Rootstocks Affect Tree Growth, Yield, and Juice Quality of ‘Marsh’ Grapefruit

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Abstract. Two adjacent rootstock trials were conducted in the east coast Indian River region of Florida with ‘Marsh’ grapefruit (*Citrus paradisi* Macf.) scion. The objective was to find rootstocks to replace sour orange (*C. aurantium* L.) because of losses to citrus tristeza virus, and to replace Swingle citrumelo [*C. paradisi* × *Poncirus trifoliata* (L.) Raf.] because of its limited usefulness in certain poorly drained coastal sites. The trials were conducted in randomized complete blocks with 12 single-tree replicates spaced 4.6 × 6.9 m. The soils were of the Wabasso and Riviera series. The first trial consisted largely of trees on citrange [*C. sinensis* (L.) Osb. × *P. trifoliata*] and citrumelo rootstocks, ‘Cipo’ sweet orange (*C. sinensis*), and various hybrid rootstocks. The second trial involved mandarin rootstocks (*C. reticulata* Blanco) and sour orange and related rootstocks. Trees were grown for 7 years and yield and juice quality data were collected for the last 4 years of that period. Those rootstocks identified as the most promising, based on combinations of smaller tree size and high productivity and juice quality, were two Sunki mandarin × Swingle trifoliata orange (TF) hybrids (C-54, C-146), a Sunki mandarin × Flying Dragon TF hybrid, C-35 citrange, and a Cleopatra mandarin × Rubidoux TF hybrid (×639). The trees on these five rootstocks cropped well leading to soluble solids (SS) values of 3000 to 4000 kg/ha when they were 7-years old. The trees on C-54 and C-146 were relatively large, somewhat taller than trees on sour orange, whereas those on C-35 and the Sunki × Flying Dragon hybrid were smaller and similar to sour orange in tree height. Fruit quality among the trees on C-35 and the Sunki × Flying Dragon hybrid had relatively high SS concentration (better than sour orange), and the other three rootstocks had relatively lower solids concentration (poorer than sour orange). The trees on C-35 and the Sunki × Flying Dragon hybrid would be good candidates for higher density orchards.

Grapefruit has long been the major fresh fruit produced in Florida. For many years the seedless white cultivar ‘Marsh’ was the dominant selection. It has slowly been replaced by pigmented seedless selections like ‘Redblush’

and ‘Ray Ruby’ (Davies and Jackson, 2009). An additional change has been the increased use of grapefruit for juice products. In recent years, ≈50% of the Florida crop was used for processing (Fla. Agric. Stat. Serv., 2010). Presently, there are 14,288 ha of pigmented selections and 5,715 ha (28% of the total) of ‘Marsh’ grapefruit in Florida, which is ≈65% of U.S. planted hectares and production (Fla. Agric. Stat. Serv., 2010).

Grapefruit is grown in three major physiographic regions of Florida. The first region is the Indian River, an area of flat land along the east coast with poorly drained soils that requires the construction of drainage ways and raised beds to grow citrus. Most areas where citrus is grown in this region have elevations of <20 m. This region accounts for nearly 75% of the land planted with grape-

fruit (Fla. Agric. Stat. Serv., 2010). The second region is the southwest, also a largely coastal area and, third, the Central Florida Ridge, which runs along the center of the state and consists of well-drained sandy soils at elevations up to 100 m.

The early reputation of Florida-grown grapefruit was established in the Indian River region where high external and internal quality were the result of particular climatic factors and the use of sour orange rootstock (*Citrus aurantium* L.). Fruit grown in this production region is often touted as the ideal because of their oblate shape with a smooth, thin skin, and excellent flavor. The use of sour orange rootstock for grapefruit was reduced for many years because of its susceptibility and considerable tree losses associated with quick decline strains of citrus tristeza disease caused by an aphid-transmitted virus (Stover and Castle, 2002). However, propagations with sour orange have increased recently because potential replacement rootstocks such as Smooth Flat Seville and Kinkoji have been explored commercially and proven to be of questionable usefulness mostly because fruit from trees on those two rootstocks often fail to meet minimum maturity standards particularly for SS concentration (Division Plant Industry, 2010; McCollum et al., 2002). As a result, a number of other rootstocks including Kuharske citrange, ×639, and Swingle citrumelo were tried as replacements for sour orange. It was subsequently learned that trees on Swingle citrumelo were suited to only particular site conditions in the Indian River region (Bauer et al., 2005). Furthermore, much of the fruit grown in the Indian River is exported to Japan, where the quality standards set by the buyers are rigid and can exceed the U.S. standards (Fellers, 1990). Therefore, our objective was to conduct two rootstock trials to evaluate a broad range of commercial and new rootstocks available at the time. Special focus was given to identify the rootstocks that increased juice SS concentration, earliness of maturity, and reduced tree size.

Materials and Methods

Plant material and propagation. The commercial cooperator produced container-grown nursery trees in a company nursery. Seeds or seedlings of the rootstocks (Table 1) originating mostly from local sources were provided to the nursery manager for propagation with ‘Marsh’ grapefruit scion, clone F57-X-E, for which the budwood source had been tested for viruses and viroids and no citrus tristeza virus (CTV), xyloporosis (X), or exocortis (E) was detected.

Field trials. The grower cooperator provided a field site (lat. 27°04′ 19.55; Long. 80°13′ 13.31; elevation, 3.6 m) west of Hobe Sound, FL, that had previously been planted with citrus. The soil series at the site is mapped as Wabasso sand, a Spodosol in the family of Alfic Haplaquods. The soil has a surface layer of black to gray sand ≈30-cm thick underlain by 30 to 50 cm of light

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Table 1. Rootstocks in two 'Marsh' grapefruit trials, Hobe Sound, FL.

Rootstock	Scientific name	Source ^a
Experiment 1		
Benton citrange	<i>Citrus sinensis</i> (L.) Osb. × <i>Poncirus trifoliata</i> (L.) Raf.	DPI
C-35 citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
Carrizo citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
Cipo sweet orange	<i>C. sinensis</i>	USDA
Cohen citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
F80-2 citrumelo	<i>C. paradisi</i> Macf. × <i>P. trifoliata</i>	DPI
F80-5 citrumelo	<i>C. paradisi</i> × <i>P. trifoliata</i>	DPI
F80-6 citrumelo	<i>C. paradisi</i> × <i>P. trifoliata</i>	DPI
F80-7 citrumelo	<i>C. paradisi</i> × <i>P. trifoliata</i>	DPI
F80-8 citrumelo	<i>C. paradisi</i> × <i>P. trifoliata</i>	DPI
F80-9 citrumelo	<i>C. paradisi</i> × <i>P. trifoliata</i>	DPI
Koethen sweet orange × Rubidoux trifoliolate orange (TF)	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
Kuharske citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
Morton citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
Rangpur × Marks TF (1261)	<i>C. limonia</i> Osb. × <i>P. trifoliata</i>	LC 53-18-1
Rangpur × Marks TF (1262)	<i>C. limonia</i> × <i>P. trifoliata</i>	LC 53-19-1
Rangpur × Swingle TF	<i>C. limonia</i> × <i>P. trifoliata</i>	LC 53-16
Rusk citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
Sacaton citrumelo	<i>C. paradisi</i> × <i>P. trifoliata</i>	DPI
Sunki mandarin × Flying Dragon TF	<i>C. reticulata</i> Blanco × <i>P. trifoliata</i>	LC 53-15
Sunki mandarin × Swingle TF (C-146)	<i>C. reticulata</i> × <i>P. trifoliata</i>	LC 58-1
Swingle citrumelo	<i>C. paradisi</i> × <i>P. trifoliata</i>	DPI
Troyer citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
US-119	Citrumelo × <i>C. sinensis</i> 'Succory'	USDA
US-802 Pummelo × TF	<i>C. grandis</i> L. × <i>P. trifoliata</i>	USDA
US-812 Sunki mandarin × Benecke TF	<i>C. reticulata</i> × <i>P. trifoliata</i>	USDA
US-896 Cleopatra mandarin × TF	<i>C. reticulata</i> × <i>P. trifoliata</i>	USDA
US-897 Cleopatra mandarin × Flying Dragon TF	<i>C. reticulata</i> × <i>P. trifoliata</i>	USDA
US-1001 Changsha mandarin × Eng. Lg. TF	<i>C. reticulata</i> × <i>P. trifoliata</i>	DPI
Uvalde citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
Yuma citrange	<i>C. sinensis</i> × <i>P. trifoliata</i>	DPI
Experiment 2		
Changsha mandarin	<i>C. reticulata</i>	DPI
Chinotto sour orange	<i>C. myrtifolia</i> Raf.	DPI
Cleopatra mandarin	<i>C. reticulata</i>	DPI
Cleopatra mandarin × Rubidoux TF (x639)	<i>C. reticulata</i> × <i>P. trifoliata</i>	DPI
Goutou	<i>C. aurantium</i> L. putative hybrid	DPI
Kinkoji	<i>C. obovoidea</i> Hort ex. Tak.	DPI
Shekwaska mandarin	<i>C. reticulata</i>	DPI
Smooth Flat Seville	<i>C. aurantium</i> putative hybrid	DPI
Sun Chu Sha mandarin	<i>C. reticulata</i>	DPI
Sunki mandarin	<i>C. reticulata</i>	DPI
Sunki mandarin × Swingle TF (C-54)	<i>C. reticulata</i> × <i>P. trifoliata</i>	LC 57-16
Yuzu	<i>C. ichangensis</i> Swing. × <i>C. reticulata</i>	DPI
Zhuluan	<i>C. aurantium</i> putative hybrid	DPI

^aDPI = FL Dept. Agric. Consumer Serv., Citrus Budwood Registration Office; USDA = Whitmore Foundation Farm; LC = University of California Field Station at Lindcove where the numbers (L to R) are either the field or genetic code. Those codes with three parts are the original ones from the plant breeder and apparently are: the year the seed was sown; the seed lot; the tree in the seed lot. Those codes with two numbers are probably the row and tree number with the field number left out.

brownish gray sand. The spodic horizon is ≈50 to 55 cm below the soil surface and is generally 15- to 30-cm thick. It is underlain by a clay horizon of fine sandy loam soil. Soils of the Wabasso series are among the better soils for growing citrus in the Indian River region (Bauer et al., 2007). The site was prepared by excavating perimeter drainage ditches and forming double-row beds on which the trees were planted. Such beds are

typically ≈15-m wide and 1-m above the natural landscape.

Two adjacent trials were planted: E.1, 31 citrange, and citrumelo rootstocks plus some related hybrids, and E.2, 14 sour oranges types, mandarins, and mandarin hybrids. Most of the trees were planted in June 1995 and a small portion was planted the following October. The spacing was 4.6 m in the row and 6.9 m between rows. The trials were designed

in randomized complete blocks with 12 single-tree replicates. We selected the larger than normal number of replicates and smaller plot size because of the known soil variability in Indian River sites. The trees were managed with a standard grove microsprinkler irrigation system, nitrogen applications totaling 160–180 kg/ha/year, and a pest management program appropriate for fresh fruit (Obreza and Morgan, 2008; Rogers et al., 2009).

Data collection and analysis. Tree height was measured periodically. Tree survival was recorded in 2004, 9 years after planting. Annual samples of 50–60 fruit were collected from each plot near the time of harvest. Juice was extracted and analyzed with standard commercial equipment at the Citrus Research and Education Center, Lake Alfred, FL (Wardowski et al., 1995). Fruit yield was measured annually with a commercial harvesting crew by placing fruit in standard containers holding 400 kg and recording volume. Data analyses were according to the experiment design with mean separation by the least significant difference test. Some variables were examined by simple linear correlation analysis at $P \leq 0.05^*$, 0.01^{**} , or 0.001^{***} .

Results and Discussion

Tree height and survival. Mean height of the trees in E.1 (citrange and citrumelo rootstocks) and in E.2 (sour orange and related selections as well as mandarin types) were virtually identical at ages 4 (2.3 vs. 2.4 m) and 9 years (3.2 vs. 3.2 m, respectively) (Tables 2 and 3). The tallest trees in E.1 were those on US-802 (3.8 m) (Table 2). They were significantly taller than those on any other rootstock except the Rangpur × Swingle TF hybrid in E.1 where the trees on most rootstocks were ≈3.0 to 3.4 m tall. Those on US-896, US-897, and Sacaton citrumelo had heights <3.0 m and the trees on Rusk citrange were the smallest (2.4 m). There were significant height differences among the trees in E.2 where the tallest ones were those on Kinkoji (3.7 m), the Cleopatra mandarin × Rubidoux TF hybrid (x639) and Smooth Flat Seville (3.6 m) (Table 3). The shortest trees were on sour orange (3.1 m).

Tree survival on many rootstocks in both trials was 100% and that on most other rootstocks was between 80% and 100% (Tables 2 and 3). Those on Sacaton citrumelo, Yuzu, and Changsha mandarin developed thin canopies and an unthrifty appearance and had the poorest survival rates (<70%). Tree decline and loss from CTV occurred among the trees on sour orange and Chinotto sour orange based on typical stem pitting symptoms apparent at the bud union.

Fruit yield. Cropping began among the trees on some rootstocks when they were 2-years old and continued the following year. The cropping in the 2nd year was typically 10 to 20 fruit per tree and was recorded, but not included in the cumulative yield. The precocious trees tended to be on those rootstocks with the highest cumulative yields at the end

Table 2. Height and survival ($n = 12$) of 'Marsh' grapefruit trees on various rootstocks (E.1) planted in 1995 at 4.6×6.9 m.

Rootstock ^z	Tree ht (m) at age		Survival (%)
	4 yr	9 yr	
US-802 Pum. $\times$ TF	2.8	3.8	100
Rangpur $\times$ Swingle TF	2.5	3.5	100
F80-7 citrumelo	2.4	3.4	100
Sunki $\times$ Swingle TF (C-146)	2.5	3.4	100
Uvalde citrange	2.7	3.4	100
Kuharske citrange	2.4	3.4	100
Cohen citrange	2.3	3.3	100
US-1001 Changsha $\times$ ELTF	2.4	3.3	100
F80-6 citrumelo	2.6	3.3	85
Rangpur $\times$ Marks TF (1261)	2.6	3.3	93
Carrizo citrange	2.5	3.3	85
F80-9 citrumelo	2.4	3.3	87
Swingle citrumelo	2.5	3.2	100
US-812 Sunki $\times$ Benecke TF	2.3	3.2	100
F80-2 citrumelo	2.4	3.2	100
Benton citrange	2.5	3.1	100
C-35 citrange	2.4	3.1	100
Cipo sweet orange	2.2	3.1	75
Koethen sweet orange $\times$ Rubidoux TF	2.1	3.0	100
Morton citrange	2.0	3.0	94
F80-8 citrumelo	2.1	3.0	88
Sunki $\times$ Flying Dragon TF	2.2	3.0	94
Sacaton citrumelo	1.9	2.9	65
US-897 Cleo $\times$ Flying Dragon TF	2.0	2.7	92
US-896 Cleo $\times$ TF	2.0	2.7	100
Rusk citrange	1.9	2.4	77
F80-5 citrumelo ^y	2.5	—	100
Rangpur $\times$ Marks TF (1262) ^y	1.5	—	94
Troyer citrange ^y	2.4	—	94
US-119 ^y	2.0	—	100
Yuma citrange ^y	2.3	—	100
Mean	2.3	3.2	—
Least significant difference	0.3	0.3	—

^zRootstocks are ranked by tree height at age 9 years.

^yBecause of relatively poor yield and other performance factors, these trees were marked for removal after 7 years and data collection was discontinued.

Table 3. Height and survival ($n = 12$) of 'Marsh' grapefruit trees (E.2) on various rootstocks planted in 1995 at 4.6×6.9 m.

Rootstock ^z	Tree ht (m) at age		Survival (%)
	4 yr	9 yr	
Kinkoji	2.7	3.7	100
Smooth Flat Seville	2.5	3.6	92
Cleopatra mandarin $\times$ Rubidoux TF ($\times 639$)	2.6	3.6	100
Goutou	2.4	3.5	100
Sun Chu Sha mandarin	2.5	3.5	100
Cleopatra mandarin	2.4	3.4	79
Sunki $\times$ Swingle TF (C-54)	2.5	3.3	100
Sunki mandarin	2.4	3.3	78
Zhuluan	2.2	3.2	95
Shekwasha mandarin	2.1	3.2	93
Sour orange	2.3	3.1	83
Changsha mandarin ^y	2.1	—	75
Chinotto sour orange ^y	2.6	—	67
Yuzu ^y	1.9	—	61
Mean	2.4	3.4	—
Least significant difference	0.4	0.3	—

^zRootstocks are ranked by tree height at age 9 years.

^yTrees were either removed or data collection was discontinued because of poor survival, low yield or citrus tristeza virus as with Chinotto sour orange.

of the experiments such as Uvalde and C-35 citranges and Sunki $\times$ Swingle TF (C-146; C-54). The early bearing also explained the high yield among those rootstocks when yield was first measured across all rootstocks at tree age 4 years (Tables 4 and 5). In the first-year of measurement, mean yield across all rootstocks was 51 and 44 kg/tree

for E.1 and E.2, respectively. Yield increased to 122 kg/tree (E.1) or 148 kg/tree (E.2) when the trees were 7-years old. The yield data were more variable than desired because of site variability. As a result, there were fewer differences among rootstocks than we experienced in other Florida field trials. Nevertheless, the trees on the highest yielding

rootstocks significantly exceeded the yields of the trees on many other rootstocks throughout the measurement period. Some of the lowest yielding trees were those on US-896, US-119, Cipo sweet orange, Koethen $\times$ Rubidoux TF citrange, F80-8 citrumelo, Yuzu, Chinotto sour orange, and Changsha mandarin partly because of smaller tree height in many instances.

Yield at tree age 4 years was correlated to yield at tree age 7 years ($r = 0.55^*$, E.1; $r = 0.75^{**}$ E.2) indicating that the trend established in the first commercial crop was continued for three additional years. Some of the variability that led to the lower correlation in E.1 was the smaller first-year yields of the trees on Yuma and Troyer citranges and F80-5 citrumelo followed by large yields at tree age 7 years, and declining yields of the trees on US-119 and Rangpur $\times$ Marks TF (1262) as those trees aged. In E.2, there were no decreases in yield, but the trees on Goutou increased more so than the trees on the other rootstocks.

There were significant differences in yield among rootstocks in each year leading to 4-year cumulative yields that ranged from only 59 to 596 kg/tree in E.1, a 10-fold difference, and 207 to 719 kg/tree in E.2 (Tables 4 and 5). Trees on the most productive rootstocks had cumulative yields >500 kg/tree. They were the most productive rootstocks primarily because their yield generally increased each year unlike the trees on many of the other rootstocks, which tended to alternate crop. The trees with the highest cumulative yield, 719 kg/tree, were those on Sunki $\times$ Swingle TF (C-54).

The relationship between cumulative yield and tree height was weakly evident in E.1 ($r = 0.40^*$) and not at all in E.2 ($r = 0.05$ ns). That is a result of there being a full range of tree height and yield combinations. For example, there were high yielding, smaller trees such as those on C-35 citrange, Sunki $\times$ Swingle TF (C-54), and Sunki $\times$ Flying Dragon TF; high yielding, taller trees like those on Uvalde citrange and $\times 639$ hybrid, and low yielding short or tall trees.

Fruit weight, juice quality, SS production. Fruit diameters (sizes) and their distribution are important variables with grapefruit because the fruit is primarily grown for the fresh market. Neither variable was measured in our trials. Instead, the mean weight of the fruit in the juice samples collected each year was recorded and is used herein as a general measure of fruit size. Those values represent only a portion of the tree crop although, in sampling, we attempted to collect fruit that were typical of the entire crop on each tree. Also, the juice samples were collected by several individuals who introduced some variability into the sampling. Fruit size is inversely related to crop size, a relationship not well documented for grapefruit (Barry et al., 2004; Zamski and Schaffer, 1996). Thus, we consider fruit weight as only a coarse estimation subject to the preceding limitations.

Fruit weight was larger at tree age 4 years than 7 years regardless of rootstock (Tables 6

Table 4. Yield (kg/tree; $n = 6$) of 'Marsh' grapefruit trees on various rootstocks (E.1) planted in 1995 at 4.6×6.9 m.

Rootstock	Tree age (yr)				Cumulative yield
	4	5	6	7	
Uvalde citrange	75	121	201	200	596
C-35 citrange	94	190	110	178	573
Sunki $\times$ Swingle TF (C-146)	74	123	146	207	550
Sunki $\times$ Flying Dragon TF	64	134	151	186	535
Rangpur $\times$ Marks TF (1261)	48	134	183	169	534
Carrizo citrange	59	139	169	140	506
F80-9 citrumelo	59	113	140	183	495
Morton citrange	53	133	185	122	493
US-812 Sunki $\times$ Benecke TF	63	70	133	178	444
Rangpur $\times$ Swingle TF	67	108	166	101	442
US-802 Pum. $\times$ TF	27	180	96	135	438
Benton citrange	71	113	121	121	425
F80-6 citrumelo	44	121	144	116	423
Swingle citrumelo	51	119	123	130	422
Sacaton citrumelo	28	113	137	138	417
Kuharske citrange	49	128	106	111	394
Yuma citrange	32	144	112	99	386
Troyer citrange	48	129	62	140	378
F80-8 citrumelo	64	118	87	106	375
US-1001 Changsha $\times$ ELTF	52	83	130	106	370
F80-2 citrumelo	35	123	80	109	348
F80-7 citrumelo	48	113	85	101	347
F80-5 citrumelo	35	82	92	106	314
US-897 Cleo $\times$ Flying Dragon TF	62	87	73	86	308
Cipo sweet orange	48	36	126	92	301
Rusk citrange	59	108	21	101	289
Cohen citrange	21	51	118	97	287
Koethen sweet orange $\times$ Rubidoux TF	47	77	70	92	285
US-896 Cleopatra mandarin $\times$ TF	44	46	76	87	253
US-119 hybrid	44	67	60	44	215
Rangpur $\times$ Marks TF (1262)	29	3	14	13	59
Mean	51	107	114	122	394
Least significant difference	24	83	113	84	—

Table 5. Yield (kg/tree; $n = 6$) of 'Marsh' grapefruit trees (E.2) on various rootstocks planted in 1995 at 4.6×6.9 m.

Rootstock	Tree age (yr)				Cumulative yield
	4	5	6	7	
Sunki $\times$ Swingle TF (C-54)	80	175	202	262	719
Cleopatra $\times$ Rubidoux TF ($\times 639$)	81	134	207	247	669
Sunki mandarin	58	166	183	180	587
Sour orange	65	141	172	169	547
Kinkoji	33	128	183	149	493
Sun Chu Sha mandarin	42	98	183	166	489
Cleopatra mandarin	35	121	152	149	457
Goutou	22	121	129	162	434
Smooth Flat Seville	35	136	127	106	404
Zhuluan	34	83	103	129	349
Shekwasha mandarin	30	90	111	100	331
Changsha mandarin	35	65	84	104	288
Chinotto sour orange	27	90	119	39	275
Yuzu	31	33	61	82	207
Mean	44	113	148	148	446
Least significant difference	24	63	65	84	—

and 7). Young grapefruit trees when they begin cropping tend to have relatively large fruit partly because smaller crops often lead to larger sizes. At tree age 7 years, mean fruit weight was 430 g in E.1 and 420 g in E.2. There were almost no significant differences among rootstocks in either trial. Trees with fruit ≥ 470 g included those on Yuma, Benton, Cohen and Morton citranges, and Kinkoji. Fruit weight was not significantly correlated with yield ($r = 0.16$ ns) in either year suggesting that fruit size was more an expression of

other factors than a direct influence of rootstock. Nevertheless, the most productive trees had fruit with weights below the mean with the notable exception of the larger fruit on the trees on Uvalde citrange (490 g). Trees on mandarin rootstocks like Cleopatra, Sun Chu Sha, and Sunki are well-known for producing fruit with smaller sizes, but that was not the case in these trials (Castle, 1987).

Grapefruit shipped for the fresh market from Florida and those that are processed must meet minimum maturity standards that

change seasonally for juice content according to fruit size, and SS concentration and SS : acid ratio (Wardowski et al., 1995). Our juice content data are means for the fruit samples and do not relate to the standards for individual fruit sizes. However, using the mean fruit weight in our trials and the required juice content of 230 ml for a typical commercial fruit size, juice content would be $\approx 53\%$ assuming 1 ml of juice weighs ≈ 1 g. Thus, the mean juice contents (by weight) and those for the fruit from the trees on most rootstocks in E.1 and E.2 were in the commercially acceptable range (Tables 6 and 7). There were no differences among most rootstocks, but fruit from the trees on Sunki $\times$ Flying Dragon TF, US-896, and US-897 had values $>60\%$ when the trees were 7-years old as compared with fruit with juice contents $<55\%$ among trees on US-802, Smooth Flat Seville, Kinkoji, Cleopatra mandarin, and Benton, Morton, and Yuma citranges.

The trial fruit were sampled in late January to late February at which time a minimum of 7.0% SS concentration is required in Florida (Wardowski et al., 1995). The mean SS concentrations were $\geq 8.0\%$ in the E.1 trees when they were 4- and 7-years old and in the trees in E.2 when they were 7-years old (Tables 6 and 7). Values $\geq 9.0\%$ occurred among the trees on 13 rootstocks in E.1 and E.2 combined and included several with values as high as 9.3% (C-35, Kuharske and Rusk citranges, Cipo sweet orange, and Yuzu) at tree age 7 years. Fruit from the trees on US-802, a pummelo hybrid, had low values in both years. The juice acid values varied significantly among rootstocks, but the values were within the normal range for commercial fruit (Fla. Agri. Stat. Serv., 2010). The SS : acid ratio minimum standards for fresh fruit are a sliding scale of values depending on SS concentration. As it increases from 8.1 to 9.5, the minimum ratio decreases from 7.0 to 6.8. All fruit from E.1 and E.2 in both years exceeded those values. There were significant differences among rootstocks and, in most instances, the higher ratios were associated with those rootstocks yielding fruit with the higher SS concentrations (Tables 6 and 7).

The quantity of SS per hectare is a common measurement for oranges that are processed, but is also meaningful with Florida grapefruit, which are normally grown for the fresh market. However, $\approx 50\%$ of the grapefruit crop is processed each year. Soluble solids per hectare is a calculation that integrates fruit yield with juice quality. At tree age 7 years, the values ranged from 4096 kg/ha [Sunki $\times$ Swingle TF (C-54)] to 248 kg/ha [Rangpur $\times$ Marks TF (1262)] across both trials (Tables 6 and 7). Soluble solids per hectare and yield were very highly correlated ($r = 0.96^{***}$) at tree age 7 years illustrating the importance of fruit yield. At that tree age in E.1, fruit from the trees on Sunki $\times$ Flying Dragon TF had a high juice content and SS concentration along with a high fruit yield leading to the highest value for SS per hectare. Some of the trees on the rootstocks with the next

Table 6. Juice quality and fruit weight ($n = 4$) of fruit harvested from 'Marsh' grapefruit trees (E.1) on various rootstocks planted in 1995.²

Rootstock	Tree age (yr)	Fruit wt (g) ^y	Juice content (%)	SS concn (%)	Acid (%)	SS/Acid ratio	SS (kg/ha) ^x
Sunki × Flying Dragon TF	4	430	64.2	8.4	0.93	9.0	1638
	7	400	60.7	9.2	0.91	10.1	3363
Sunki × Swingle TF (C-146)	4	560	56.7	7.6	0.96	8.0	899
	7	430	56.7	8.5	0.86	9.9	3194
Uvalde citrange	4	460	59.9	8.7	0.95	9.1	1759
	7	490	56.6	8.8	0.92	9.6	3176
F80-9 citrumelo	4	500	57.9	8.3	0.97	8.5	803
	7	430	57.5	9.1	0.87	10.4	2999
US-812 Sunki × Benecke TF	4	460	60.8	8.6	0.93	9.3	999
	7	420	58.7	8.7	0.84	10.4	2912
C-35 citrange	4	540	56.5	8.4	0.95	8.8	1861
	7	400	58.5	9.3	0.91	10.2	2791
Rangpur × Marks TF (1261)	4	470	56.3	7.8	0.88	9.0	1146
	7	440	55.1	8.6	0.82	10.5	2503
Carrizo citrange	4	560	54.1	7.8	0.88	8.8	1227
	7	450	56.1	8.8	0.85	10.3	2213
Troyer citrange	4	580	53.0	7.4	0.92	8.0	544
	7	430	55.8	8.8	0.85	10.4	2154
Rangpur × Swingle TF	4	510	57.2	7.9	0.93	8.4	1135
	7	420	55.6	8.4	0.90	9.3	2077
Swingle citrumelo	4	560	57.0	7.6	0.95	8.0	922
	7	410	57.5	8.7	0.88	9.9	2049
Sacaton citrumelo	4	470	57.3	8.1	0.91	8.9	871
	7	420	55.8	8.6	0.86	10.0	2041
Benton citrange	4	550	58.1	8.2	0.89	9.2	1444
	7	470	54.5	9.1	0.85	10.8	1925
Morton citrange	4	440	61.6	8.4	0.96	8.8	967
	7	470	54.9	8.9	0.87	10.3	1907
Rusk citrange	4	470	65.6	8.5	0.87	9.8	1259
	7	330	59.8	9.3	0.89	10.5	1820
Yuma citrange	4	530	54.3	8.1	1.01	8.1	185
	7	500	51.2	8.6	0.89	9.6	1747
US-802 Pum. × TF	4	500	52.7	7.1	0.95	7.5	576
	7	520	50.9	7.8	0.87	9.0	1733
F80-8 citrumelo	4	460	63.4	8.3	0.91	9.1	1160
	7	370	57.1	9.3	0.81	11.4	1729
Kuharske citrange	4	490	55.2	7.9	0.90	8.8	1085
	7	460	54.8	8.5	0.83	10.2	1684
F80-2 citrumelo	4	520	56.5	7.9	0.97	8.2	535
	7	420	56.0	8.2	0.85	9.6	1647
F80-6 citrumelo	4	480	58.1	7.7	0.95	8.2	1023
	7	440	54.3	8.3	0.86	9.7	1612
US-897 Cleopatra mandarin × Flying Dragon TF	4	410	59.5	8.6	1.00	8.7	873
	7	340	63.1	9.1	0.91	9.9	1579
US-1001 Changsha mandarin × ELTF	4	510	55.8	7.2	0.93	7.8	692
	7	480	51.9	8.1	0.88	9.2	1567
US-896 Cleopatra mandarin × TF	4	420	59.5	8.3	0.95	8.7	672
	7	360	63.0	8.9	0.83	10.8	1562
Cipo sweet orange	4	620	52.9	7.9	0.88	9.0	880
	7	320	60.9	9.5	0.85	11.2	1518
Cohen citrange	4	520	55.6	7.4	0.92	8.0	569
	7	480	53.8	8.5	0.92	9.3	1447
Koethen sweet orange × Rubidoux TF	4	560	53.7	8.3	0.89	9.3	839
	7	420	58.8	9.0	0.84	10.7	1546
F80-5 citrumelo	4	530	53.5	7.7	0.96	8.0	291
	7	460	53.3	8.5	0.82	10.3	1500
F80-7 citrumelo	4	500	54.9	7.9	0.94	8.4	911
	7	470	54.2	8.5	0.88	9.7	1485
US-119	4	410	62.8	8.8	1.03	8.6	1113
	7	390	59.5	9.2	0.96	9.5	762
Rangpur × Marks TF (1262)	4	510	56.4	7.7	0.90	8.6	311
	7	450	56.8	8.5	0.83	10.3	248
Mean	4	500	57.5	8.0	0.93	8.6	942
	7	430	56.6	8.8	0.87	10.1	1953
Least significant difference	4	120	6.7	0.8	0.07	1.0	792
	7	150	3.5	0.6	0.06	0.9	1276

²Fruit samples collected 25 Feb. 2000 (tree age 4 years) and 29 Jan. 2003 (age 7 years). Data are sorted by soluble solids (SS) per hectare, tree age 7 years. Rootstocks sorted by soluble solids/ha, tree age 7 years.

^yDetermined from the fruit sample collected for juice analysis.

^xCalculated as fruit yield/ha (wt) × % juice × SS concentration.

highest quantities of SS per hectare such as Sunki × Swingle TF (C-146) had significantly lower SS concentrations, but among the highest fruit yields leading to large quantities of high SS per hectare. Likewise in E.2, the trees on the two rootstocks with the highest values, Sunki × Swingle (C-54) and Cleopatra mandarin × Rubidoux TF (×639), had below average juice SS concentrations, but high juice contents and fruit yields.

The most successful rootstock in Florida for fresh-market grapefruit has been sour orange for trees grown in the well-known Indian River district in the coastal flatwoods of the east coast. Several rootstocks in our trials have considerable promise as replacements for sour orange.

Comparative performance among citrange and citrumelo rootstocks. One purpose of our trials was to compare rootstocks within groups, e.g., citranges, citrumelos, mandarins, sour oranges, sour orange types, and others. We assembled as many members of each group as practical for evaluation because such comparisons are uncommon. Among the citranges in E.1, Uvalde and C-35 citranges ranked among the best performing rootstocks. On the basis of our trial results, both rootstocks would be deemed promising. However, they illustrate an important point about performance consistency as a prominent factor leading to commercial acceptance (Castle, 2010). C-35 citrange was developed and tested in California (Cameron and Soost, 1986; Kupper et al., 1994; Roose, 1996). Additional trials in many parts of the world led to commercialization including in Florida [M. Roose (CA) and growers in Australia, Dominican Republic, and Mexico, personal communication]. The high performance level of trees in our trial and other Florida trials with C-35 illustrate its promise as a rootstock for Florida citrus compared with all the citrange rootstocks tested (McCoy et al., 2004). Uvalde citrange is an old rootstock that has been tested for many years with inconsistent results (Castle, 1987; Castle and Baldwin, 2010; Wutscher, 1979). Thus, Uvalde citrange never received commercial interest and is not grouped with the overall promising rootstocks in our trials. Likewise with Morton citrange that was almost always the second best performing rootstock behind Swingle citrumelo in grapefruit trials conducted in Texas (Wutscher, 1979), but was an average rootstock in our trials. Its commercial adoption has been further hindered by a lack of seed production.

Other citranges such as Carrizo and Troyer were in the middle of the rankings, which may explain why they are not popular for use with grapefruit scions in the Florida coastal flatwoods (Stover and Castle, 2002). Various scions on Koethen sweet orange × Rubidoux TF have been under evaluation in Florida for many years, but smaller tree size has limited commercial adoption. Trees on K × R citrange are comparable to C-35 citrange in tree height and juice quality (Castle and Phillips, 1980). In Florida trials, tree losses from blight or Phytophthora foot and root rots have been

Table 7. Fruit weight and juice quality ($n = 4$) of fruit harvested from 'Marsh' grapefruit trees (E.2) on various rootstocks planted in 1995.^z

Rootstock	Tree age (yr)	Fruit wt (g) ^y	Juice content (%)	SS concn (%)	Acid (%)	SS/Acid ratio	SS (kg/ha) ^x
Sunki × Swingle TF (C-54)	4	460	59.8	7.8	0.90	8.7	1601
	7	410	59.8	8.5	0.87	9.8	4096
Cleopatra mandarin × Rubidoux TF (×639)	4	480	59.6	7.6	0.93	8.2	1677
	7	430	56.0	8.1	0.90	9.0	4054
Sunki mandarin	4	530	56.6	8.3	1.00	8.3	1225
	7	420	56.0	9.1	0.98	9.2	3023
Yuzu	4	540	56.4	8.0	0.94	8.5	855
	7	380	60.8	9.3	0.91	10.2	2744
Sun Chu Sha mandarin	4	560	55.4	7.7	0.98	7.9	918
	7	400	58.9	8.8	0.86	10.2	2568
Sour orange	4	420	59.8	8.2	0.96	8.6	1203
	7	400	57.0	8.7	0.95	9.2	2317
Cleopatra mandarin	4	540	52.4	7.3	0.96	7.6	474
	7	410	54.4	8.3	0.94	8.9	2159
Zhuluan	4	470	55.5	8.2	0.97	8.5	759
	7	420	56.1	8.5	0.94	9.1	1714
Kinkoji	4	560	52.1	7.6	0.99	7.7	425
	7	480	52.3	8.4	0.92	9.1	1639
Goutou	4	550	51.5	6.9	0.95	7.3	233
	7	430	53.5	8.2	0.87	9.4	1587
Changsha mandarin	4	500	58.5	7.6	0.91	8.4	651
	7	420	54.5	9.1	0.99	9.2	1469
Shekwasha mandarin	4	510	54.2	7.6	0.94	8.2	765
	7	440	53.2	8.6	0.98	8.9	1409
Smooth Flat Seville	4	500	54.1	7.1	0.92	7.8	474
	7	460	51.8	8.2	0.92	9.0	915
Chinotto sour orange	4	470	56.2	8.3	1.00	8.3	1048
	7	400	56.1	8.8	0.96	9.2	670
Mean	4	510	55.8	7.7	0.95	8.1	879
	7	420	55.7	8.6	0.93	9.3	2178
Least significant difference	4	120	7.3	0.8	0.09	1.1	867
	7	120	6.0	0.6	0.06	0.8	529

^zFruit samples collected on 25 Feb. 2000 (tree age 4 years) and 29 Jan. 2003 (age 7 years). Data are sorted by soluble solids (SS)/ha, tree age 7 years.

^yDetermined from the fruit sample collected for juice analysis.

^xCalculated as fruit yield per hectare (wt) × % juice × SS concentration.

minimal and trees have sometimes yielded well for their size (Castle et al., 2010a), but at other times not so well as reported herein.

The citrumelo rootstock rankings were distributed throughout the list of rootstocks tested in E.1. Only one citrumelo rootstock, F80-9, appeared among the highest yielding rootstocks. In another trial with 'Marsh' grapefruit scion in a different coastal soil, the trees on F80-9 had above-average yield, but there were only small differences among various citrumelo rootstocks (Castle and Bauer, 2005). The trial trees were all eventually removed because of a decline associated with the soil series. A similar lack of large differences among citrumelo rootstocks was also the result in trials with 'Hamlin' and 'Valencia' sweet oranges in sites of coastal flatwoods soil series (Castle et al., 1988; Castle and Baldwin, 2008; Youtsey and Lee, 1995).

Comparative performance among the mandarin and mandarin hybrid rootstocks. Five mandarin rootstocks and two hybrids were tested in E.2. Among those rootstocks, tree survival ranged from a low of 75% (Changsha mandarin) to no tree loss (Sun Chu Sha mandarin and the two hybrids rootstocks: ×639 and C-54). The cause of the losses among the trees on Changsha, Sunki or Cleopatra mandarins was not obvious as some trees declined and became unthrifty with thin

canopies. Trees on mandarin rootstocks are affected by blight, but generally not until they are 10- to 15-years old (Castle, 1987). We have evaluated Cleopatra, Changsha, and Sunki mandarin rootstocks in other Florida trials with mixed survival results, but blight was not an issue in the trial reported herein (Castle et al., 2005; Castle and Bauer, 2005; Castle and Baldwin, 2010; Wheaton et al., 1991). The top performing rootstocks in E.2 were the hybrids, ×639, C-54, and Sunki mandarin. There were few significant differences in yield and SS production among them, and they were generally different from those on the other mandarin rootstocks. What further distinguishes C-54 and Sunki mandarin is their relatively short tree height and high yields, a combination that makes them promising for use as rootstocks for grapefruit in higher density plantings.

Two of the remaining mandarin hybrids are the recently released USDA rootstocks, US-812 and 897 that were included in E.1. They offer meaningful advantages over other commercial rootstocks in Florida such as tolerance to poor site conditions and associated pests and diseases, and in the case of US-897, significant dwarfing of the scion that would allow substantially higher planting density and easier management and harvesting (Castle et al., 1993, 2006). US-812 is a

Sunki mandarin × Benecke TF hybrid and yielded just below what would be selected for the most promising group in these trials. The 7-year-old trees on US-812 were medium-sized, produced high quality fruit, and yielded about 74% of the fruit and 86% of the SS per hectare of the top producing rootstock.

Comparative performance among sour orange and related rootstocks. Trees on sour orange, Chinotto sour orange, and four-purported hybrids (Smooth Flat Seville, Kinkoji, Goutou, and Zhuluan) were included in E.2 (Deng et al., 2008). The relatively poor survival of the trees on sour orange and Chinotto sour orange was the result of CTV as determined from the observations of classical stem pitting symptoms in the vicinity of the bud union. No losses occurred among the trees on the other rootstocks because of their reported tolerance to tristeza virus (Castle et al., 1992). In this group, the highest ranking rootstock for fruit yield was sour orange. The trees on sour orange and Chinotto sour orange exhibited typical traits, i.e., they grew well on the variable soils of the Florida coastal regions, were susceptible to tristeza virus and produced fruit with high SS concentrations as routinely reported in other work (Castle, 1987; McCollum et al., 2002; Wutscher, 1979). The trees on related rootstocks like Smooth Flat Seville and Goutou also exhibited those traits, but fruit quality was relatively low as experienced in other trials (Castle et al., 1992; McCollum et al., 2002). Thus, these rootstocks as a group generally produced high quality fruit, but did not have high overall rankings because of relatively low fruit yield.

Other rootstocks. Two Rangpur × Marks TF siblings, 1261 and 1262, were tested in E.1 and produced quite different results (Tables 2, 4, and 6). The trees on 1262 performed poorly and declined early in the trial, which explains their low yields. Those on 1261 were of average height and were more productive in fruit yield and SS per hectare than those on many of the citrange and citrumelo rootstocks. The fruit yield and juice characteristics of the trees on Rangpur × Swingle TF hybrid were average among the rootstocks tested, but the trees were relatively tall making it less desirable for use in modern orchards. Therefore, the Rangpur × TF rootstocks are of limited commercial promise in Florida.

'Cipo' sweet orange was tested because of its unusual procumbent or weeping growth habit and the potential for that trait to be transmitted to the scion (Bowman, 1994, 1997). Sweet orange selections are frequently included in trials, but often are not among the top performers (Castle, 1987; Wutscher, 1979). The trees on 'Cipo' were of average height with no procumbent growth apparent and produced only ≈50% of the fruit yield and SS of those on the highest ranking rootstocks (Tables 4 and 6).

Promising rootstocks. In our trials, five rootstocks appeared to be exceptionally promising for growing grapefruit for the fresh market or processing on the basis of yield, juice quality, and moderate to smaller

tree size. C-54, a Sunki mandarin $\times$ Swingle TF hybrid, was recently named 'Carpenter' by the University of California and described as producing a medium- to large-sized tree with good yield (Kupper et al., 2010). Considering both trials, trees on that rootstock were the most productive for fruit yield and quantity of SS per hectare. A sibling rootstock, C-146, had similar characteristics along with the Sunki $\times$ Flying Dragon TF hybrid. C-22, another sibling to C-54, performed well with red grapefruit in Texas (Louzada et al., 2008). Trees on C-35 citrange were also relatively short in tree height, but among the highest yielding, a desirable combination. We have included C-35 in other unreported trials with grapefruit scion where they performed as reported herein. In one of those trials, we measured the distribution of fruit sizes on whole-tree crops. The trees on C-35 citrange produced large, usually oblate-shaped fruit with smooth, thin peels.

Trees on $\times$ 639, a hybrid of Cleopatra mandarin $\times$ Rubidoux TF, produced 7% less fruit than C-54, but their quantities of SS per hectare at age 7 years were not different. $\times$ 639 has been among the top three rootstocks in Florida nursery propagations in recent years for many of the common commercial citrus cultivars (Division Plant Industry, 2010). Trees on $\times$ 639 were consistently good performers in trials with navel and common orange selections (Castle and Baldwin, 2005; Castle et al., 2000, 2010a).

Describing the rootstocks mentioned above as having exceptional promise is partly based on the magnitude of difference between them and the other rootstocks in both trials especially Swingle citrumelo. For example, the difference between the trees on C-146 and Swingle citrumelo in fruit yield was 30% and 55% in SS per hectare at age 7 years. Those on C-54 in E.2 produced 31% more fruit than the trees on sour orange and 77% more SS per hectare. However, note that the trees on the high yielding rootstocks were also distinguished by their consistent performance over the 4-year-measurement period and steadily increasing yield in most instances. The yields of trees on other rootstocks also increased, but less so with some tendency toward alternate bearing. "Consistency" as a decision criterion in rootstock testing and as a social factor determining commercial potential is never mentioned in the citrus rootstock literature. However, it can be a particularly meaningful factor especially when taking into account soil variability (Castle, 2010; Castle and Baldwin, 2010). Furthermore, a complete assessment of rootstocks for grapefruit scions should include factors that are important considerations for fresh-market fruit that we did not measure such as fruit sizes for packing, fruit shape, and peel thickness.

Other rootstocks with promise. The trees on US-812 had similar characteristics to those on $\times$ 639 in that their yield was among the highest and tree height was average. SS production when the trees were 7-years old was not different from the values of the trees

on the Sunki $\times$ Swingle TF or Sunki $\times$ Flying Dragon TF hybrids or C-35. Also, evidence to date indicates US-812 would be a good choice for use in calcareous soils (Castle et al., 2006).

Predicting relative rootstock performance: Cumulative yield vs. annual yields. We have been proposing recently that citrus rootstock trials can be substantially completed within 7 to 8 years after planting (Castle et al., 2010a, 2010b). In E.1, yield at age 4 years was well-correlated with cumulative yield ($r = 0.58^*$) and in subsequent individual years that relationship increased to $r = 0.97^{***}$. Likewise in E.2, the highly significant correlation values changed from 0.84 to 0.94. Thus, the yields of individual years were predictive of the cumulative yields. However, we recognize that while it is possible that the cumulative yield after 4 years of annual measurement may not relate well to yield in later years, our proposal has been validated where we measured yield over longer terms (Castle et al., 2010a, 2010b).

Conclusions

After growing trees for 7 years and measuring standard horticultural variables for the last 4 years of that period, two Sunki mandarin $\times$ Swingle TF hybrids (C-54 and C-146), Sunki $\times$ Flying Dragon TF, C-35 citrange, and a Cleopatra mandarin $\times$ Rubidoux TF hybrid ($\times$ 639) were identified as the most promising rootstocks for grapefruit scions. That assessment applies to fruit grown for processing, but further trials are needed to determine fruit sizes and peel quality for a more complete assessment of their potential as rootstocks for growing fresh fruit. These five rootstocks are rated as most promising by comparison with the commercial standard rootstocks, Swingle citrumelo, sour orange, and Cleopatra mandarin and because of their potential for use in modern orchards planted at spacings closer than the tradition ones (Kupper et al., 1994). Furthermore, the relationships among rootstocks were established early in the trials. Data from the first cropping years were significantly correlated with the cumulative results supporting the contention that traditional long-term field trials for the collection of most horticultural data may not be necessary.

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