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Rootstocks and the Performance and Economic Returns of 'Hamlin' Sweet Orange Trees

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***Abstract*. 'Hamlin' is a principal sweet orange grown in Florida for processing. It is productive but produces juice with low soluble solids content and poor color. A long-term trial was conducted in central Florida to determine rootstock effects on yield and juice quality and the effect of economic analysis on the interpretation of the horticultural results. The trees were a commonly used commercial selection of 'Hamlin' sweet orange [*Citrus sinensis* (L.) Osb.] propagated on 19 rootstocks planted in a randomized complete block design of three-tree plots with six replicates in a Spodosol soil at a density of 350 trees/ha. Routine horticultural data were collected from the original trial (H1) for 10 years. Trees on some rootstocks that grew and yielded poorly were removed within a few years and replaced with a second trial (H2) with 13 rootstocks from which data were collected for 5 years. The H1 data were financially analyzed to compare the relative usefulness of horticultural and economic data in interpreting results and making rootstock decisions. In H1 after 10 years, tree height ranged from greater than 5 m [Volkamer lemon (*C. volkameriana* Ten. & Pasq.)] and Cleopatra mandarin (*C. reshni* Hort. ex Tan.) to 2.4 m {Flying Dragon trifoliate orange [*Poncirus trifoliata* (L.) Raf.]}. In H2, the trees on somatic hybrid rootstocks were ≈2 m tall after 8 years and 4.4 m among those on mandarins and C-32 citrange (*C. sinensis* × *P. trifoliata*). Tree losses from citrus blight were generally low except for the trees on Carrizo and Troyer citranges (greater than 50%). Horticulturally, the highest performing trees in H1, measured by cumulative yield and soluble solids production over 10 years, were those on Carrizo, Troyer, and Benton citranges; poor performers were those on Smooth Flat Seville and Kinkoji (putative sour orange hybrids). Fruit yield and soluble solids production were directly related to tree height regardless of the difference among rootstocks in juice quality. The same relationship existed among the trees in H2 in which the best rootstocks were C-32 and Morton citranges. Trees on Swingle citrumelo (*C. paradisi* Macf. × *P. trifoliata*) ranked no. 12 of 19 rootstocks and 9 of 13 rootstocks in H1 and H2, respectively. Financial interpretation of the outcomes to include tree replacement resulting from blight losses did not substantially change the horticultural interpretations. Additional financial analyses demonstrated that the performance of trees on rootstocks with relatively low productivity/tree, like those on C-35 citrange and Kinkoji, would equal those on more vigorous rootstocks when tree vigor was properly matched with spacing. Yield determined the economic outcomes and financial analysis aided the interpretation of rootstock horticultural effects but did not greatly alter the relationship among rootstock results. Highly significant correlations between annual and cumulative data indicated that relative rootstock performance among 'Hamlin' orange trees in Florida could be reliably determined based on the first 4 cropping years.**

Oranges grown for processing are the mainstay of the Florida and Brazilian citrus industries unlike most other citrus industries of the world where oranges are grown for the fresh market. There are two principal cultivars, Hamlin and Valencia, that represent the early and late portions of the Florida fruit season, respectively. They have contrasting characteristics: 'Hamlin' is a relatively productive cultivar but the fruit have notably low-quality juice with poor color, whereas 'Valencia' is less productive, but juice quality is the world standard for comparison (Saunt, 2000). Furthermore, the performance of each cultivar varies according to rootstock (Hutchison, 1977; Hutchison et al., 1992; Wheaton et al., 1991, 1995; Wutscher and Bistline, 1988a, 1988b; Wutscher and Hill, 1995). In general, a broader range of rootstocks is satisfactory for 'Hamlin' than for 'Valencia'. For example, Cleopatra mandarin with 'Hamlin' scion is a high-yielding combination that begins to bear well as a young tree (Castle, 1987). 'Valencia' clones on the same rootstock are well known for low yields, especially in the first cropping years (Castle, 1987; Wutscher, 1979).

Rootstock research has a long history in Florida and elsewhere. The commercial rootstock situation has been relatively stable for many years in Florida and has changed little in recent years. The popular choices have been Swingle citrumelo [*Citrus paradisi* Macf. × *Poncirus trifoliata* (L.) Raf.] and Carrizo citrange [*C. sinensis* (L.) Osb. × *P. trifoliata*] (Castle et al., 1988). Nevertheless, research has continued because of such factors as freezes, undiscovered soil factors (Bauer et al., 2005), and real estate development, which have forced relocation to less desirable locations in Florida. In those areas, the soils are different and more variable and certain traditional rootstocks like rough lemon (*C. jambhiri* Lush.) and Carrizo citrange were not suitable. The discovery of citrus canker and Huanglongbing (HLB) diseases in Florida has brought renewed interest in size-controlling rootstocks, including those that might reduce the number of annual shoot flushes that attract the insect vector of HLB. Other long-standing risks associated with citrus tristeza virus, *Phytophthora* sp. and Diaprepes root weevil, still provide an incentive to create new rootstocks and conduct evaluations (Castle and Baldwin, 1995; Castle et al., 1993, 2006; Hutchison, 1986).

Most rootstock trials are conducted with common horticultural objectives and typically involve measuring yield and certain standard fruit and juice quality variables such as fruit size and juice soluble solids concentration (Bevington and Cullis, 1990; Castle and Baldwin, 2005; Castle et al., 2000, 2010; Economides, 1993; Gardner and Horanic, 1967; Roose et al., 1989). The evaluation outcomes are normally determined using horticultural and sometimes other data. It is uncommon in rootstock trials for the economic consequences to be calculated as in citrus and apple orchard system trials (Boswell et al., 1975; Muraro et al., 1995; Robinson and Hoying, 2004; Wheaton et al., 1995). Therefore, our objectives were to conduct a rootstock evaluation with financial analysis and compare the individual usefulness of horticultural and financial data and their combination in rootstock selection decisions.

Materials and Methods

Plant material. Two trials were planted. Seeds of the rootstocks for the original trial (H1; Table 1) were gathered from official source trees maintained by the Florida Department of Agriculture and Consumer Services, Bureau of Citrus Budwood Registration, Winter Haven, FL, except for C-35 and other numbered hybrids, which were obtained from the University of California, Riverside, and trees at the Citrus Research and Education Center (CREC), respectively. Cuttings of the somatic hybrids were provided by Dr. Jude Grosser, CREC. The seeds and cuttings were taken to a local commercial nursery for propagation with a popular virus/viroid tested clone of 'Hamlin' sweet orange (1-4-1XE).

Trial location, design, and management. The trees were planted on an 8-ha commercial

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site in St. Cloud, FL (lat. 28°15′11.90″; long. 81°14′19.35″). The soils are Spodosols of the Myakka series, an Aeric Haplaquods. They typically occur in nearly level, poorly drained areas of the Florida flatwoods. The A horizon is ≈15 cm thick and consists of light to very dark gray sand underlain by the E horizon of light-colored sand to a depth of ≈60 cm. The Bh horizon appears at the bottom of the E horizon and is an organic, reddish brown to black spodic layer ≈25 to 50 cm thick. The site was prepared for citrus by excavating a perimeter drainage ditch to maintain the water table, which eliminated the need to construct beds for planting the trees.

Trees on 25 rootstocks were planted 4.3 × 6.7 m in Sept. 1986 in a randomized complete block design of east–west rows with six replicates of three-tree, in-row plots. Bittersweet sour orange (*C. aurantium* L.), sour orange, Palestine sweet lime (*C. limettioides* Tan.), rough lemon (*C. jambhiri* Lush.), and procimequat [*C. aurantifolia* (Christm.) Swing. × (*Fortunella japonica* (Thunb.) Swing. × *F. hindsii* (Champ.) Swing.] were included in the original trial; however, a freeze in Dec. 1989 severely damaged the trees on Palestine sweet lime, rough lemon, and Volkamer lemon and they were all removed except for three replicates on Volkamer lemon. It was also apparent that citrus tristeza virus had infected many trees and was already causing decline among the trees on Bittersweet and standard sour orange so all trees on those rootstocks were removed except one replicate. The procimequat trees were also removed because they grew poorly and were deemed unacceptable.

The tree removals provided sufficient space to establish a second trial of 13 rootstocks (H2; Table 1A) with three replicates of three-tree plots in Dec. 1991. Rootstock seeds for the replacement trial were obtained from the same sources as the first trial and the trees were grown at the same nursery. The trees were irrigated with microsprinklers and otherwise managed according to recommended standards for weed and pest control. The trees as they matured were provided with 60 to 220 kg N/ha annually in three applications of dry fertilizer (Obreza and Morgan, 2008). They were not topped but were hedged annually on both sides after ≈8 years.

Data collection and statistical analysis. Tree losses were recorded annually. Citrus blight was diagnosed either visually or by trunk water flow (Derrick and Timmer, 2000; Lee et al., 1984). The recording of losses continued until the trees were 21 years old. Because of concern that certain tree losses might be the result of *Phytophthora nicotiana* foot or root rot disease or citrus tristeza virus, the site was extensively sampled in 1993. Composite soil samples consisting of three 2.5 × 15-cm cores taken under the canopy of the center tree in each plot were plated on semiselective agar medium and colony-forming units counted (Bright et al., 2004). For the tristeza assay, samples of five leaves/tree were collected from each plot and assayed

Table 1. Height and survival (n = 6) of 'Hamlin' sweet orange trees on 20 rootstocks (H1) planted 4.3 × 6.7 m in 1986 at St. Cloud, FL.

Rootstock	Tree ht (m) at 3 yrs	7 yrs	10 yrs	Survival (%)[z]
Kinkoji *C. obovoidea* Hort. ex Tak.	2.6	3.9	4.3	100
Rusk citrange *Citrus sinensis* (L.) Osb. × *Poncirus trifoliata* (L.) Raf.	2.3	3.1	3.1	94
Smooth Flat Seville *C. aurantium* putative hybrid	2.7	4.2	5	94
Cleopatra mandarin *C. reticulata* Blanco	2.7	4.4	5.2	89
Flying Dragon trifoliate orange	1.6	2.5	2.5	89
Sunki mandarin	2.7	4.0	4.7	89
F80-8 citrumelo *C. paradisi* Macf .× *P. trifoliata*	2.5	3.7	3.7	88
Shekwasha mandarin	2.4	4.0	4.3	83
Swingle citrumelo	2.5	3.7	4.2	83
Koethen swt. org. × Rubidoux trif. org. citrange	2.2	3.4	3.6	78
C-35 citrange	2.3	3.1	3.1	76
Yuma citrange	2.7	4.0	4.2	72
Benton citrange	2.8	3.8	4.1	67
Calamandarin *C. madurensis* (Lour.) × *C. reticulata* Blanco; putative hybrid	2.7	4.4	5.3	67
Valencia sweet orange	2.9	4.3	4.8	53
Rangpur × Troyer citrange *C. limonia* Osb. × Troyer	2.3	3.4	3.5	50
x639 Cleopatra mandarin × *P. trifoliata*	2.7	4.0	4.4	50
Troyer citrange	2.8	4.1	4.5	44
Carrizo citrange	2.9	4.1	4.4	40
Volkamer lemon (n = 3) *C. volkameriana* Ten. & Pasq.	2.4	4.3	5.1	22
Mean	2.5	3.8	4.2	
P value	<0.001	<0.001	<0.001	
Least significant difference	0.2	0.3	0.4	

[z]As of 2007.

Table 1A. Height and survival (n = 3) of 'Hamlin' sweet orange trees on 13 rootstocks (H2) planted 4.3 × 6.7 m in 1991 at St. Cloud, FL.

Rootstock	Tree ht (m) at 4 yrs	8 yrs	Survival (%)[z]
Cleopatra mand. + Flying Dragon trif. org. *Citrus reticulata* Blanco + *Poncirus trifoliata* (L.) Raf.	1.9	2.0	100
Cleopatra mand. + Swingle citrumelo Cleo. mand. + (*C. paradisi* Macf. × *P. trifoliata*)	2.2	2.7	100
C-32 citrange *C. sinensis* (L.) Osb. × *P. trifoliata*	3.1	4.2	100
Goutou *C. aurantium* putative hybrid	3.0	3.8	100
Hamlin swt. org. + Flying Dragon trif. org.	1.6	1.7	100
Morton citrange	2.7	3.8	100
Murcott *C. reticulata* × *C. sinensis*	3.3	4.0	100
Sun Chu Sha mandarin	3.2	4.4	100
Swingle citrumelo	2.7	3.7	100
1575-21 citrange 'Ridge Pineapple' swt. org. × *P. trifoliata*	2.5	2.7	89
1584 *P. trifoliata* × *C. jambhiri* 'Milam'	2.6	4.0	89
1675 citrange	2.7	2.9	67
Zhuluan *C. aurantium* putative hybrid	2.8	3.8	67
Mean	2.6	3.4	
P value	<0.0001	<0.0001	
Least significant difference	0.3	0.4	

[z]As of 2007.

for tristeza virus by enzyme-linked immunosorbent procedures using polyclonal and monoclonal antibodies to distinguish mild and severe Florida strains (Permar et al., 1990; Rocha-Pena et al., 1991). Damage from the Dec. 1989 freeze was assessed ≈3 months afterward by rating the trees according to the type and extent of damage on a scale of: 0 = no damage; 1 = mostly leaf drop and little shoot damage; 2 = leaf drop and extensive shoot damage; and 3 = leaf drop, shoot damage, and bark splits on the trunk.

Annual measurement of juice quality began when the H1 and H2 trees were 3 years old. Samples of 50 fruit were collected from three replicates just before harvest and sampling continued for a total 10 and 4 years, respectively. Juice was extracted and analyzed using commercial equipment at the CREC, Lake Alfred, FL. Juice subsamples were collected for color measurement (Fellers, 1990). Yield was measured during commercial harvest (usually in November or December) by recording the volume of fruit placed in standard harvesting bins holding 400 kg of fruit. Data were analyzed using PROC GLM (SAS Institute, Cary, NC) according to the field design and to accommodate an occasional missing plot. The freeze rating data were not analyzed. Tree height, yield, and soluble solids data were also examined by simple linear correlation analysis.

Financial analysis. Prevailing industry production and harvesting costs and returns during the H1 trial were used in the analysis (financial assumptions and cost and return numbers are available from R.P. Muraro). The actual yields, tree losses with replacement, and juice quality data from H1 were used to calculate annual net operating income and annual and cumulative cash flows. Virtually all tree losses resulted from blight, but they occurred toward the end of the trial period (13 years); thus, the costs associated with the replacement trees are included in the analysis, but the trees were generally too young to collect any useful data. To address the time value of money, a discount rate (because a dollar today is worth more than one received in future years) of 15% was used for the cash flow calculations and estimated internal rates of return. The analyses are of hypothetical 1-ha groves on individual rootstocks using actual tree losses and certain other tree spacing situations deemed reasonable from observations of tree development and final canopy size during the course of the trial. The financial outcomes included ending grove value.

Results and Discussion

Tree height and freeze damage. The H1 trees had a mean height of 2.5 m 3 years after planting (Table 1). The tallest trees were those on Carrizo, Benton, and Troyer citranges and Valencia sweet orange, but they did not differ significantly from those on most rootstocks. The smallest trees, 1.6 m, were those on Flying Dragon trifoliate orange. Mean height increased to 3.8 m when the trees were 7 years old with the tallest trees being 4.4 m. Those on Volkamer lemon had grown vigorously after recovering from the 1989 freeze and attained a height similar to the most vigorous trees. Mean tree height was 4.2 m after 10 years. The trees on Cleopatra mandarin and Volkamer lemon were then among the tallest at heights greater than 5 m. The trees on those rootstocks of intermediate vigor such as C-35 and Rusk citranges and Flying Dragon trifoliate orange had essentially stopped height growth after 7 years. In H2, the trees on the somatic hybrid rootstocks were the smallest and remained so after 8 years (Table 1A). Those on C-32 citrange, Murcott, and Sun Chu Sha mandarin were among the most vigorous. The rootstock used to link the trials was Swingle citrumelo. Those trees were nearly the same height in both trials at comparable ages.

There were no unaffected trees after a severe freeze in Dec. 1989 imposed the first damage on H1. Those on Flying Dragon trifoliate orange and sour orange were slightly damaged (rating of 1); those on the citrumelo, citrange, and mandarin rootstocks, Kinkoji, and Smooth Flat Seville were ≈2 to 3 on the rating scale; and those on the remaining rootstocks had some bark splits on the trunk and small shoot damage.

Tree health and survival. Tree loss occurred primarily from blight. No *Phytophthora nicotiana* was detected in the soil and no foot rot was observed. All trees in H1 and H2 were infected with mild and/or severe local strains of tristeza virus, which quickly eliminated the trees on sour orange rootstocks. The trees on the remaining rootstocks were apparently unaffected, which supports the contention, in particular, that Smooth Flat Seville, Goutou, and Zhuluan are tolerant of the virus strains present in Florida (Castle et al., 1992; Grimm and Garnsey, 1968).

Blight was first observed among H1 trees on Carrizo citrange and the Rangpur × Troyer citrange hybrid when they were ≈9 to 10 years old. Observations continued until 2007 when the H1 and H2 trees were 21 and 16 years old, respectively. At those ages, blight had affected trees on all rootstocks except for those on Kinkoji (H1) and the somatic and other hybrids, and in H2, the trees on Goutou, Murcott, two citranges, Swingle citrumelo, and Sun Chu Sha mandarin (Tables 1 and 1A). Blight losses among rootstocks like Carrizo and Troyer citranges with survival rates less than 50% matched commercial experience (Castle and Baldwin, 1995; Derrick and Timmer, 2000); however, the relatively high survival rates among the trees on Cleopatra mandarin and the other mandarins in H1 were unusual (Castle et al., 1993, 2006). Swingle citrumelo is considered a tolerant rootstock as confirmed by the high survival rates in H1 and no loss in H2. The time course of blight loss was also an important component of the overall loss. There were virtually no losses among trees on Benton and C-35 citranges (H1) until they were ≈15 years old and those on the lower vigor Rusk citrange had almost no loss. The losses to blight in H2 among the trees on citrange 1675 and Zhuluan also occurred late in the observation period (Table 1A). Particularly noteworthy was Valencia sweet orange, a rootstock generally considered to be very tolerant to blight (Castle, 1987; Castle and Baldwin, 1995; Cohen, 1972; Derrick and Timmer, 2000; Wutscher, 1979). Losses occurred among the trees on that rootstock, but only after 15 years.

Yield and juice quality. Trees on the citrange and citrumelo rootstocks in H1 produced greater than 50 kg/tree of fruit at age 3 years; those on Rusk citrange yielded nearly 80 kg (Table 2). Those on Flying Dragon trifoliate orange (small tree size) and Volkamer

Table 2. Yield (kg/tree; n = 6) of 'Hamlin' sweet orange trees on 20 rootstocks (H1) planted 4.3 × 6.7 m in 1986 at St. Cloud, FL.[z]

	Tree age (yrs)										
Rootstock	3	4	5	6	7	8	9	10	11	12	Cumulative
Carrizo citrange	51	75	135	242	212	331	291	341	406	286	2370
Troyer citrange	51	80	146	274	238	340	278	314	371	253	2344
Calamandarin	23	75	129	256	232	347	269	325	379	271	2304
Cleopatra mandarin	16	68	112	272	221	326	276	315	348	295	2247
Smooth Flat Seville	12	75	135	254	215	303	256	301	372	309	2230
x639	34	80	140	267	221	320	274	302	335	251	2223
Valencia sweet orange	30	85	123	221	206	331	270	285	364	268	2181
Benton citrange	76	83	152	246	220	315	251	282	284	243	2151
Sunki mandarin	44	67	128	235	213	299	254	294	334	245	2113
Kinkoji	32	82	132	247	217	298	252	272	317	252	2101
Volkamer lemon	6	20	87	216	217	319	275	306	392	240	2077
F80-8 citrumelo	68	106	141	250	220	295	234	262	277	223	2074
Yuma citrange	22	68	120	231	211	301	253	276	314	236	2031
Shekwasha mandarin	16	54	119	229	192	299	248	285	307	248	1997
Swingle citrumelo	64	81	115	219	192	270	235	269	293	241	1978
Koethen swt. org. × Rubidoux trif. org.	37	68	116	195	191	250	204	244	255	216	1775
Rangpur × Troyer citrange	65	81	107	171	164	207	178	223	253	165	1613
C-35 citrange	66	61	96	152	141	190	147	203	195	157	1406
Rusk citrange	78	55	97	150	147	180	155	183	193	136	1372
Flying Dragon trif. org.	21	32	37	86	82	119	96	103	135	93	804
Mean	40	70	118	220	197	282	235	269	306	231	1970
Least significant difference	15	19	22	30	25	34	30	36	48	50	

[z]Statistical comparisons based on F-test each year of $P < 0.0001$.

lemon (cold damage) rootstocks had significantly lower yields, whereas many of the other trees had yields ranging between ≈20 and 40 kg/tree. Mean yield increased to 220 kg/tree in the fourth cropping year and remained at that level with some annual fluctuation. Peak mean yield, 306 kg/tree, occurred when the trees were 11 years old at which time the most vigorous trees on Carrizo citrange and Volkamer lemon produced ≈400 kg/tree. The trees on less vigorous rootstocks, like Rusk and C-35 citranges and Flying Dragon trifoliate orange, produced less than 200 kg/tree. After 10 years, cumulative yield ranged from 2370 kg/tree (Carrizo citrange) to ≈2000 (Volkamer lemon, Shekwasha mandarin) to 804 kg/tree (Flying Dragon trifoliate orange).

The H2 trees began to crop in their second year. Yields were similar to those in H1 for the first few cropping years, but when the trees were 6 years old, the H1 mean yield was ≈64% higher (H1: 220 versus H2: 134 kg/tree) (Tables 2 and 2A). In H2, the trees on C-32 and Morton citranges grew vigorously and along with those on the 1575-21 hybrid produced ≈50 to 150 kg/tree of fruit when young. The trend established in the initial years continued so that after 5 years, the trees on C-32 had the highest cumulative yield. The lowest yields were from the trees on the somatic hybrids, which also had the smallest tree heights.

Rootstock significantly affected juice quality each year it was measured in H1 and H2 except for juice content in H2 (Tables 3 and 3A). With a few exceptions, more than 50% of the fruit weight was the result of juice content. There was little variability among rootstocks in soluble solids concentration, which ranged from ≈8.0 to 8.4 when the trees were young; at age 6 years, the range increased (Volkamer lemon: 9.4; Flying Dragon trifoliate orange: 12.7). However, some of the difference between years was the result of harvest date, which was early in Year 4 (October) and later (December) in Year 6. Rootstock affected juice acid content and, thus, ratio, which determines stage of maturity. Higher ratios, generally because of lower acidity, indicate advanced maturity. In Florida's climatic conditions, it is well known in the commercial industry that fruit at the end of Stage II (enlargement)/beginning of Stage III (maturation) in development advance in juice ratio approximately one-half of a point/week or ≈2 points/month. That difference in ratio offers possible options for selecting more than one rootstock for a cultivar to lengthen the harvesting season of fruit processing according to legal juice quality standards.

The mean juice content among the 3- and 5-year-old trees on the H2 rootstocks was 59% and 55%, respectively, and rootstock was not a significant factor (Table 3A). However, rootstock strongly affected the other juice variables. Mean soluble solid concentration increased from 9.5 to 10.7 as the trees aged and juice acid concentration declined, but, like in H1, the later time of sample collection in Year 5 explains the higher values in that year as compared with Year 3. Fruit with the highest quality tended to be from the trees on the somatic hybrid rootstocks. Those trees were smaller and produced the smallest-sized fruit (data not given). Sweet orange fruit quality is inversely related to fruit size, so the higher juice quality among the trees on the somatic hybrid rootstocks was at least partially an indirect effect (Barry et al., 2004).

Productivity: soluble solids/hectare. In the Florida juice industry, fruit are sold based on their soluble solids content. Thus, growers are interested in producing the maximum soluble solids/ha, which was strongly affected by rootstock (Tables 3 and 3A). In general, soluble solids/ha and cumulative solids were related to tree size and the quantity of fruit (yield). Trees like those on Flying Dragon trifoliate orange in H1 produced high-quality juice but relatively low cumulative soluble solids/hectare over the 10-year trial period because of smaller tree size. The most productive trees were those on Carrizo citrange, which had more than three times the cumulative soluble solids of the trees on Flying Dragon trifoliate orange. In H2, it was again the smaller trees (e.g., those on the somatic hybrid rootstocks) that had the lowest soluble solids production, whereas more vigorous trees like those on C-32 and Morton citranges and Sun Chu Sha mandarin had the highest annual and cumulative production of soluble solids/hectare.

H1 included three commercial rootstocks: Swingle citrumelo, Carrizo citrange, and Cleopatra mandarin. There were trees on 10 rootstocks that exceeded the cumulative yield (kg/tree) of those on Swingle citrumelo by ≈28% to 35%. Most of those rootstocks were Kinkoji, Smooth Flat Seville, the citranges, and mandarins, including Cleopatra mandarin. The trees on Carrizo citrange were the highest producers, and only those on that rootstock and Benton and Troyer citranges, Calamandarin, and x639 surpassed Cleopatra mandarin. Among the younger trees in H2, Swingle citrumelo was the commercial rootstock for comparison. Its cumulative 4-year soluble solids production/hectare was exceeded by the production of trees on eight other rootstocks with a maximum difference of 39%.

In our rootstock comparisons, soluble solids production integrates yield and juice quality and is the key variable that would ordinarily be the foundation of horticulturally based rootstock decisions when fruit is being grown for juice. The only other meaningful factor in our trial was blight loss. On that basis, the results of H1 and other experience indicate that the optimal combination of low blight risk with reasonable horticultural performance might occur among trees on some of the mandarin rootstocks like Cleopatra and x639 along with Kinkoji and Smooth Flat Seville (Castle et al., 1992). The blight risks, especially among the latter two rootstocks, are relatively low and their soluble solids production was good; however, the cumulative soluble solids production among the trees on the top five rootstocks far outweighed their higher blight risks. In H2, too little time had passed to determine blight tolerance, so the better rootstock choices may be C-32 and Morton citranges and Sun Chu Cha mandarin based on cumulative soluble solids alone. That ranking, however, may change as the trees age. If the trees on the Sun Chu Sha mandarin in H2 performed like the other mandarin rootstocks in H1, then its relative position may decline.

Cumulative soluble solids production is a useful measure of performance, but it does not consider tree size, which also directly determines performance. Trees in new orchards on the rootstocks included in our trials would not all be spaced the same because of differences in their canopy size thereby changing the performance outcomes among rootstocks and possibly changing the relative importance of the horticultural factors affecting the outcomes. The differences among rootstocks would be reduced if, e.g., trees on C-35 citrange were grown at a slightly higher planting density and compared with those on Swingle citrumelo as they performed under the trial conditions. However, yield would likely remain the dominant factor determining the soluble solid/hectare outcomes. There

Table 2A. Yield (kg/tree; n = 3) of 'Hamlin' sweet orange trees on 13 rootstocks (H2) planted 4.3 × 6.7 m in 1991 at St. Cloud, FL.[z]

Rootstock	Tree age (yrs) 2	3	4	5	6	Cumulative
C-32 citrange	51	110	152	195	203	711
Morton citrange	49	82	174	194	141	640
Sun Chu Sha mandarin	35	66	139	208	178	627
1584	38	79	147	171	167	602
Murcott	39	68	129	180	131	546
1575-21 citrange	62	83	139	129	129	543
Zhuluan	28	71	122	143	174	539
Goutou	31	61	113	184	144	533
Swingle citrumelo	41	69	122	138	136	507
1675 citrange	36	51	115	143	96	441
Cleopatra mand. + Swingle citrumelo	25	32	71	92	41	261
Cleopatra mand. + Flying Dragon trif. org.	13	16	51	51	41	172
Hamlin + Flying Dragon trif. org.	11	12	30	41	27	122
Mean	32	58	108	134	114	480
Least significant difference	15	22	30	45	35	

[z]Statistical comparisons based on F-test each year of $P < 0.0001$.

Table 3. Juice quality (n = 3) of fruit harvested from 'Hamlin' sweet orange trees on 20 rootstocks (H1) planted 4.3 × 6.7 m in 1986 at St. Cloud, FL.

Rootstock	Tree age (yrs)	Juice content (%)	Soluble solids conc. (%)	Acid (%)	SS/acid ratio	Soluble solids (kg/ha)[z]	Cumulative 10-year SS (kg/ha)
Carrizo citrange	4	56.7	8.2	0.52	15.8	1,135	
	6	59.6	11.5	0.67	17.4	6,344	53,980
Troyer citrange	4	47.8	8.5	0.50	17.2	982	
	6	55.7	11.3	0.65	17.2	6,233	48,352
Benton citrange	4	56.3	8.3	0.53	15.7	1,391	
	6	57.6	11.4	0.77	14.7	6,201	47,424
Calamandarin	4	50.7	8.0	0.50	16.0	953	
	6	57.6	10.2	0.61	16.9	5,107	45,851
x639	4	55.7	8.1	0.49	16.5	1,220	
	6	57.3	10.8	0.63	17.1	5,910	45,689
Yuma citrange	4	57.4	8.3	0.53	15.5	1,239	
	6	58.0	11.0	0.73	15.1	5,620	44,398
Cleopatra mandarin	4	56.6	8.0	0.52	15.5	882	
	6	57.4	10.2	0.58	17.6	5,672	44,183
Kinkoji	4	58.6	8.3	0.54	15.4	1,387	
	6	58.1	10.7	0.62	17.2	5,426	43,991
F80-8 citrumelo	4	56.3	8.3	0.52	16.0	1,533	
	6	57.3	11.4	0.68	16.9	5,391	43,669
Smooth Flat Seville	4	54.7	8.0	0.51	15.6	1,069	
	6	56.4	10.3	0.62	16.6	5,141	43,507
Sunki mandarin	4	54.8	8.5	0.55	15.5	966	
	6	55.9	10.7	0.64	16.7	4,947	43,485
Swingle citrumelo	4	57.9	8.7	0.55	15.8	1,402	
	6	57.3	10.9	0.64	17.2	4,821	41,991
Shekwasha mandarin	4	47.4	8.1	0.52	15.7	630	
	6	56.0	10.5	0.62	17.0	4,674	40,715
Valencia	4	54.4	8.2	0.53	15.5	1,258	
	6	54.0	10.1	0.60	16.8	4,025	40,532
Koethen swt. org. × Rubidoux trif. org.	4	56.5	8.4	0.54	15.5	1,049	
	6	58.4	11.7	0.69	16.9	4,966	39,827
Volkamer lemon	4	39.1	8.2	0.56	14.7	187	
	6	53.5	9.4	0.67	14.1	3,800	34,714
Rangpur × Troyer citrange	4	55.2	8.3	0.54	15.3	1,443	
	6	57.3	11.0	0.67	16.4	3,783	33,623
C-35 citrange	4	59.2	8.8	0.56	15.8	1,077	
	6	58.1	11.8	0.73	16.1	3,780	32,950
Rusk citrange	4	53.4	8.4	0.53	16.2	797	
	6	58.1	12.0	0.67	17.8	3,951	30,135
Flying Dragon trif. org.	4	58.7	8.4	0.54	15.8	511	
	6	54.1	12.7	0.70	18.2	1,905	16,727
Mean	4	54.3	8.3	0.53	15.8	1,053	39,634
P value		<0.001	<0.015	<0.133	<0.016	<0.001	
Least significant difference		6.7	0.4	0.04	1.0	370	
Mean	6	56.9	11.0	0.66	16.7	4,885	
P value		<0.016	<0.001	<0.001	<0.001	<0.020	
Least significant difference		3.0	0.4	0.06	1.4	1,103	

[z]Calculated as fruit yield/ha (wt.) × % juice × SS concentration.
SS = soluble solids.

are no apparent examples in H1 in which small or moderate tree size combined with good to high juice quality (e.g., trees on Flying Dragon trifoliate orange or C-35 rootstocks) would likely compensate for the higher yields achieved on the more vigorous rootstocks regardless of juice quality. Therefore, the longer-term H1 data were financially analyzed to determine if the interpretation of the results would differ by adding a financial component to the horticultural outcomes (Table 4).

Economic analysis. After 13 years, discounted cash flows with ending orchard value included ranged from $16,813 to $551/ha in H1. The trees on Benton and Troyer citranges and F80-8 citrumelo produced the highest cash flows (greater than $15,000) followed closely ($13,000 to $15,000) by those on Carrizo citrange, x639, Kinkoji, Sunki mandarin, and Swingle citrumelo. The smallest cash flows were among the trees on Flying Dragon trifoliate orange (the smallest trees) and Rangpur × Troyer (highest blight loss), which resulted in a negative (–2.3) or small (4.4) internal rate of return (IRR), respectively. Those on Volkamer lemon also had a small cash flow and IRR largely because they had not fully recovered from earlier freeze damage. In the absence of cold weather complications, 'Valencia' trees on Volkamer lemon were very productive and generated high incomes (Castle et al., 2010). The trees on Flying Dragon trifoliate orange had no losses and produced excellent quality juice; however, under the trial conditions, they produced no return on the investment. When the spacing was adjusted for tree size by increasing the planting density to 672 trees/ha, income increased, but the IRR would still be unsatisfactory (Table 4). The change for trees on other rootstocks was more positive. By increasing the planting density 64% for those on C-35, cash flow nearly doubled from $9,873 to $18,046/ha. A similar change occurred among the trees on Koethen sweet orange × Rubidoux trifoliate orange citrange. Trees of more intermediate size on other rootstocks like Swingle citrumelo, Kinkoji, and Smooth Flat Seville showed small gains in cash flow but IRR reductions by increasing planting density. The reduction in IRR was the result of additional nursery tree and establishment costs not recovered during the trial period.

Relative value of horticultural and economic analysis. Financial analysis expanded and somewhat altered the horticultural interpretations of the H1 results. Trees on those rootstocks with the highest cumulative soluble solids were generally those with the largest cash flows and best IRRs. However, our hypothetical calculations show that it is important to make comparisons at planting densities appropriate for each rootstock and that yield determines financial outcomes as reported for other 'Valencia' and 'Hamlin' trials (Castle et al., 2010; Wheaton et al., 1995). In H1, trees on Carrizo citrange were among the better performing ones despite 26% loss from blight, a result that confirms the generally excellent reputation of that rootstock and the importance of yield (Castle et al., 2010). For the same reasons, Troyer citrange was a high-performing rootstock, an outcome of some historical significance given that Carrizo and Troyer are considered to be siblings (Savage and Gardner, 1965). The low blight losses, good fruit quality, and intermediate sizes of the trees on Koethen sweet orange × Rubidoux trifoliate orange, C-35, and Rusk citranges would not lead to choosing those rootstocks based only on their horticultural data. However, in the hypothetical calculations based on appropriate tree spacing, they rose to the top three cash flow rankings.

Prior horticultural and financial experience with Rusk citrange was similar to our experience in H1 (Wheaton et al., 1995). Nevertheless, Rusk citrange has not attracted any commercial interest because of perceived "risks" and/or timing issues (Castle, 2010). Rootstock evaluations are reasonably comprehensive. However, the relative importance of horticultural traits as evaluated by researchers along with the desired consistency of results may not match commercial expectations. In the case of Rusk citrange, its overall performance in various trials has been noteworthy, but it has certain undesirable traits, too. Rusk citrange fruit yield few seeds and we have experienced difficulty at times in establishing trial trees. Furthermore, trees on Rusk citrange are small, an attribute not of particular interest in the Florida industry until recently. The normal "risks" associated with pests and disease and long-term performance combined with these other "risks" of Rusk citrange have precluded commercial interest.

Table 3A. Juice quality (n = 3) of fruit harvested from 'Hamlin' sweet orange trees on 13 rootstocks (H2) planted 4.3 × 6.7 m in 1991 at St. Cloud, FL.

Rootstock	Tree age (yrs)	Juice content (%)	Soluble solids conc. (%)	Acid (%)	SS/A ratio	Soluble solids (kg/ha)	Total 4-year SS (kg/ha)[z]
C-32 citrange	3	59.8	9.5	0.73	13.0	2,167	
	5	56.2	10.2	0.65	15.7	3,886	13,493
Morton citrange	3	60.0	9.9	0.71	14.1	1,694	
	5	56.8	10.7	0.63	17.0	4,054	12,705
Sun Chu Sha mandarin	3	58.1	9.4	0.7	13.5	1,271	
	5	55.8	10.4	0.65	16.1	4,208	12,258
1584	3	58.8	9.0	0.69	13.0	1,446	
	5	56.6	10.3	0.65	15.9	3,461	11,156
Murcott	3	57.7	9.6	0.72	13.4	1,306	
	5	52.9	10.7	0.72	14.9	3,515	10,458
1575-21 citrange	3	59.9	9.8	0.75	13.1	1,702	
	5	55.5	11.4	0.66	17.2	2,843	10,378
Goutou	3	58.6	9.2	0.69	13.3	1,138	
	5	52	10	0.65	15.4	3,332	9,949
Zhuluan	3	59.2	9.1	0.71	12.8	1,326	
	5	54.7	9.7	0.64	15.2	2,637	9,853
Swingle citrumelo	3	59.2	9.4	0.78	12.3	1,353	
	5	55.3	10.3	0.66	15.6	2,724	9,676
1675 citrange	3	59.2	9.7	0.74	13.2	1,018	
	5	58.5	11.2	0.71	15.9	3,269	8,997
Cleopatra mand. +	3	58.8	9.4	0.64	14.6	599	
Swingle citrumelo	5	54.5	11.1	0.68	16.4	1,938	4,959
Cleopatra mand. + Flying	3	58.7	10.4	0.77	13.6	348	
Dragon trif. org.	5	54.5	12.1	0.73	16.7	1,178	3,643
Hamlin + Flying Dragon	3	57.8	9.6	0.68	14.2	238	
trif. org.	5	57.9	11.5	0.67	17.2	952	2,435
Mean	3	58.9	9.5	0.7	13.4	1,200	
P value		0.48	<0.001	<0.001	<0.002	<0.001	
Least significant difference			0.3	0.04	0.8	439	
Mean	5	55.5	10.7	0.7	16.1	2,923	
P value		0.65	<0.0001	0.05	0.029	<0.001	
Least significant difference		5.9	0.5	0.05	1.4	1,006	

[z]Trees aged 3 to 6 years.
SS = soluble solids.

Table 4. Discounted annual cash flows (U.S. dollars/ha) and internal rates of return (IRR) based on historical data (1985–1999) for a hypothetical 1-ha grove of 'Hamlin' trees on 19 rootstocks (H1) planted at 4.3 × 6.7 m (348 trees/ha) at St. Cloud, FL.[z]

	Discounted cash flow with ending orchard value, 15% rate		IRR with capital investment and ending orchard value (%)
Rootstock	Blight with resets	Tree loss (%)	Blight with resets
Benton citrange	16,813	6	16.1
Troyer citrange	15,894	6	16.1
F80-8 citrumelo	15,670	6	15.6
Carrizo citrange	14,388	26	14.5
Swingle citrumelo	13,748	6	14.2
x639 (Cleo × TF)	13,390	13	13.7
Kinkoji	13,177	0	14.6
Sunki mandarin	13,022	6	14.1
Valencia sweet orange	11,770	0	14.7
Calamandarin	11,567	6	12.1
Cleopatra mandarin	11,515	0	14.3
Smooth Flat Seville	11,466	0	14.8
Koethen swt. org. × Rubidoux trif. org.	11,071	6	13
Shekwasha mandarin	10,159	0	12.9
Rusk citrange	10,001	0	9.2
C-35 citrange	9,873	0	10.5
Rangpur × Troyer citrange	7,301	45	4.4
Volkamer lemon	3,174	13	6.7
Flying Dragon TF	551	0	–2.3
Adjusted tree spacing			
Koethen swt. org. × Rub. trif. org. (3.0 × 6.1)	20,852	6	15.5
Rusk citrange (3.0 × 6.1)	18,646	0	14.3
C-35 citrange (3.0 × 6.1 m; 538 trees/ha)	18,046	0	13.7
Swingle citrumelo (3.7 × 6.7)	15,630	6	12
Kinkoji (3.7 × 6.7; 408)	14,699	0	12.2
Smooth Flat Seville (3.7 × 6.7)	12,276	0	11.3
Flying Dragon TF (2.4 × 6.1; 672)	8,262	0	6.4

[z]Tree loss is at the end of the financial analysis period, 1998–1999 season, when the trees were ≈13 years old.

New rootstock evaluation model. Rootstock evaluations are normally thought of as an activity taking at least 10 years, but when does the relationship among rootstocks actually become established in a field trial? We propose that Florida citrus rootstock evaluation trials based on 4 cropping years of data are generally sufficient to assess rootstock potential and relationships, a conclusion we also reached in our report of rootstock trials with 'Valencia' scion (Castle et al., 2010). In H1, most horticultural variables and financial outcomes were highly correlated, e.g., cumulative soluble solids production versus cash flow, $r = 0.91$; cumulative yield versus tree height, $r = 0.88$; and in Year 5, annual soluble solids and yield had reached values of $r = 0.92$ and $r = 0.84$, respectively, with their cumulative values. Those r values increased up to $r = 0.97$ thereafter, indicating that rootstock relationships were evident and reasonably stable after the third cropping year. Thus, could these relationships predict the H2 results if that trial had continued for additional years? In H2, cumulative yield (4 years) was highly correlated with tree height ($r = 0.91$); the correlation of yield when the trees were 3 years old versus cumulative yield was $r = 0.80$ and improved the next year to 0.95 with those variables remaining highly correlated. Those results show that yield was directly related to tree height and that the effects of rootstock were apparent after 4 years of cropping. Differences in juice quality among trees on the various rootstocks were not large enough to alter those relationships in our trial or replace yield as the main factor in determining yield and financial outcomes.

Conclusions

Our objective was to evaluate fruit quality variables and yield related to rootstock selection, conduct a financial analysis, and compare the relative usefulness of horticultural and financial data in rootstock selection decisions. Rootstocks had measurable effects on 'Hamlin' sweet orange tree growth, yield, and juice quality as reported in other work (Castle and Baldwin, 2005; Wutscher and Hill, 1995). We conclude that for 'Hamlin' orange trees grown under central Florida conditions: 1) two promising new rootstocks, C-32 citrange and the trifoliate orange–Milam hybrid (1584), were identified; 2) the horticultural results confirm the commercial popularity of Carrizo citrange, Swingle citrumelo, and Cleopatra mandarin among Florida citrus growers and elsewhere, outcomes also supported by the financial data; 3) virtually all the rootstocks we tested were suitable for use with 'Hamlin' with the exception of the somatic hybrids, procimequat, Rangpur × Troyer (blight), and a few other rootstocks that succumbed to citrus tristeza; 4) the best horticultural and financial results were obtained from the larger trees because yield was directly related to tree height. However, when the performance of trees on certain less vigorous rootstocks was adjusted to more appropriate spacings, they joined the group of best performing trees as determined by the financial results; 5) the horticultural results were expanded by the financial analyses but not meaningfully altered, thus the conventional horticultural data alone could be effectively used to make rootstock decisions; and 6) reliable interpretations of 'Hamlin' rootstock field trials can probably be rendered within the first 4 years of cropping. It could be argued that $\approx$7 years in the field (3 years of initial growth followed by 4 cropping years) is insufficient to assess such factors as vegetative compatibility and response to diseases like blight. However, our results show that yield is the major component of horticultural and financial outcomes and can compensate for high levels of tree loss resulting from disease and for differences in juice quality among rootstocks. Trials of the proposed length lead to more efficient use of the land resource because of a shorter turnover time for trials, and the lowest performing rootstocks could be indentified early, removed, and then replaced.

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