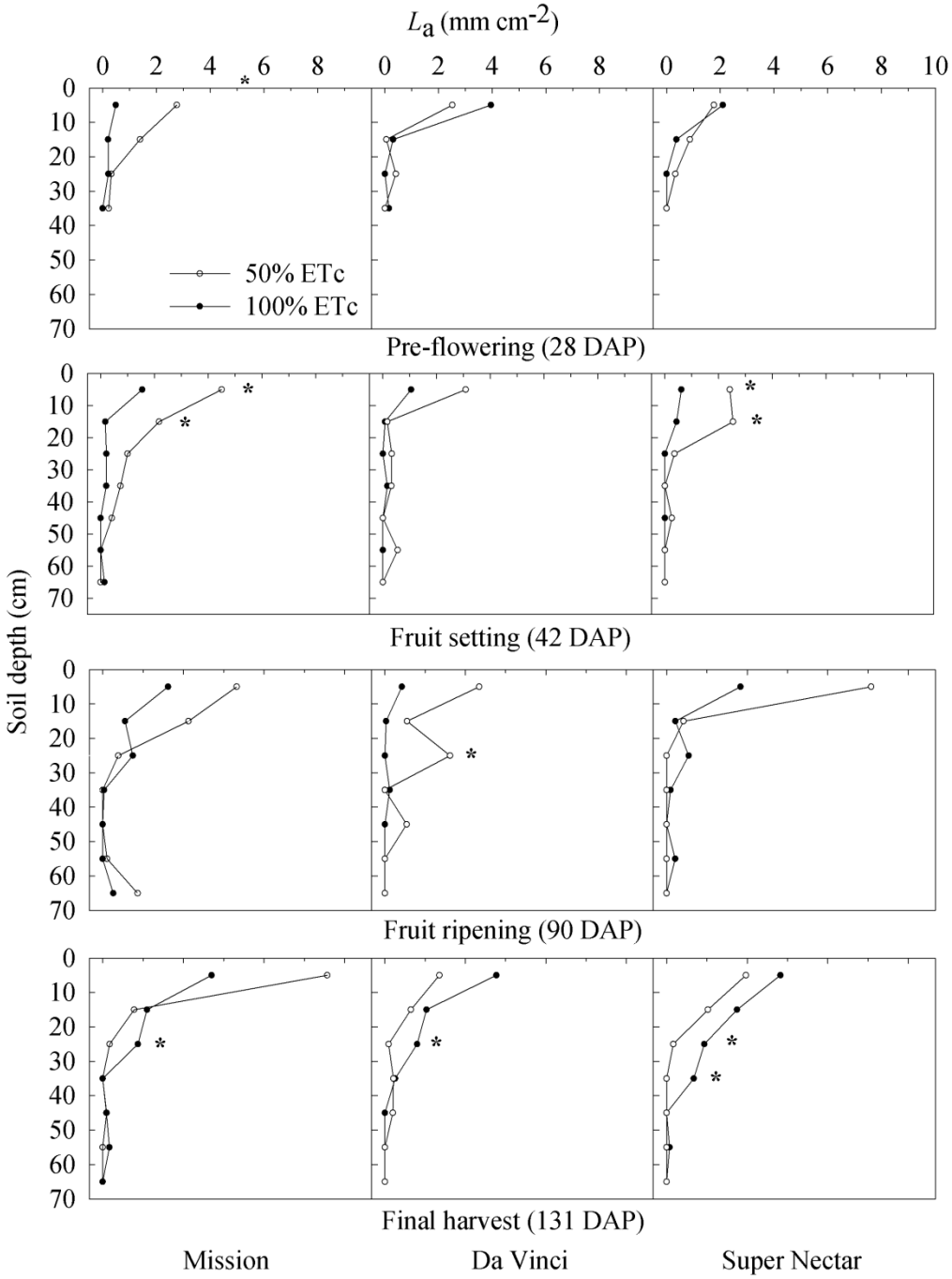

Figure 5.3 Effect of irrigation rates and cultivars on root length intensity (L_a) for different soil depths in 2011. Data presented as mean values for irrigation rates with in cultivars for different growth stages/ days after planting (DAP) (n=6). Asterisk (*) represents significant differences between irrigation rates at $P \leq 0.05$

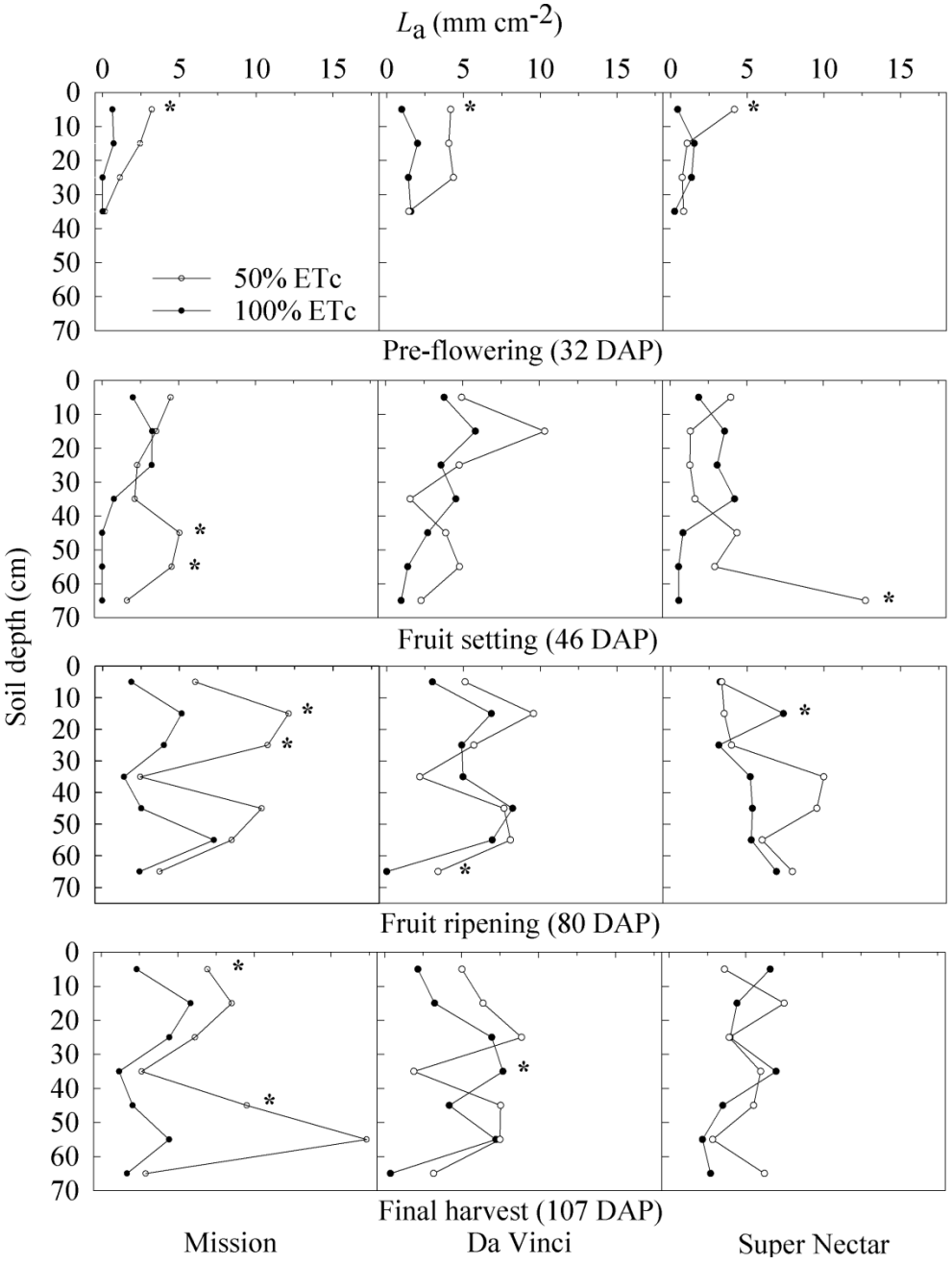

Figure 5.4 Effect of irrigation rates (50% and 100% ETc) and cultivars (Mission, Da Vinci and Super Nectar) on root length intensity (L_a) for different soil depths in 2012. Data presented as mean values for irrigation rates with in cultivars for different growth stages/ days after planting (DAP) (n=6). Asterisk (*) represents significant differences between irrigation rates at $P \leq 0.05$

5.3.5 Minirhizotron vs. soil core method

In 2011, both soil core and minirhizotron methods recorded similar trends in root growth distribution at 50% and 100% ETc (Fig. 5.5). However, in 2012 soil core measured higher root growth in upper soil layers (0-20 cm) while minirhizotron captured more root growth in deeper soil layers (50 - 60 cm), particularly at 50% ETc.

Pearson's correlation analysis between RLD (soil core) and L_a (minirhizotron) resulted in considerably lower r values. In 2011, standing root length estimates with soil core and minirhizotron methods were positively correlated (r = 0.383; $P < 0.001$), but in 2012 both methods showed no relationship (r = -0.037; $P = 0.683$) which can be attributed to an underestimation of standing root length with minirhizotron method. However, the overall average standing root length estimates within cultivars across soil depths were almost similar for the two methods except for cv. Da Vinci (Fig. 5.6).

5.4 Discussion

Implementation of deficit irrigation in drought-prone regions of the world has become essential. Water stress sensitivity of cultivars varies with their yield potential . Thus, investigations on root growth response towards water deficit are very critical to further understand the variability of adaptation mechanisms among to water limited conditions.

5.4.1 Impact of weather and soil conditions on root growth

Prevailing weather conditions can have a considerable impact on root growth patterns of melon cultivars, directly through modification of soil status (i.e. moisture, temperature), or indirectly by influencing shoot growth or through biasness in root

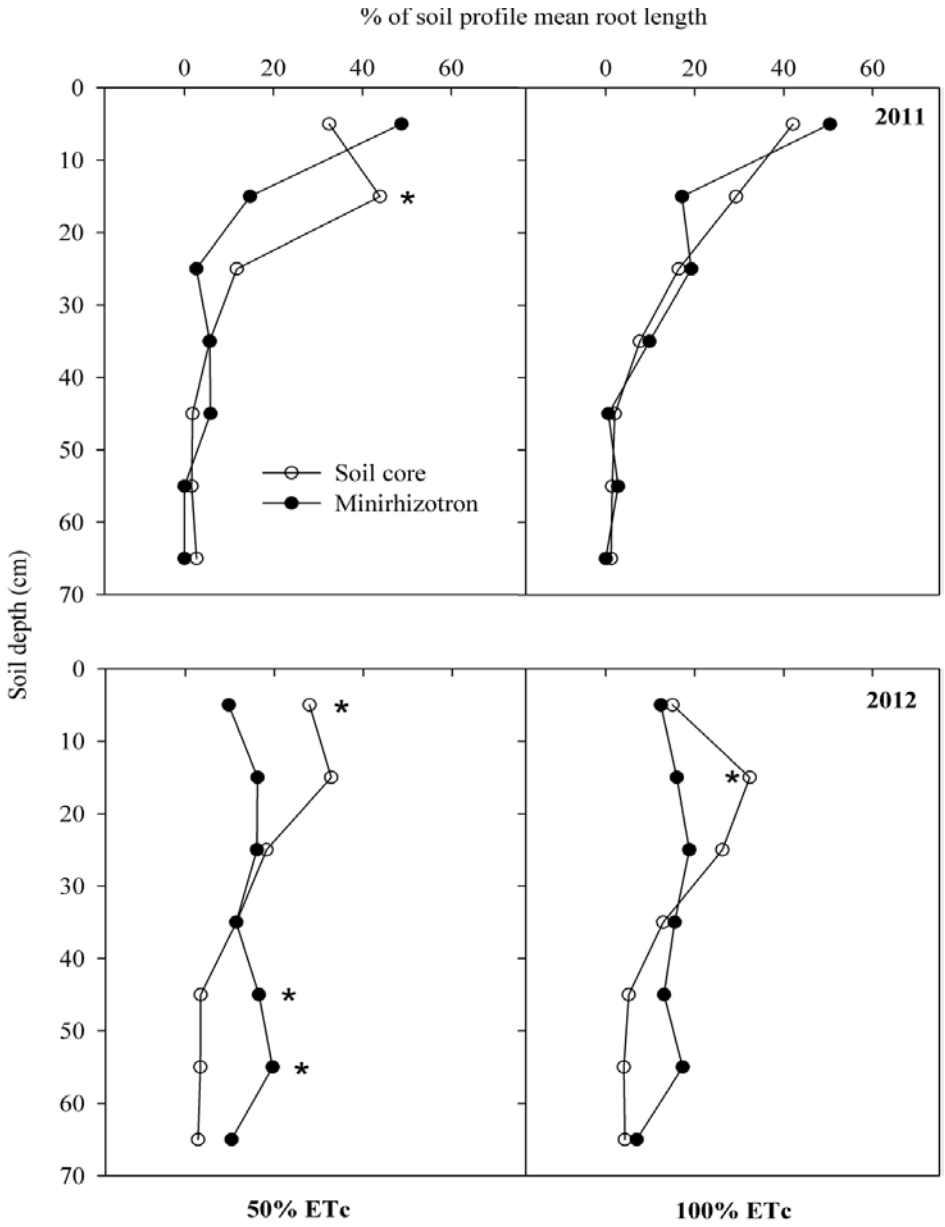

Figure 5.5 Standing root growth estimates (% of soil profile mean root length) as influenced by method (Soil core and Minirhizotron) for irrigation rates [50% (left) and 100% ETc (right)] at final harvest in 2011 and 2012 seasons. Asterisk (*) represents significant differences between irrigation rates at $P \leq 0.05$

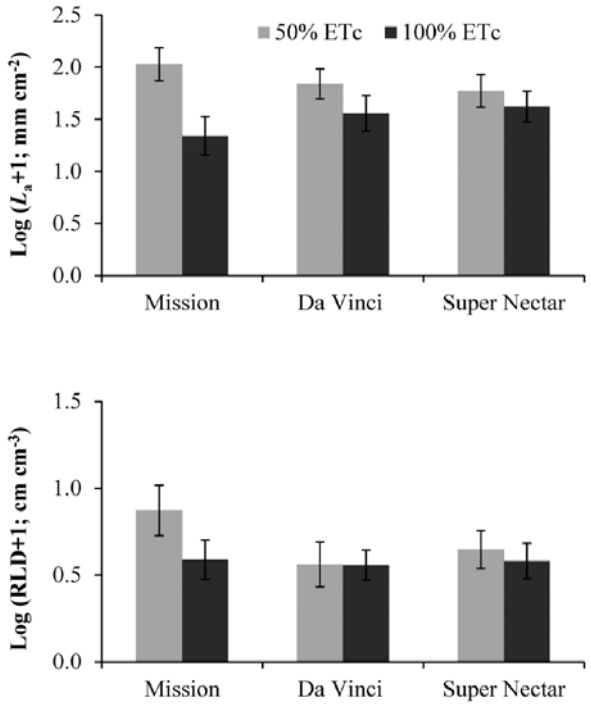

Figure 5.6 L_a (minirhizotron method) and RLD (soil core method) in response to irrigation rates and cultivars at final harvest in 2012. Values represent the mean ± 1 SE

growth estimates due to soil dryness which in turn creates soil-tube interface problems. In this experiment, L_a varied significantly between years (Table 5.5). Under soil water deficit drought and other combined stresses can impact root growth through increases in mechanical impedance (Whitmore and Whalley, 2009). For example, in 2011 water deficit may have induced increase in soil strength, preventing deep penetration of roots through the hard clay pan below 30 cm of soil depth conversely, in 2012 higher rainfall received during the seedling establishment period might have decreased soil strength, facilitating root growth in deeper soil layers (> 40 cm) (Table 5.1). Further, a dry period during the third week of May to the first week of July, 2012 (Fig. 5.1), immediately after the establishment of differential irrigation, might have caused roots to explore deeper

soil layers containing high moisture levels. Similarly, Kirkham et al. (1998) reported that the presence of a clay pan at 25 cm impeded maize root growth, but when the soil profile held higher moisture at the beginning of the dry period root growth was enhanced below the pan layer.

There is another possibility that in 2012 higher soil fertility status particularly NO_3-N (Table 5.2) may have induced a priming effect on root growth during seedling establishment which contributed to increased root growth throughout the growing season irrespective of irrigation rates and cultivars (Fig. 5.4). According to Hodge (2004) roots proliferate more in N rich soil patches.

Soil moisture conditions also affect the settlement of the soil around the tube both in degree and time. The soil dryness due to less rainfall received during the establishment period in 2011 might have resulted in poor soil-tube contact particularly in deeper soil layers (< 30 cm soil depth) in this year as compared to in 2012. Thus, the lower root growth estimates in 2011 as compared to in 2012 can also be attributed to these soil-tube interface artifacts (Rytter and Rytter, 2012). Similarly, Muñoz-Romero et al. (2012) reported that minirhizotrons recorded less RLD in a drier year as compared to a wet year in chickpea (*Cicer arietinum* L.)

5.4.2 Root growth patterns along soil depth

Deficit irrigation inhibited root growth at 20 to 40 cm of soil depth (Fig. 2). A higher bulk density (1.42 g cm^{-3}) at 20 - 40 cm of soil depth coupled with soil water deficit under deficit irrigation might have increased the soil strength and inhibited root proliferation in this layer (Unger and Kaspar, 1994; Coelho and Or, 1999; Bengough et

al., 2006). However, roots which were able to cross this layer proliferated in deeper soil layers (> 40 cm) and contributed to higher L_a below 40 cm of soil depth. Contrary to a subsurface drip irrigation study in tomato (Machado et al. 2003) where the root system was mostly concentrated at the depth of the drip tape, melon roots were distributed over the entire 70 cm soil profile, except for a decrease in L_a between 20 - 40 cm soil depths (Fig. 5.2).

5.4.3 Irrigation and cultivars interactions on root growth patterns

Overall, deficit irrigation promoted deep root growth in all cultivars at the fruit setting stage, but later in the season under cumulative stress only cv. Mission could sustain enhanced root growth at deeper layers (> 40 cm) (Fig. 5.4). Similarly, Reid and Renquist (1997) reported that moderate stress in tomato promotes deeper root growth. Enhanced root growth (RLD) in cv. Mission under deficit irrigation has also been confirmed with soil core sampling at the final harvest (Fig. 5.6). Though not significantly, cv. Da Vinci also showed improvements in root growth under deficit irrigation (Fig. 5.4). Therefore, *reticulatus* melon cvs. Mission and Da Vinci showed greater potential for adaptation to deficit water conditions.

Long duration, high yielding ability (> 100 t ha^{-1}) and severe yield reduction (43% in 2011 and 36% in 2012) under deficit irrigation suggest high water requirements of cv. Super Nectar (data not shown). Further, the reduction in L_a under cumulative water deficit indicates the sensitivity of this *inodorus* melon cultivar to deficit irrigation. Oliveira et al. (1996) also reported a decrease in root length intensity and tomato fruit yield with a decrease in volume of irrigation water applied.

5.4.4 Volumetric soil moisture dynamics

In this study, although the differences in volumetric water content between 50% and 100% ETc irrigation rates were not clearly distinguishable (Fig. 5.1), yet deficit irrigation had a significant impact on fruit yield (data not shown) and root growth patterns of melon cultivars (Fig. 5.4). According to Whitmore and Whalley (2009), very small fluctuations in volumetric water content can result in very large changes in water potential particularly under water deficit conditions. Further, Coelho and Or (1999) argued that in frequently irrigated crops (such as this melon study) with highly active root systems, root distribution in the soil profile may not represent root effectiveness and thus, plant water uptake may vary in space depending on soil available water conditions.

The discrepancies among soil moisture dynamics and root growth patterns can be attributed to the fact that the total measurable root length may not responsible for water uptake form the soil. Robinson et al. (1991) argued that only a fraction of the total root length is physically and physiologically active in water and nutrient uptake. For example, in cereal and legume grains, Hamblin and Tennant (1987) reported that water extraction from soil by crops was better correlated with maximum rooting depth than with total root density. Thus, the longer and deep roots may not be directly responsible for water and nutrient uptake but, they are functionally important in long distance transport of water from active roots to the shoots (Wenzel et al., 1989) which makes them important for drought tolerance.

5.4.5 Comparison of minirhizotron and soil core methods

The underestimation of melon root growth with minirhizotrons in the upper soil layers (Fig. 5.5), might have resulted from tube installation artifacts (Upchurch and Ritchie, 1983; Samson and Sinclair, 1994; Muñoz-Romero et al., 2010). Although tubes were carefully installed to prevent moisture, light and temperature fluctuations, preferential root growth in the soil-tube interface region might have contributed to higher root growth in the deeper layers (Heeraman and Juma, 1993). The high rooting intensity in deeper soil layers (> 30 cm) in 2012 might itself have increased the probability of roots intersecting the tube surface, which, resulted in enhanced root growth estimates (Upchurch and Ritchie, 1983; Heeraman and Juma, 1993). Another possibility is that the very fine roots are lost in washing and sampling procedures RLD estimates in the deeper soil layers which resulted in lower estimates in soil core RLD (Coelho and Or, 1999).

Root studies in field crops are limited by the spatial variability in root growth, time investment and destructive nature of conventional methods such as the soil core (Wiesler and Horst, 1994). Thus, in spite of some shortcomings, the minirhizotron method offers an advantage of measuring temporal fine root growth dynamics at the same location in a quick and non-destructive way. Previous studies have also reported inconsistency in estimating fine root growth dynamics in the soil tube interface and bulk soil (Upchurch and Ritchie, 1983; Heeraman and Juma, 1993), but this limitation may not necessarily affect the relative fine root growth patterns (Rytter and Rytter, 2012). Due to these discrepancies, Box and Ramsuer (1993) suggested that minirhizotron

estimates should be calibrated with destructive methods for each soil, climate and crop or in some cases cultivar. In our melon study, the overall average standing root length estimates with minirhizotron were comparable to the soil method estimates although the root growth patterns in 2012 showed some dissimilarity (Fig. 5.5). Considering our results, limitations and potential errors, the minirhizotron method can be of considerable use for studying cultivar adaptation to water deficit where monitoring of the temporal and spatial (i.e. depth) root growth patterns is very critical (Rytter and Rytter, 2012) while soil core can give a snapshot of standing root length at a given time which can be used to corroborate the reliability of the minirhizotron results.

CHAPTER VI

IMPACT OF DEFICIT IRRIGATION ON *RETICULATES* AND *INODORUS* MELONS (*CUCUMIS MELO* L.): LEAF GAS EXCHANGE AND GROWTH CHARACTERISTICS

6.1 Background

The irrigation water supply has become limited and expensive due to the increased frequency and intensity of droughts and severe restrictions on ground water use, for irrigated crops, which is likely to affect melon cultivation in semiarid regions of south Texas (Leskovar et al., 2001; Leskovar and Piccinni, 2005). Thus, to sustain melon production in the region, the implementation of '*more crop per drop*' strategy is urgently needed (Blum, 2011). Under sustained deficit irrigation (SDI) plants are supplied with water below their crop evapotranspiration (ETc) demands throughout the growing season (Fereres and Soriano, 2007) and thus, are deliberately exposed to a gradual moisture stress, which, depending upon the crop and/or cultivar sensitivity may have deleterious effects on crop physiology, growth and yield.

Plants can avoid losses associated with drought stress through morphological and physiological adaptations (Blum, 2005), but these responses may vary with interactions among crops/ cultivars, growth stages, environments and severity, timing and duration of water stress (Cattivelli et al., 2008) . Some examples include improved root growth in melons (Sharma et al., 2014), decrease in leaf dry mass ratio in wheat (*Triticum aestivum* L) (Boogaard et al., 1996), reduction in specific leaf area in *Amaranthus* spp. (Liu and

Stützel, 2004), and restricted shoot growth with unchanged root growth in maize (*Zea mays* L.) (Sharp and Davies, 1979). Most of these growth traits are rapidly affected by very mild stress, while, prolonged water deficit can also adversely affect leaf gas exchange (Huck et al., 1983) due to stomatal closure and low intercellular CO_2 (C_i) concentration (Raschke and Hedrich., 1985). Under greenhouse conditions, water stress decreased net CO_2 assimilation rate, stomatal conductance (g_s) intercellular CO_2 concentrations (C_i), and transpiration rate (E) of melon seedlings (Huang et al., 2010; Agehara and Leskovar, 2012). Most of such studies have been conducted under controlled conditions, while field experiments to assess the impact of water deficit on growth and leaf gas exchange of melons are lacking.

Plant morphological and physiological processes differ in their sensitivity to water stress. For example, Subbarao et al. (1995) reported that leaf area development is more sensitive to water stress than photosynthesis and transpiration in grain legumes. While, Ashraf et al. (2002) argued that the decreased photosynthetic rate (P_N) is the most common physiological response to moisture stress, due to stomata closure and inhibition of Calvin cycle enzymes like Rubisco, particularly when plants are exposed gradual water stress under field conditions (Medrano et al., 1997). Indeed, it is the total crop photosynthesis, not the P_N, which contributed in the past to improvement in yield of grain crops, thus maintenance of leaf area is more important than P_N (Richards, 2000). Within this context, identifying traits useful for selecting melon cultivars tolerant to soil moisture deficit has become a priority in the present study.

Melons (*Cucumis melo* L.) are highly productive under well water conditions (Sharma et al., 2014) and are considered to be sensitive to water stress. Under water deficit conditions, melons exhibited significant reductions in fruit yield (Fabeiro et al., 2002; Cabello et al., 2009) and quality (Lester et al., 1994; Long et al., 2006). The high stomatal density on both upper and lower surfaces of melon leaves (Abdulraham et al., 2011; Sharma et al., 2013), may result in high stomatal conductance and hence enhanced sensitivity to mesophyll or parenchymatous outer cortical tissue dehydration. Genetic adaptive responses to water deficit have been reported in several crops such as, *Amaranthus* spp. (Liu and Stützel, 2004), cotton (*Gossypium hirsutum* L. r. latifolium Hutch) (Brito et al., 2011) and okra (*Abelmoschus esculentus* (L.) Moench) (Ashraf et al., 2002). Melon has shown positive association between P_N and fruit yield (Kitroongruang et al., 1992) possessing a wide genetic variability for leaf gas exchange traits (De et al., 2008). However, morphological and physiological adaptation responses to water deficit of melon cultivars from diverse horticultural groups have not been investigated.

The objective of this study was to determine the effect of deficit irrigation (50% ETc) on growth adaptation and physiological traits of three diverse melon cultivars belonging to the muskmelon, Tuscan and honeydew groups. The selected cultivars differ in their fruit shape, size, color, ripening behavior, and maturity. It was hypothesized that differences in fruit characteristics among these cultivars would also be exhibited in morphological and photosynthetic adaptation responses to deficit soil moisture. We

expect, this information will be useful in melon breeding for screening cultivars with specific traits linked to drought adaptation.

6.2 Materials and methods

6.2.1 Plant material and treatments

The experimental details are as described in sections 4.2.1 and 4.2.2. Vapor pressure deficit, cumulative monthly rainfall and average temperature of the experimental site are given in Fig. 6.1.

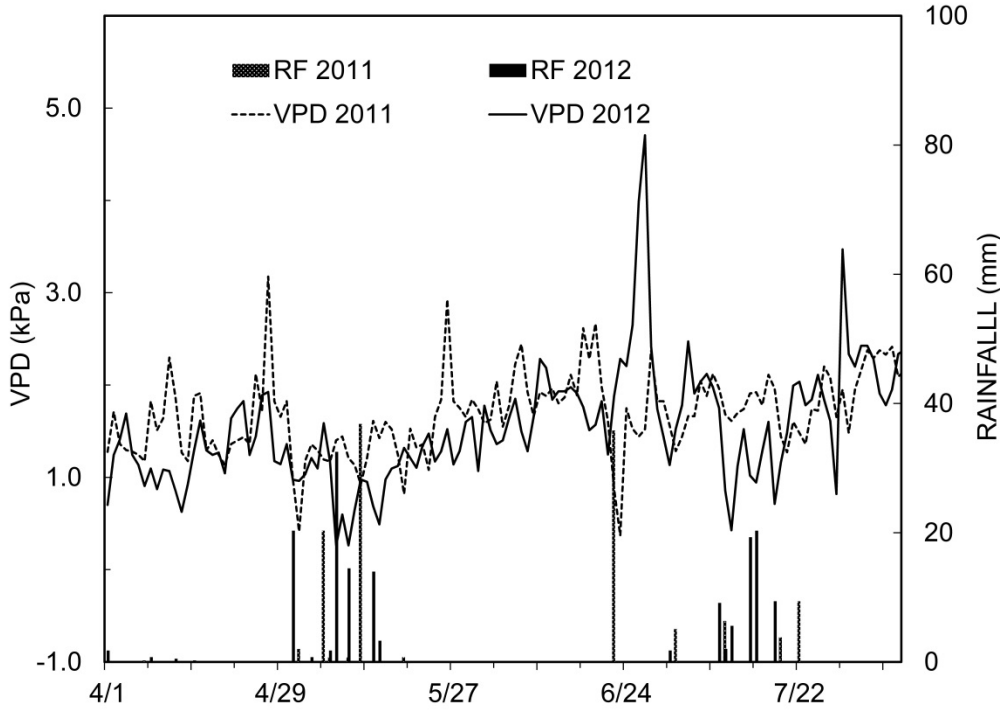

Figure 6.1 Daily vapor pressure deficit (VPD) (lines) and rainfall events (bars) at Uvalde, TX in 2011 and 2012 seasons

6.2.2 Gas exchange and chlorophyll fluorescence measurements

Net photosynthesis rate (P_N, µmol CO_2 m^{-2} s^{-1}), stomatal conductance (g_s, mol H_2O m^{-2} s^{-1}), intercellular CO_2 concentration (C_i, µmolCO_2 mol^{-1}), and transpiration rate (E, mmol H_2O m^{-2} s^{-1}), were measured at 53, 67, 95 and 110 day after planting (DAP) in 2011 and 36, 50, 64, 81 and 95 DAP in 2012. Two random plants were selected in each plot and fully expanded mature leaves (4^{th} or 5^{th} from the main growing vine tip) were used for measurements. A portable photosynthesis system LI-6400 (LI-COR Inc., Lincoln, NE, USA) equipped with an open-flow infra-red gas analyzer was used at steady state (PAR 2000 µmol $m^{-2}s^{-1}$, reference CO_2 concentration 400 µmol mol^{-1}, air flow rate 500 µmol s^{-1} and block temperature 30 $^{\circ}$C) for all measurements (Agehara and Leskovar, 2012).

To measure the efficiency of light absorption, chlorophyll fluorescence was determined by using portable pulse modulated fluorometer (OS-30P, OPTISCIENCES, USA). The same leaves used for gas exchange measurements were pre-adapted to dark period for 30 min by attaching dark adaptation clips on each leaf. The sensor of the fluorometer was inserted in the cuvette on the leaf clip and F_v/F_m values were recorded. Since, F_v/F_m gives the measure of efficiency of excitation energy captured by the open photosystem II reaction centers (Oyetunji et al., 2007), it provides an indication of the photo-/ thermo-stability of photosynthetic machinery. Chlorophyll fluorescence was recorded at 36, 64 and 81 DAP in 2012 season. Leaf chlorophyll index was also measured immediately on the same leaves using a chlorophyll Soil Plant Analysis Development SPAD-502 meter (Konica Minolta Sensing, Tokyo, Japan). Five readings

were taken per leaf on two plants per plot, around 1 cm away from the margin avoiding major leaf veins. All measurements were done between 11:00 AM to 15:00 PM (Hamidou et al., 2007).

6.2.3 Plant water status measurements

Leaf water potential (Ψ_l) was measured as described in Agehara and Leskovar (2012), using a pressure chamber (Model 3005; Soil moisture Equipment, Santa Barbara, CA). For measuring relative water content (RWC), one entire leaf from two plants per plot was collected and Water use efficiency (WUE) was calculated. After fresh weight (FW) was recorded, leaves were floated on deionized water in a petri dish and hydrated in the darkness for 4 h. Thereafter, the turgid weight (TW) was recorded, and the samples were subsequently dried to a constant weight at 85°C to determine the dry weight (DW) (Goreta et al., 2007). The RWC expressed as a percentage was calculated as follows:

$$RWC= [(FW- DW) / (TW-DW)] \times 100$$

6.2.4 Growth and yield measurements

Total leaf area and dry matter content of leaves, stems and fruit were determined twice, at 37 (i.e. before starting differential irrigation) and 68 DAP (i.e. 30 days after applying deficit irrigation). Six plants per treatment were sampled by cutting them at ground level and separated in to leaf, stem and fruits. At each sampling total leaf area per plant (LA) was measured using a portable leaf area meter (LI 3100, Licor, Lincoln, Nebraska, USA). Leaf, stem and fruit fresh weight was recorded and all three plant components were dried to a constant weight at 85 °C to determine their respective dry

weights to calculate the above ground biomass (ABM) (Agehara and Leskovar, 2012). Specific leaf area (SLA) was calculated as the total plant leaf area was divided by the dry mass of leaves.

Fruits were harvested at half to full slip stage between 18 June (78 DAP, day after planting) to 5 August 2011 (126 DAP) and between 25 June (71 DAP) and 24 July 2012 (100 DAP) and total fruit yield (TFY) (t ha^{-1}) was recorded.

6.2.5 Statistical analysis

Data for each variable were subjected to the analysis of variance (ANOVA) with a split plot design using generalized linear model procedures (SAS 9.1, SAS Inst., Cary, N.C., USA). Irrigation regime (50% ETc and 100% ETc) was the main plot, cultivar (Mission, Da Vinci and Super Nectar) the subplot, and sampling dates (DAP) the sub-sub plot factor (McIntosh, 1983). Where significant main effects were found, means were separated by Duncan's multiple-range test. Relationships among P_N, g_s, E, F_v/F_m, SPAD, LA, SLA, Leaf number (LN), TFY, WUE and ABM were determined by correlation analysis.

6.3 Results

Overall, deficit irrigation (50% ETc) resulted in significant decrease in P_N (P = 0.029) and g_s (P = 0.007) in the 2011 season (Table 6.1). Data for 2012 showed a similar, but not statistically significant trend (Table 6.2). The melon cultivars also exhibited significant differences for P_N and E parameters in both seasons, with Da Vinci having the lowest values for both the traits as compared to cv. Mission and Super Nectar. The lowest stomatal conductance was also recorded in Da Vinci in both years, but the

difference was only significant in 2012 (Table 6.1, 6.2). Sampling dates also had significant effect on all the leaf gas exchange parameters in 2011 and 2012 seasons (Table 6.1, 6.2), indicating that leaf gas exchange varied with phenological stages and weather conditions. In 2011, leaf gas exchange parameters *viz.*, g_s, *E* and *Ci* followed a gradual decreasing trend over the sampling dates; however, both P_N and water use efficiency (WUE; P_N/E) increased at 67 DAP though P_N decreased thereafter while, WUE remained unchanged at 95 DAP and then increased at 110 DAP. Similarly, in 2012, P_N and WUE significantly increased up to 64 DAP and decreased thereafter. While, g_s increased at 50 DAP and decreased during rest of the season. Further, *E* and C_i followed a decreasing trend, except a significant increase at 95 DAP. Stomatal limitations (L_s) significantly increased at 64 and 81 DAP and again decreasing at 95 DAP.

In 2011, cultivar × sampling date interactions were significant for P_N (P = 0.0001), g_s ($P \leq 0.0004$), *E* ($P \leq 0.0001$) and C_i ($P \leq 0.0777$) (Table 6.1), indicating that leaf gas exchange responses to deficit irrigation varied among the cultivars and sampling dates (Fig. 6.2). P_N increased up to 67 DAP in Mission, 95 DAP in cv. Da Vinci while started decreasing in cv. Super Nectar after 53 DAP (Fig. 6.2). Similar trends were observed for g_s and *E*. C_i decreased in all the cultivars at 67 DAP, it remained unchanged in cvs. Mission and Da Vinci up to 95 DAP, but decreased in cv. Super Nectar at 95 DAP. Thus, a consistent decrease in gas exchange was noticed in Da Vinci, while the decrease was more rapid in Mission and it was more variable in Super nectar.

Table 6.1 Net photosynthetic rate (P_N), stomatal conductance (g_s), transpiration rate (E), intercellular CO_2 concentration (C_i), and water use efficiency (P_N/E) of melon cultivars as influenced by irrigation rates over sampling dates (DAP) in 2011

Treatment	P_N (µmol m^{-2} s^{-1})	g_s (mmol m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	C_i (µmol mol^{-1})	WUE (µmol $mmol^{-1}$)
Irrigation (IR, ETc)					
50%	18.6 b[z]	0.21 b	6.5	153.7	3.2
100%	21.7 a	0.28 a	7.3	169.5	3.1
Cultivars (C)					
Mission	21.4 a	0.25	7.12 a	287.8	3.2
Da Vinci	19.6 b	0.22	6.69 b	287.7	3.2
Super Nectar	19.4 a	0.27	6.90 a	286.2	3.1
Sampling date (DAP)					
53	23.8 a	0.50 a	10.1 a	235.9 a	2.4 b
67	25.0 a	0.29 b	8.28 b	171.5 b	3.1 a
95	18.2 b	0.20 c	6.38 d	162.6 c	3.1 a
110	14.8 b	0.09 ± c	3.89 d	89.2 d	3.7 a
Source of variance (P-value)					
D	0.0001	0.0001	0.0001	0.0001	0.0107
IR	0.0286	0.0069	0.1067	0.2473	0.5729
IR×D	0.1746	0.0067	0.3553	0.6636	0.4729
C	0.2641	0.0836	0.3692	0.7503	0.2845
IR×C	0.0936	0.1152	0.0962	0.2252	0.1661
C×D	0.0001	0.0004	0.0001	0.0777	0.4822
IR×C×D	0.6686	0.8380	0.7163	0.6125	0.6233

[z]Means in a column followed by the same letter are not significantly different at P≤ 0.05 according to the Duncan's multiple range test

ETc = Crop evapotranspiration, DAP = days after planting

Table 6.2 Net photosynthetic rate (P_N), stomatal conductance (g_s), transpiration rate (E), intercellular CO_2 concentration (C_i), and water use efficiency (P_N/E) and stomatal limitations (L_s) of melon cultivars as influenced by irrigation rates over sampling dates (DAP) in 2012

Treatment	P_N (µmol $m^{-2}s^{-1}$)	g_s (mmol $m^{-2}s^{-1}$)	E (mmol $m^{-2}s^{-1}$)	C_i (µmol mol^{-1})	WUE (µmol $mmol^{-1}$)	L_s
Irrigation (IR, ETc)						
50%	20.1	0.75	11.9	284.4	1.84	0.23
100%	20.5	0.77	12.2	290.1	1.79	0.21
Cultivars (C)						
Mission	21.1 a[z]	0.75 ab	12.4 a	287.8	1.83	0.22
Da Vinci	19.1 b	0.65 b	11.6b	287.7	1.79	0.23
Super Nectar	20.7 a	0.79 a	12.3 a	286.2	1.83	0.23
36	14.6 e	1.13 b	17.0 a	333.5 a	0.85 d	0.11 c
50	24.3 b	1.44 a	13.0 b	316.2 b	1.88 b	0.13 c
64	26.3 a	0.52 c	9.30 d	250.8 d	2.85 a	0.31 a
81	19.5 c	0.30 c	9.74 d	248.3 d	2.02 b	0.33 a
95	16.8 d	0.47 c	11.18 c	287.5 c	1.48 c	0.23 b
Source of variance						
D	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
IR	0.5132	0.1718	0.5680	0.1461	0.3685	0.0949
IR×D	0.2063	0.4185	0.6528	0.5107	0.5766	0.4281
C	0.0026	0.0087	0.0381	0.6357	0.2920	0.5355
IR×C	0.4023	0.6212	0.6302	0.1883	0.5060	0.1522
C×D	0.0058	0.0333	0.0335	0.0219	0.4401	0.0044
IR×C×D	0.4479	0.7040	0.3134	0.0381	0.1851	0.0701

[z]Means in a column followed by the same letter are not significantly different at P≤ 0.05 according to the Duncan's multiple range test. ETc = Crop evapotranspiration, DAP = days after planting

WUE showed an increasing trend over time for all cultivars. Fig. 6.3 shows the irrigation rate and cultivar interactions for P_N and g_s between 53 and 110 DAP in 2011. Deficit irrigation did not reduce P_N and g_s in cv. Da Vinci, rather it was improved at 67 DAP.

Similarly in 2012, cultivar × sampling date interactions were significant for P_N (P = 0.005), g_s (P = 0.033), E (P = 0.033), Ci (P = 0.022) and Ls (P = 0.004) (Table 6.2). In general, P_N and L_s increased up to 64 DAP, however g_s decreased significantly at 64 DAP and remained decreased thereafter. Similar to 2011 results, the decrease in gas exchange was more consistent in cv. Da Vinci while it was more rapid in cvs. Mission and Super Nectar (Fig. 6.4). WUE showed similar trend in all the cultivars and increased up to 64 DAP and decreased thereafter (Fig. 6.4).

Deficit irrigation did not affect water potential (Ψ_l) and relative water content (RWC) of melon cultivars when measured 81 DAP. However, under 50% ETc a numerical increase in Ψ_l of cvs. Mission and Super Nectar, was recorded. RWC of all the three cultivars remained similar at both the irrigation rates (data not shown).

Chlorophyll fluorescence (F_v/F_m) in melons was not affected by deficit irrigation (Fig. 6.5). Similarly, 50% ETc did not cause any leaf chlorosis in all the cultivars as indicated by no significant differences in chlorophyll index (Data not shown). Deficit irrigation caused a numerical increase in stomatal density of all the cultivars as compared to 100% ETc (Fig. 6.6). May be this helped in maintaining RWC at 50% ETc.

No difference in LA, ABM and SLA were observed among the irrigation rates at 37 DAP (i.e. before starting differential irrigation). However, at 68 DAP (i.e. 30 days of

differential irrigation), 50% ETc significantly reduced leaf number per plant (LN) by 43% ($P \leq 0.001$), leaf area per plant (LA) by 50% ($P = 0.001$), above ground biomass per plant (ABM) by 37% ($P \leq 0.001$), and specific area (SLA) by by 14% (P = 0.001)

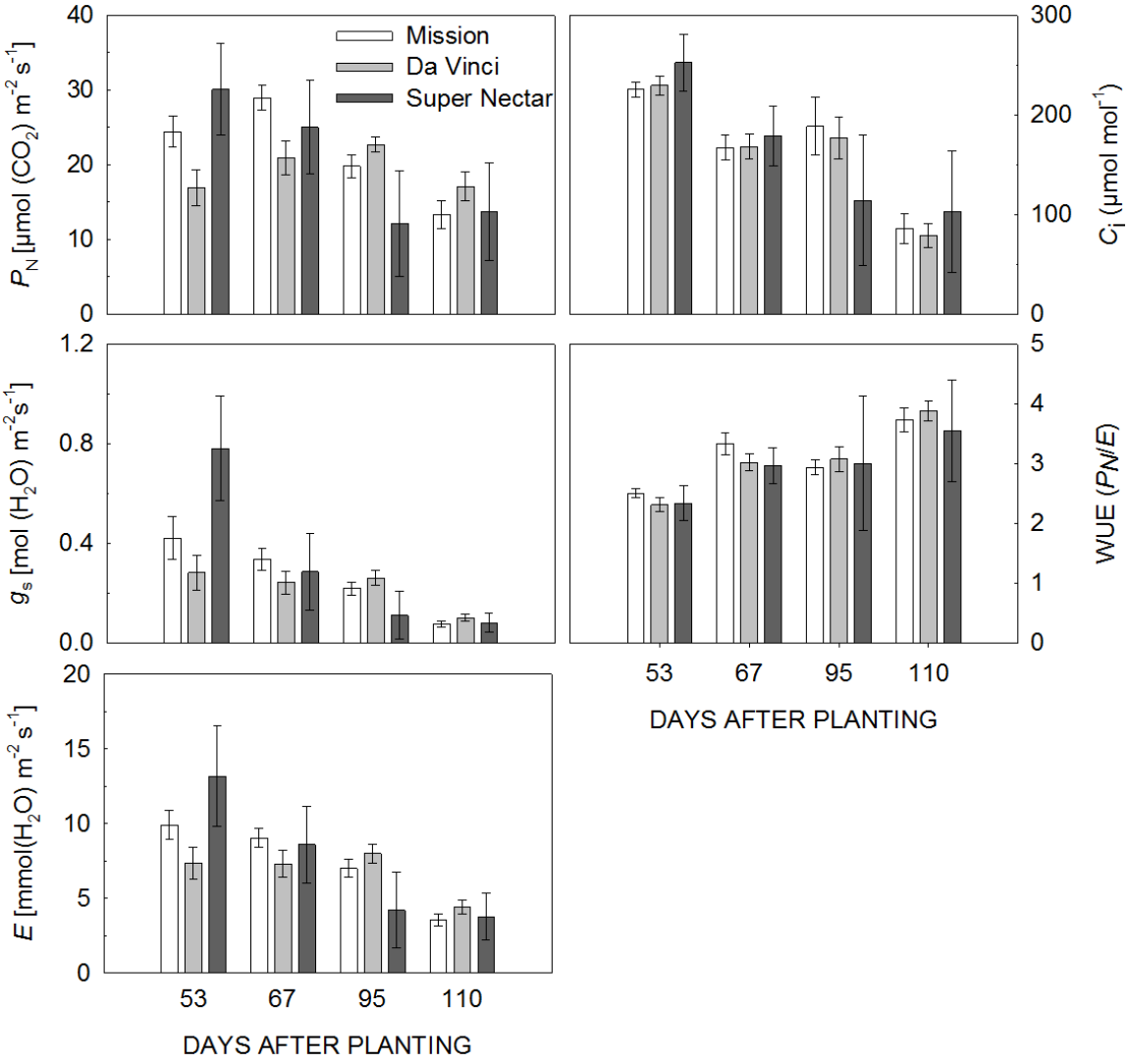

Figure 6.2 Net photosynthetic rate (P_N), stomatal conductance (g_s), transpiration rate (E); intercellular CO_2 concentration (C_i), and water use efficiency (WUE, P_N/E) of melon cultivars between 53 and 110 days after planting in 2011.Vertical bars represent 95% confidence intervals (n=12)

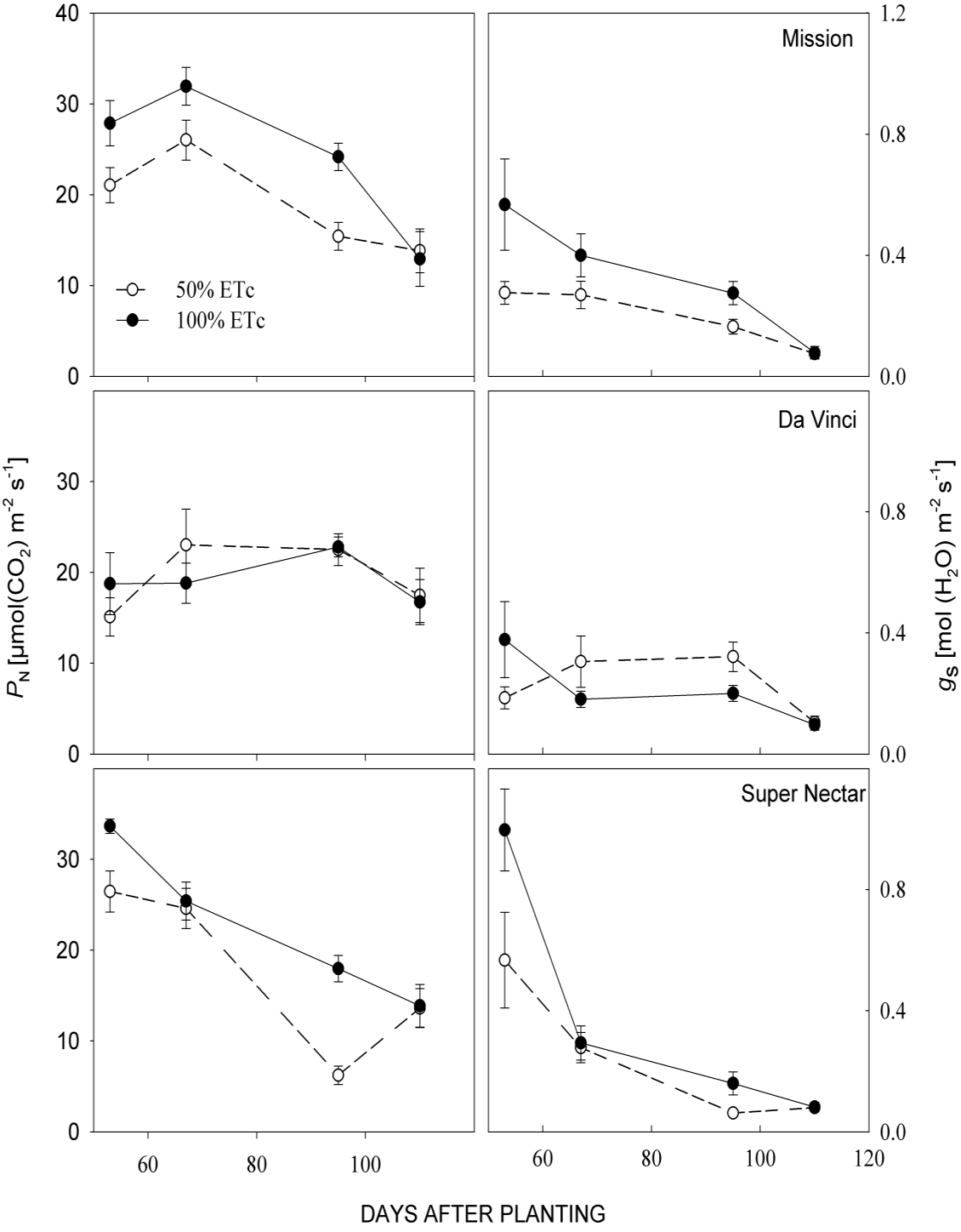

Figure 6.3 Net photosynthetic rate (P_N) and stomatal conductance (g_s) of melon cultivars in response to irrigation rates over days after planting in 2011. Values are represented as mean ± 1 SE (n = 6)

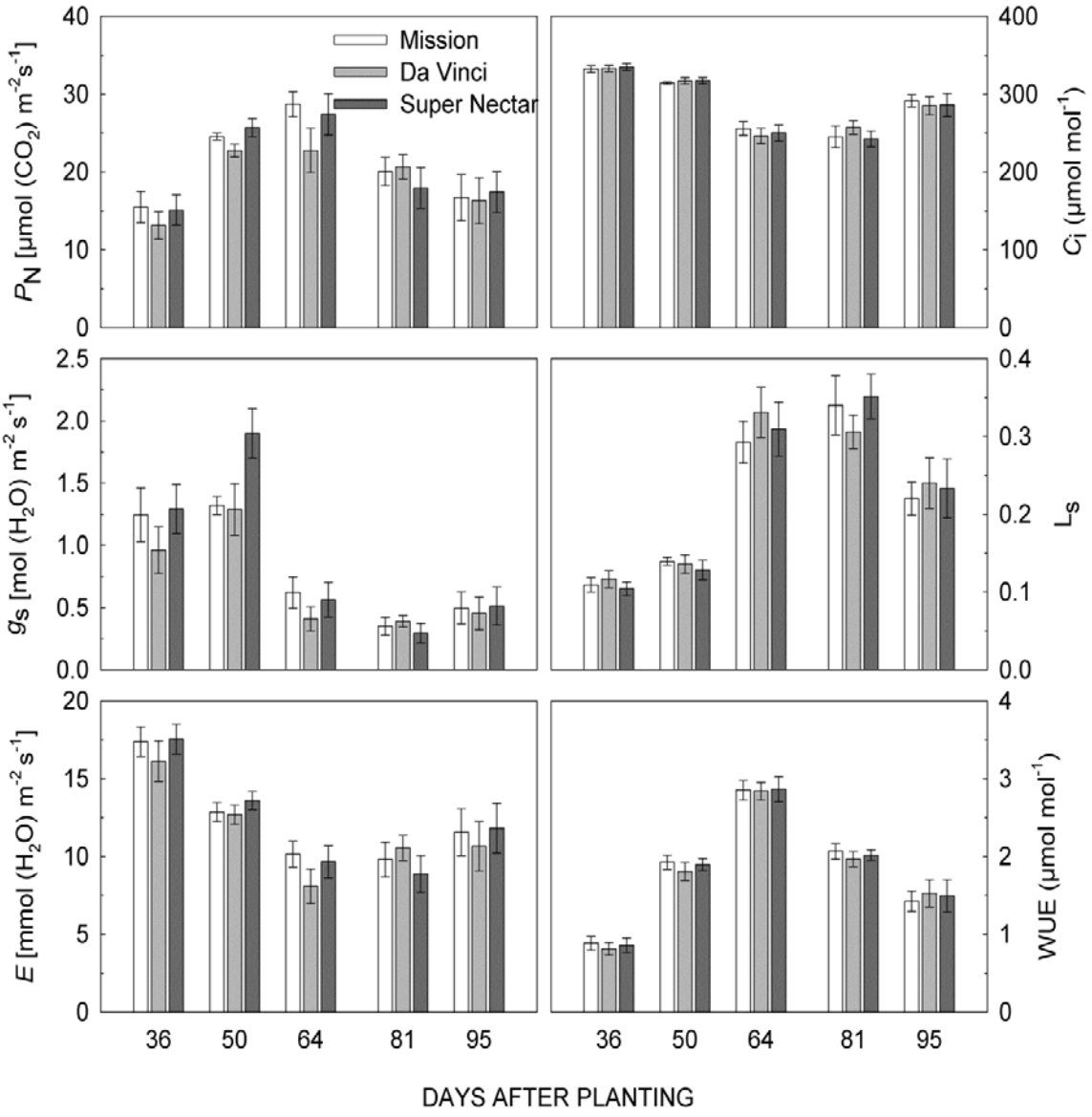

Figure 6.4 Net photosynthetic rate (P_N), stomatal conductance (g_s), transpiration rate (E); intercellular CO_2 concentration (C_i); non-stomatal limitation value (L_s) and water use efficiency (WUE, P_N/E) of melon cultivars over days after planting in 2012.Vertical bars represent 95% confidence intervals (n=12)

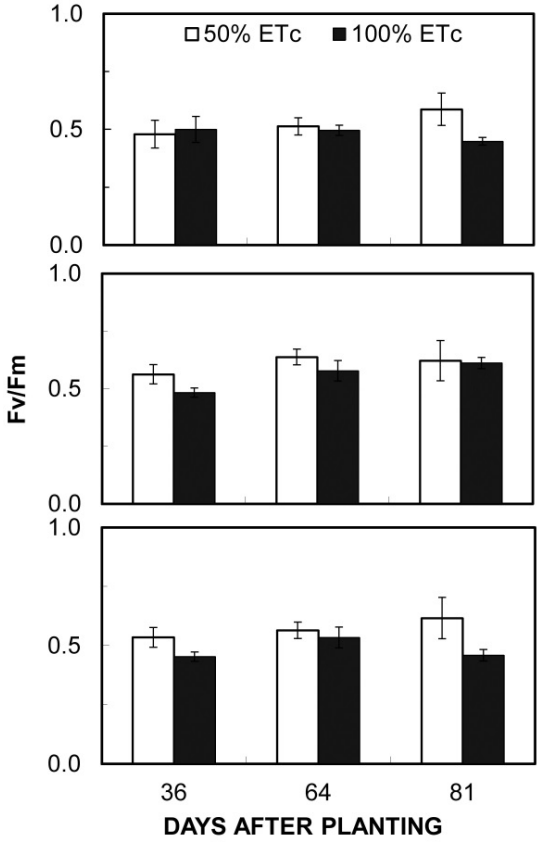

Figure 6.5 Maximum quantum yield (F_v/F_m) and chlorophyll index (SPAD) of melon cultivars in response to irrigation rates over days after planting in 2012. Values are represented as mean ± 1 SE (n = 6)

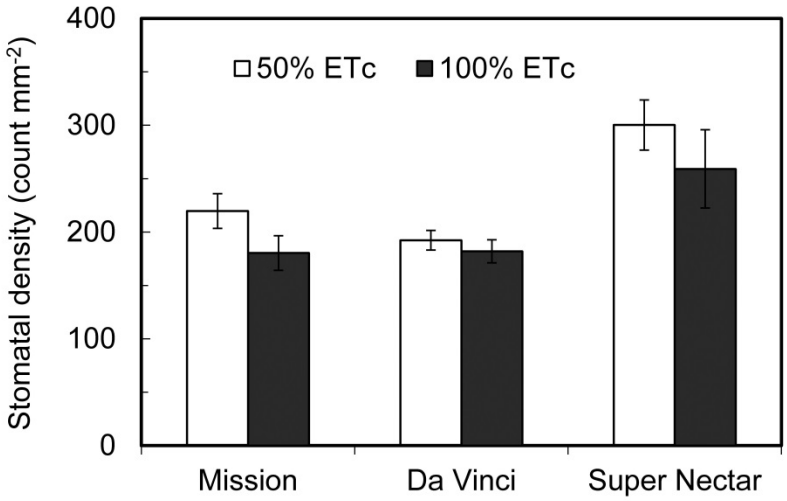

Figure 6.6 Stomatal density of melon cultivars in response to irrigation rates over 81 days after planting in 2012. Values are represented as mean ± 1 SE (n = 3)

as compared to 100% ETc (Table 6.3). These reductions varied in extent with cultivars. Leaf area and specific area decreased in all the cultivars while, LN and ABM decreased in Mission and Da Vinci. The trend was similar in Super Nectar, but not significant.

Fig. 6.7 depicts the allocation of ABM to leaf, stem and fruit components at 68 DAP. Deficit irrigation caused a significant reduction in leaf (LDW), stem (SDW), and fruit (FDW) dry weights in cvs. Mission and Da Vinci as compared to 100% ETc. In cv. Super Nectar the reduction was statistically significant only for stem dry weight (P = 0.025). Overall, deficit irrigation reduced LDW by 49, 53, and 18%, SDW by 54, 53 and 21% and FDW by 40, 43 and 3% in cvs. Mission, Da Vinci and Super Nectar, respectively.

Table 6.3 Number of leaves per plant (LN), leaf area per plant (m^2; LA), total above ground biomass (g dry weight; ABM), specific leaf area (cm^2 g^{-1} dry weight) of melon cultivars as influenced by irrigation rates at 37 and 68 DAP in 2012.Values are presented as mean ± SE.

		37 DAP*			68 DAP			
Main factor		LA	ABM	SLA	LN	LA	ABM	SLA
Irrigation rate (IR, ETc)								
50%		0.40[az]	26.4 a	235.7 a	260.5 b	1.92 b	539.7 b	117.0 b
100%		0.38 [a]	27.4 a	220.5 a	455.8 a	3.82 a	853.6 a	136.3 a
Cultivar (CV)								
Mission		0.38 [a]	26.3 a	230.3 a	372.0 a	2.74 a	625.9 a	124.8 b
Da Vinci		0.41 [a]	28.2 a	218.5 a	336.8 a	2.97 a	710.8 a	124.4 b
Super Nectar		0.37 a	25.8 a	238.5 a	365.8 a	2.91 a	753.4 a	130.8 a
Interaction (IR × CV)[†]								
Mission	50%	0.37 a	24.5 a	243.0 a	241.0 b	1.66 b	434.0 b	114.7 b
	100%	0.39 a	28.1 a	217.7 a	503.0 a	3.82 a	817.7 a	134.9 a
Da Vinci	50%	0.42 a	26.8 a	214.5 a	210.0 b	1.61 b	479.9 b	110.8 b
	100%	0.41 a	29.6 a	222.5 a	463.5 a	4.32 a	941.6 a	137.9 a
Super Nectar	50%	0.40 a	27.8 a	249.6 a	330.5 a	2.50 b	705.3 a	125.3 b
	100%	0.33 a	23.0 a	221.8 a	401.0 a	3.32 a	801.6 a	136.2 a

[z]Means in a column followed by the same letter are not significantly different at P≤ 0.05 according to the Duncan's multiple range test

ETc = Crop evapotranspiration, DAP = days after planting

[†]For interaction effects letters indicate significant difference between irrigation rates within each cultivar

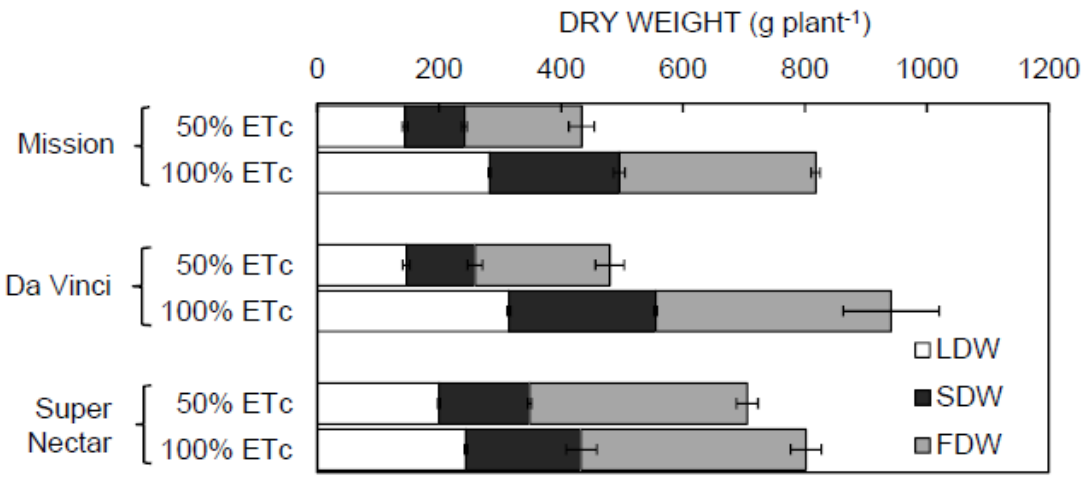

Figure 6.7 Above ground biomass allocation to leaf (LDW), stem (SDW), and fruit (FDW) dry weight of melon cultivars in response to irrigation rates at 68 days after planting in 2012. Values are represented as mean ± 1 SE (n = 3)

Under 50% ETc, the ABM had a strong correlation with leaf area per plant (LA) (r = 0.920) and number of leaves per plant (LN) (r = 0.888) (Table 6.4). Similarly, TFY had significant correlation with LA (r = 0.736), LN (r = 0.873) and SLA (r = 0.786) which indicates that under water deficit a decrease in TFY and ABM was associated with decrease in leaf area per plant. Moreover, under 100% ETc, ABM was positively correlated with LA. TFY had no correlation with ABM, LA and LN. This indicates that under optimum moisture conditions an increase in LA can result in enhanced ABM but not necessarily a corresponding increase in the fruit yield.

There were significant interactions between irrigation rates and cultivars for total fruit yield in both the seasons (Fig. 6.8). Deficit irrigation significantly reduced total

Table 6.4 Pearson's correlation coefficients among leaf gas exchange, growth and yield parameters of melon cultivars at 50% and 100% ETc in 2012

	P_N	g_s	E	F_v/F_m	SPAD	LA	LN	TFY	WUE
					50% ETc				
SLA	0.274^{ns}	0.116^{ns}	0.293^{ns}	-0.300^{ns}	-0.155^{ns}	0.821**	0.888**	0.786**	-0.194^{ns}
ABM	-0.064^{ns}	-0.136^{ns}	0.030^{ns}	-0.033^{ns}	-0.586^{ns}	0.920**	0.888**	0.696*	-0.175^{ns}
TFY	0.509^{ns}	0.369^{ns}	0.535^{ns}	-0.417^{ns}	-0.264^{ns}	0.736*	0.873**	-	-0.334^{ns}
WUE	-0.390^{ns}	-0.621*	-0.705*	0.236^{ns}	-0.077^{ns}	-0.116^{ns}	-0.210^{ns}	-	-
					100% ETc				
SLA	-0.444^{ns}	-0.509^{ns}	-0551^{ns}	0.418^{ns}	-0.152^{ns}	0.352^{ns}	-0.178^{ns}	-0.174^{ns}	0.287^{ns}
ABM	-0.375^{ns}	-0.595^{ns}	-0.480^{ns}	0.342^{ns}	-0.181^{ns}	0.798**	0.398^{ns}	-0.422^{ns}	0.292^{ns}
TFY	0.364^{ns}	0.306^{ns}	0.327^{ns}	0.127^{ns}	-0.140^{ns}	-0.617^{ns}	-0.465^{ns}	-	0.138^{ns}
WUE	0.149^{ns}	-0.180^{ns}	-0.200^{ns}	-0.071^{ns}	-0.124^{ns}	0.198^{ns}	0.027^{ns}	-	-

*, ** show significant difference at $P \leq 0.05$ and 0.01 respectively

ns, not significant at $P > 0.05$

P_N = net photosynthetic rate, g_s = stomatal conductance, E = transpiration rate, F_v/F_m = quantum yield, SPAD = chlorophyll index, LA = leaf area per plant, LN = number of leaves per plant, SLA = specific leaf area, ABM = total above ground biomass, TFY = total fruit yield and WUE = water use efficiency (P_N/E)

fruit yield in all the cultivars in 2012, and a similar trend was observed in 2011 though the reduction in yield was significant only in cv. Super Nectar (Fig. 6. 9). The highest yield reduction was measured in cv. Super Nectar, 38% (P = 0.001) in 2011 and 33% (P= 0.001) in 2012 in response to deficit irrigation. Similarly, cvs. Mission and Da Vinci recorded a 26% (P = 0.004) and 31% (P = 0.001) reduction in TFY in 2012, and an 11% (P = 0.214) and 14% (P = 0.119) reduction in 2011 respectively.

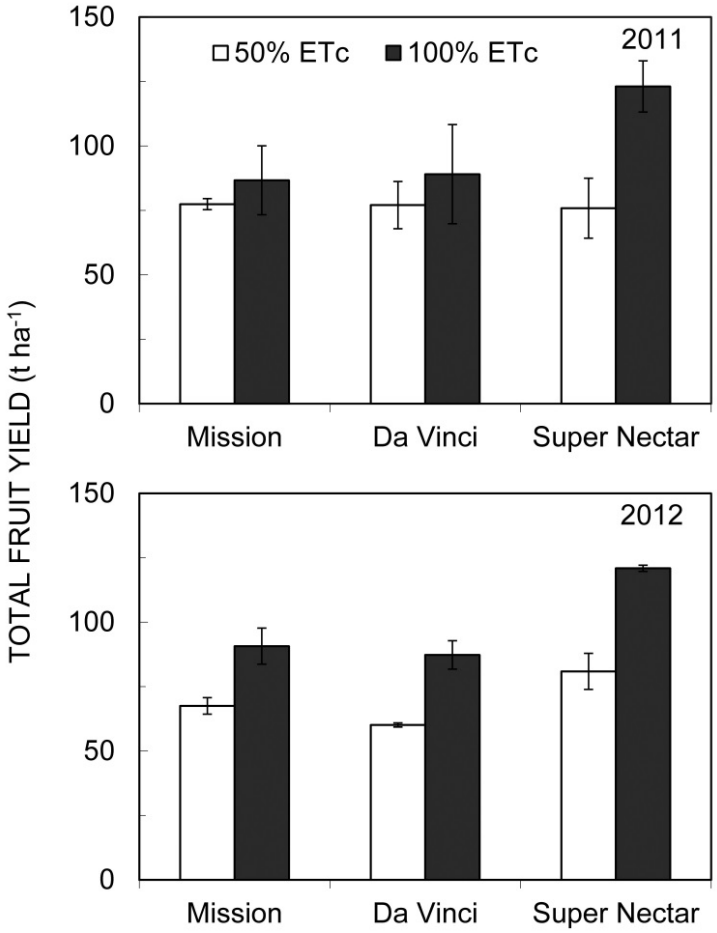

Figure 6.8 Total fruit yield of melon cultivars in response to irrigation rates in 2011 and 2012. Values are represented as mean ± 1 SE (n = 3)

6.4 Discussion

Melons are usually cultivated in arid to semi-arid conditions during hot and dry summers and thus, are often subjected to extreme droughts and high temperatures. These weather extremes adversely affect growth and photosynthetic capacity of plants which in turn reduces their yield potentials (Kusvuran, 2010; Sharma et al., 2014). Thus, adjustments in morphological, physiological and biochemical traits in response to changes in the environment of a crop or cultivar determine its adaptability to water deficit conditions. Kusvuran (2010) mentioned that the potential for drought tolerance in melon genotypes, which was further corroborated by a significant genotypic variability for leaf gas exchange traits in this crop (De et al., 2008). Thus, further information on growth and leaf gas exchange of melon cultivars will enhance understanding of their adaptation mechanisms to water deficit conditions, which can be applied to implement water saving strategies (e.g. deficit irrigation) with minimum yield losses.

Deficit irrigation (50% ETc) reduced the leaf gas exchange parameters in melon in both seasons, but differences were not significant in 2012 (Table 6.2). This year to year variation for photosynthetic traits is not unusual, in the drought prone environments where stress events vary in timing, duration and severity (Cattivelli et al., 2008). During this study period, the experimental site experienced the most severe drought since 1950's, with varied drought events in timing and severity in both years (Fig. 6.1). Overall 2011 was a drier year with a higher VPD (Fig. 6.1), as compared to 2012, which resulted in significant reduction in P_N and g_s in 2011. Janoudi et al. (1993) also reported

that increased VPD induced stomatal closure in cucumber (*Cucumis sativus* L.) plants which limited CO_2 availability and ultimately resulted in reduced photosynthesis.

Plants under deficit irrigation decrease in P_N (14%) and g_s (25%) (Table 6.1), suggesting that under water stress stomatal closure prevented water loss at the expense of CO_2 for photosynthesis (Agehara and Leskovar, 2012). Though with deficit irrigation WUE may increase (Sun et al., 2013), but the results of this study did not show significant improvement in WUE. However, WUE had a negative correlation with g_s under 50% ETc in comparison to 100% ETc (-0.390 vs. -0.149) to (-0.621 vs. -0.180) (Table 6.4), indicating that decrease in g_s increased WUE under water deficit conditions (Fig. 6.2, 6.4, Table 6.4).

Leaf gas exchange of melons varied with growth stages and climatic conditions. P_N increased significantly up to fruit development stage (67 DAP in 2011 and 64 DAP in 2012) irrespective of the cultivars and irrigation rate. Further, a decrease in stomatal conductance (42 - 63%) at this stage resulted in a significant increase in WUE (Table 6.1 and 6.2). This was also reported by (Sun et al., 2013). During fruit ripening (95 DAP in 2011), the combination of cumulative water deficit and high VPD (Fig. 6.1), resulted in further decrease in g_s causing a significant reduction in P_N, which can be attributed to reduced C_i. Janoudi et al. (1993) also reported that CO_2 limitation reduced P_N in cucumber plants.

Under 50% ETc, g_s and P_N decreased in cvs. Mission and Super Nectar while, these were maintained in cv. Da Vinci (Fig. 6.3). The latter cultivar was also more stable for all gas exchange traits over the sampling dates as compared to cvs. Mission and

Super Nectar (Fig. 6.2 and 6.4). Thus, lower g_s (Fig. 6.3 and Table 6.1) and ability to sustain P_N under 50% ETc, cv. Da Vinci indicates the potential of this cultivar for physiological adaptation to water deficit conditions. These results together with positive association of P_N with total fruit yield (Table 6.4) also indicates the possibility of using the leaf photosynthetic capacity as a selection criteria for drought tolerance in melons (Ashraf and Harris, 2013). Conversely, the cultivar Super Nectar had a higher g_s during initial growth stages (53 DAP in 2011 and 50 DAP in 2012) (Fig. 6.2, 6.3, 6.4), indicating that the possibility for honey dew melons to have higher transpiration requirements as compared to Tuscan and muskmelon types.

The significant differences between irrigation treatments for the maximum photochemical efficiency of PSII (F_v/F_m) (Fig. 6.5) reveals that the photochemical apparatus was not damaged by the intensity of the water deficit imposed through the application of 50% ETc, indicating that PSII in melon was stable under water deficit conditions. In cotton, Brito et al. (2011) also reported no differences for quantum yield between stressed and watered conditions, despite genotypic differences for quantum yield between stressed and watered conditions, despite genotypic differences for other physiological parameters, for example membrane leakage and carbon isotope composition existed. These results suggested that quantum yield (F_v/F_m) may not be useful trait in differentiating melon cultivars for their responses to water deficits.

No significant interactions between irrigation rate and cultivars were observed for RWC and leaf water potential (Ψ_l) (data not shown). However, deficit irrigation caused a numerical decrease (< 0.3 MPa) in Ψ_l in cvs. Mission, and Super Nectar while,

it was maintained in cv. Da Vinci. According to Hsiao (1973), water stress can be termed as mild, moderate, and severe if Ψ_l is lowered by less than 0.8, 1.2 to 1.5, and >1.5 MPa respectively under water deficit conditions. Thus, these results indicated cvs. Mission and Super Nectar experienced a moderate and mild level of water stress. The maintenance of Ψ_l in Da Vinci can be attributed to lower g_s and E in this cultivar, while a less reduction in Ψ_l in cv. Mission can be attributed to the enhanced root length intensity (mm cm^{-2}) under deficit irrigation (Sharma et al., 2014), which might have increased water uptake potential in this cultivar (Table 6.2 and Fig. 6.3).

Leaf area expansion is more sensitive to water stress than photosynthesis and transpiration (Subbarao et al., 1995). Under slow and gradual water deficit development; plants adjust their transpiring surface by reducing leaf growth to balance between transpiration demand and reduced water uptake (Hsiao, 1982). Crop transpiration is reduced linearly with reduction in leaf area under soil water deficit conditions (Ritchie, 1985). Therefore, adjustment and maintenance of optimum leaf area under water deficit conditions is the major plant process in determining crop productivity (Subbarao et al., 1995). In our study, although the photosynthetic traits were not affected by deficit irrigation in 2012, a significant reduction in total leaf area (50%) and leaf number (43%), and SLA (14%) was recorded under deficit irrigation as compared to 100% ETc (Table 6.3). Under water deficit, reduction in leaf number and leaf area have also been reported in strawberry (Razavi et al., 2008), and SLA in *Amaranthus* spp. (Liu and Stützel, 2004).

The ability of melons to adjust leaf area in response to deficit irrigation appears to be cultivar dependent in cvs. Mission, Da Vinci and Super Nectar decreased LA by

50, 50, and 20% and LN by 60, 60 and 20%, respectively. Genotypic differences for leaf area expansion under water stress have been reported in *Amaranthus* spp. (Liu and Stützel, 2004) and groundnut (Muchow, 1985; Subbarao et al., 1995). However, SLA reduction under 50% ETc was 10% more in Da Vinci than in Mission and Super Nectar, indication a decreased transpiring area and an increased leaf thickness in Da Vinci. Further, Liu and Stützel (2004) also reported that genotypes differed in their water conserving strategies, cv. WS80-192 exhibited reduction in SLA to control water loss .They also argued that drought tolerance is determined by a conservative balance between the water transpiring and absorbing plant organs. Thus, plants try to control water loss by decreasing leaf area. Further, the thicker leaves have higher chlorophyll density and exhibit more photosynthetic capacity than thinner leaves. Under water deficit, the maintenance of higher P_N in Da Vinci under water deficit could be attributed to higher reduction in SLA in comparison to Mission and Super Nectar.

Despite the benefit of water deficit tolerance for survival, it can have adverse impact on yield potential. Yield responses to deficit irrigation varied among cultivars. In both the years, cv. Super Nectar recorded highest yield reductions in response to deficit irrigation, while Mission and Da Vinci had significant reductions in 2012 which can be attributed to the significant drought experienced during fruit setting stage in 2012, which induced reduction in leaf area and thereby, total crop photosynthesis improving crop productivity. Richards (2000) reviewed that the maintenance of total crop photosynthesis is more important than the increase in the rate of photosynthesis per unit leaf area.

Reduction in leaf area and fruit yield has also been reported in strawberry under field conditions during severe deficit irrigation (Liu et al., 2007).

Generally, honeydew melon (cv. Super Nectar) take longer time from planting to fruit ripening as compared to cantaloupes (cv. Mission) and Tuscan type, melons (cv. Da Vinci). Deficit irrigation caused the lowest ABM reduction in cv. Super Nectar (10%) than in cvs. Mission (50%) and Da Vinci (50%) (Table 6.3). Conversely, the highest reduction in total yield was recorded in Super Nectar (Fig. 6.8). These contradictory results can be attributed to late maturity/ longer cropping season of cv. Super Nectar due to which it was exposed to drought for longer period before the final harvest. This was also evident from the significant reduction in root length in this cultivar at final harvest stage (Sharma et al., 2014), which might have resulted in balance between water loss and absorbing surfaces. Similarly, Cattivelli et al. (2008) reviewed that earliness is an effective breeding strategy for improving yield in environments where the crops are exposed to terminal droughts.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The overall goal of this research study was to evaluate the performance of melon (*Cucumis melo* L.) genotypes from diverse groups under natural and stressful conditions. The specific objective was to identify the generally stable and/or specifically adapted genotypes for particular locations/ irrigation management and soil type. All results of this study confirmed the differential response of melon genotypes to varying environments for root growth, yield and fruit quality traits. The overview of previous reports provided a substantial evidence of ubiquitous presence of G×E interactions for yield and quality traits in melons. Results of study will be useful for planning breeding strategies aimed at improving fruit yield and quality traits through multi-traits selections, allocation of resources for multi-location testing and selection of melon genotypes for particular environmental conditions.

7.1 G×E interactions for fruit yield and quality

In this experiment, fruit yield and the quality of nine melon genotypes from *reticulatus* (Mission, Oro Duro, Sol Real, Journey, TAMU 146, TAMU 1405, and TAMU F39) and *inodorus* (TAM Orange Casaba and Orange Dew) groups were evaluated across nine environments comprised of three locations (College Station, Uvalde and Weslaco, Texas) and three years (2010, 2011 and 2012). The nine genotypes included five commercial cultivars and four Texas A&M AgriLife melon breeding lines.

The objectives of the study were to characterize G×E interactions for restructuring current melon breeding strategies to develop improved cultivars for south central Texas, select ideal genotypes for commercial production, and identify generally stable or specifically adapted genotypes to the target environments using GGE biplot, a new statistical tool. The variance components and G×E interactions were calculated using a generalized linear model procedure (SAS 9.2 version, SAS Inst., Cary, N.C., USA).

Yield and yield components were mostly affected by E and G×E interactions. The G×E component of variance was higher than G, except for average fruit weight. Furthermore, the significant spatial (G×L) interactions for yield traits suggested the possibility to develop location specific cultivars. However, the temporal fluctuations in productivity emphasized the need to select year to year stable cultivars for target environments. Moreover, where the large fruit size does not influence the marketability, for example for developing cultivars for fresh cut industry, the better heritability of fruit weight can be utilized (e.g. TAMU OC). The characterization of G×E interactions for fruit quality traits (e.g. β-Carotene and firmness) can provide greater gains than in traits typically influenced by the environment such as, fruit yield and vitamin C content. The results of this study, confirmed the general regional adaptability of the most popular commercial cv. Mission. Texas A&M AgriLife breeding lines showed potential for utilization in the development of high yield with high fruit quality. The findings of this study also reinforce the idea of identifying optimum environments which best represent the target environment for melon cultivar screening and selections.

7.2 Impact of soil type on root growth responses

This study was conducted at two locations *viz.* Uvalde (clay soil) and Weslaco (sandy loam soil), with six melon genotypes, *viz.* Mission, Journey, TAMU 146, TAMU 1405, TAMU F39 and TAMU Orange Casaba in 2011 and 2012. Root growth distribution patterns of melon genotypes vary among locations or soil types. Root growth was distributed throughout the soil profile in the sandy loam soil of Weslaco, while it was confined to the shallow layers in clay soil of Uvalde, possibly due to differences in clay content of the soil types, which may have affected the downward movement of water and nutrients, the extent of nutrient mineralization in soil types and/or influenced the minirhizotron root growth estimates through soil-tube interface contact artifacts. These two year investigations indicated that climatic variations also influence root growth distribution patterns as well as fruit yield of the six melon genotypes.

The root distribution data also revealed that under high input, intensive production systems, such as plastic mulch plus subsurface drip irrigation, large root systems may not be required for high yielding potential in clay soils, however under sandy loam soils melon cultivars extend their root systems to deeper soil layers. Considering the root growth adjustments and/or the ability to adapt under different soil conditions, TAMU breeding lines showed potential for use in developing cultivar capable of sequestering limited soil resources in a wide range of environments. Furthermore, the great rooting ability of TAMU breeding lines under both sandy and clay soil types and equivalent yield potential to commercial hybrids confirms their

suitability for developing genetically improved cultivars with wide range of environmental stability.

7.3 Impact of deficit irrigation on yield and fruit quality

This study evaluated root growth, yield and fruit quality responses of melon cvs. Mission (cantaloupe; *reticulatus*), Da Vinci (tuscan; *reticulatus*) and Super Nectar (honeydew; *inodorus*) to two irrigation rates (100% and 50% crop evapotranspiration, ETc) on a silty clay soil of Uvalde in 2011 and 2012. The results indicate that the deficit irrigation practice saved more than 40% of irrigation water, at the expense of a significant reduction in melon fruit yield mainly due to a reduction in fruit size. The drought adaptation responses varied with the melon group and/or cultivar. Deficit irrigation increased root growth in Mission, decreased in Da Vinci and had no effect in the cv. Super Nectar. Water use efficiency was maintained in cv. Mission and Da Vinci, but decreased in cv. Super Nectar. In Mission and Da Vinci cultivars, deficit irrigation strategies showed efficacious for water limited regions with moderate yield reductions and without any loss in fruit quality. However, it is important to note that Super Nectar (honeydew type) needs adequate irrigation conditions for achieving maximum yield potentials.

7.4 Impact of deficit irrigation root growth patterns

Knowledge of root growth patterns is important to understand cultivar adaptations to deficit irrigation, particularly for subsurface drip irrigated crops where root systems are more confined than furrow or sprinkler systems.

Root studies were conducted over two years using the minirhizotron technique, as described in chapter IV. This study showed that environmental conditions due to years have a large impact on root growth estimates of the melon cultivars. Even though years were considered dry, 2011 was even drier than 2012 in the initial growth stages of the crop. These conditions in 2011 may have prevented deep root growth and/or influenced minirhizotron root growth estimates through soil-tube interface contact artifacts. Melon plants showed an ability to extend root growth beyond the limited wetted regions around the drip emitters (located at 15 cm depth) particularly under water deficit conditions, though the responses varied among cultivars. Mission (cantaloupe; *reticulatus*) and Da Vinci (tuscan; *reticulatus*) showed better adaptation to water deficit conditions by enhancing or maintaining root growth, while cv. Super Nectar (honeydew; *inodorus*) showed more sensitivity to water deficit due to decreased root growth. Minirhizotrons provided useful information on spatial and temporal root growth dynamics particularly in deeper soil layers in a non-destructive way which makes it a potential tool in screening cultivars for water deficit adaptation.

7.5 Impact of deficit irrigation on physiological parameters

Information on growth and leaf gas exchange of melon cultivars is critical for understanding their adaptation mechanisms to water deficit conditions, which can then be applied to implement water saving strategies (e.g. deficit irrigation) with minimum yield losses. In the deficit irrigation study described in chapters IV and V, growth and morpho-physiological responses of cvs. Mission, Da Vinci and Super Nectar were characterized.

Total fruit yield and biomass production of the three melon cultivars investigated in the present study were strongly associated with leaf area, leaf number and specific leaf area under water deficit conditions, but poorly with P_N, g_s and E. Thus it appears that adaptation responses to water deficit conditions in melons are related to the maintenance of leaf area during water stress and, thus, to the total crop photosynthesis. The early maturing cultivars Mission and Da Vinci escaped the cumulative stress developed through gradual water deficit over the growing season and showed root growth and leaf gas exchange adaptation, respectively. However, the cv. Super Nectar had higher yield penalties due to late maturity and longer crop duration. Thus, early maturing and short duration melon cultivars that have the capacity to maintain leaf area development and root growth under water deficit conditions can better sustain productivity in drought-prone semiarid growing regions, such as the southwest Texas.

CHAPTER VIII

RECOMMENDATIONS

Selection of cultivars in the short term and modification of breeding programs in the long term are important strategies to deal with G×E interactions. Therefore, decisions should be based on the scientific understanding of the crop germplasm and its interaction with the target environments (Paolo, 2002). Due to the nature of multiple harvests in muskmelon, G×E interaction studies are very challenging, complex and labor intensive, thus melon breeders restrict the number genotypes and environments to a manageable level, depending upon the availability of time and resources. With such limitations, conclusions from G×E interaction studies are partially useful to modify long term breeding strategies for the target environment, as there may be difficult to extend generalized applications to other genotypes and environments.

On the other hand, these studies can be useful for cultivar recommendations and evaluations of elite breeding lines at the final stages of a melon breeding program. Since muskmelon has wide phenotypic heterogeneity for fruit characteristics, a caution should be taken in selecting genotypes for a G×E study. The inclusion of genotypes from diverse horticultural groups such as *inodorus* and *reticulatus* types may lead to biased conclusions either in favor or against some genotypes for particular traits, such as fruit weight. For example, TAMU Orange Casaba (*inodorous* type) produced higher fruit yield because of large fruit size, in reality it may not a right choice for commercial cultivation, in comparison to *reticulatus* cultivars.

This study has confirmed the presence of G×E interactions for both yield and quality traits. To restructure breeding strategies, more G×E interactions studies that include a higher number of environments and genotypes are needed. Thus, in melon breeding programs G×E interactions should never be ignored, rather these should be considered more precisely and extensively, using proper analysis and statistical software (i.e. GGE biplot) to explore the specific adaptations and general stability.

In the immediate future, extensive applications of genetic engineering techniques are expected to produce more resilient cultivars with multiple favorable genes for various biotic and abiotic stresses. However, Paolo (2002) indicated that most of the useful molecular markers are environment specific and thus, these can be used for specific adaptations. For wider adaptations, phenotypic selections with multi-environment testing will be more important than marker assisted selections. The application of biotechnological tools will not reduce or eliminate the importance of G×E interactions in breeding programs, particularly for traits expressing large G×E interactions such as fruit yield. Moreover, the public resistance to accept genetically modified vegetables is likely to enhance the importance of conventional breeding tools, such as specific adaptations for high levels of phytochemicals.

Another limitation of this research study was the difficulty in detecting expected significant differences in root growth among treatments, due to the inherent high variability of this trait. An experimental design involving a limited number of genotypes and higher number of replications and years will be more robust and reduce coefficient variance to reach stronger conclusions. Since root studies are tedious, expensive and

time consuming, it will be more practical if first a large number of genotypes are screened under controlled conditions, and then only promising genotypes with desirable traits are selected for further evaluations and with more replications in field conditions. The variation in root growth estimates that were related to soil tube interface artifacts may be resolved by installing tubes a month before planting, rather than at the time of planting, as done in this study.

In the deficit irrigation study, it has been implied that plant growth, leaf gas exchange and root growth responses to water deficit have been influenced by rainfall differences among the two years. Thus, repeating experiments over more than two years and/or using rainout shelters may provide stronger evidence of these responses under water deficit conditions. Finally, the application of genetic engineering techniques such as molecular markers can be integrated more precisely to confirm the environmental responses of selective traits linked to drought tolerance that may be associated with wider adaptability and fruit quality.

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