Early Performance of Selected Citrus Rootstocks Grafted with 'Valencia' Sweet Orange in Commercial Settings within a Citrus Greening Endemic Environment

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Summary. Citrus greening or Huanglongbing (HLB) has caused sweet orange (*Citrus sinensis*) yield in Florida to decrease by 55% since the disease was first discovered in 2005. As a consequence, the profitability and sustainability of citrus (*Citrus* sp.) production in Florida have been jeopardized, as evidenced by the 62% reduction in the number of citrus growers statewide. Because there is still no effective treatment or management strategy to cure the disease, it is crucial to optimize grove practices and management. The use of improved rootstocks could increase the tolerance of citrus scions to biotic and abiotic stresses, thereby allowing growers to cope better with the impact of HLB in the field. We used yield data collected from commercial trials over the course of multiple seasons to assess the side-by-side performance of various commercially available rootstocks developed by the two major breeding programs in Florida in HLB-endemic field conditions. We found that some of the rootstocks attained not only statistically significant differences in yield relative to the control but also meaningful differences in revenue. Those estimates provide evidence regarding the effect of rootstock during the first few seasons after planting. Our findings are useful to improve growers' decision-making processes regarding rootstock selection for new groves.

Citrus (*Citrus* sp.) growers' selection of a rootstock is a key decision that can affect the profitability and longevity of a grove. Using improved rootstocks can induce traits in a scion that make citrus trees more resilient to pests and diseases and can enhance their horticultural attributes, such as size, yield, and fruit quality (Bowman et al., 2016; Wutscher and Bowman, 1999; Wutscher and Hill, 1995). Since the outbreak of citrus greening or Huanglongbing (HLB), research of rootstocks has gained renewed interest because of the impact they can have on coping with the disease (Castle et al., 2020).

Caused by the bacterium *Candidatus* Liberibacter asiaticus (*C*Las) and transmitted by the asian citrus psyllid (*Diaphorina citri*), HLB is a devastating disease that affects major commercial citrus production areas worldwide. First found in Florida in 2005, HLB spread rapidly throughout the state, where it is now endemic. As a consequence, statewide sweet orange (*Citrus sinensis*) yield has decreased by 55% and production has decreased by more than 70% (Singerman et al., 2017; U.S. Department of Agriculture, 2019). Hodges et al. (2014) estimated that HLB caused $7.80 billion in economic losses between 2006 and 2013. At the farm level, growers have sustained losses, thus forcing many to exit the industry. From 2002 to 2017, the number of citrus growers in Florida decreased by 4614 (62%) (Singerman and Rogers, 2020; Singerman et al., 2018).

Because there is still no effective treatment or management strategy to cure the disease, it is crucial for growers to optimize grove practices and management. One way to achieve such a goal would be to plant rootstocks that provide enhanced tolerance to the disease, thereby resulting in higher production. However, the results of recent studies of the effect of rootstock on tolerance to HLB in field trials have been inconsistent (Albrecht et al., 2012; Bowman et al., 2016; Stover et al., 2016). According to Bowman et al. (2016), such results are partly attributable to erratic disease spread and development of symptoms. For example, Albrecht et al. (2012) and Stover et al. (2016) showed little or no rootstock effect on growth, HLB symptoms, and *C*Las titer. However, in some cases, Albrecht et al. (2012) found that older infected trees showed rootstock effects on yield following *C*Las infection.

This study aimed to provide estimates of the performance of different rootstocks grafted with 'Valencia' sweet orange scions in commercial field conditions within an HLB-endemic environment. To the best of our knowledge, these are the first estimates obtained from side-by-side trials that compared the performance of rootstocks developed by two breeding programs in Florida, namely that of the University of Florida and the U.S. Department of Agriculture (USDA). Therefore, those estimates can be particularly useful to growers deciding which rootstocks to plant. Importantly, this analysis evaluated the biological (i.e., yield) and economic (i.e., revenue) performance. Yield was measured as the number of pounds of solids per acre because that unit is the basis on which growers are paid for their crop and is, therefore, key to profitability and sustainability.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.4536	lb	kg	2.2046
1.1209	lb/acre	$kg \cdot ha^{-1}$	0.8922

Materials and methods

Our data included annual yields from grower-run trials using a completely randomized design conducted by the Citrus Research and Development Foundation (CRDF), Lake Alfred, FL. There were three trials in different locations within Florida; two sites were in central Florida (Lake Placid and Babson Park) and one site was in southwest Florida (Felda). Each site was managed by a different grower. At each site, the following rootstocks were evaluated: UFR-2 (a complex allotetraploid from somatic hybrids {[*Citrus clementina* × (*Citrus paradisi* × *Citrus reticulata*)] + *Citrus grandis* × (*C. reticulata* + *Poncirus trifoliata*)}; UFR-3 and UFR-4 (same pedigree as UFR-2); UFR-16 (*Citrus maxima* × *Citrus depressa*); US-812 (*C. reticulata* × *P. trifoliata*); and US-942 (*C. reticulata* × *P. trifoliata*). Rootstock US-897 (*C. reticulata* × *P. trifoliata*) was also evaluated at the Babson Park site. The acronyms UFR and US denote rootstocks developed by the University of Florida and the USDA, respectively. Table 1 shows the list of rootstocks and their corresponding release date and number of propagations during 2019–20 statewide (Florida Department of Agricultural and Consumer Services, 2020), which together account for ≈53% of the total citrus propagations in the state.

Most trees at each location were planted in 2015. However, trees on rootstocks UFR-3 and UFR-16 in Lake Placid and Babson Park were planted between 2 and 12 months later than those on the other rootstocks. Because of such differences in planting time, we did not analyze such rootstocks (in Lake Placid and Babson Park) because of concerns regarding the variability induced by the different growing conditions (i.e., weather and growing time) those trees were subjected to relative to all other trees.

The trials also included trees on traditional commercial rootstocks used in each region, which were used as a control. Therefore, in Lake Placid, the rootstock used as control was sour orange (*Citrus aurantium*); in Babson Park, it was Carrizo citrange (*C. sinensis* × *P. trifoliata*); and in Felda, it was Swingle citrumelo (*C. paradisi* × *P. trifoliata*). Each rootstock was replicated five times; therefore, there were 25 plots in Lake Placid, 30 plots in Babson Park, and 35 plots in Felda. In Lake Placid and Babson Park, yield data were collected during three seasons, 2017–18, 2018–19, and 2019–20; however, in Felda, data were also collected in 2016–17.

Table 1. List of citrus rootstocks with the corresponding release date and number of propagations during 2019–20 that were evaluated using annual yields from grower-run trials. The acronyms UFR and US denote rootstocks developed by University of Florida and USDA, respectively.

Rootstock	Release date	Propagations in 2019–20 (no.)[z]
Carrizo citrange	1938	N/A
Sour orange	Long established	181,615
Swingle citrumelo	1974	380,000
UFR-2	2015	N/A
UFR-3	2015	N/A
UFR-4	2015	49,017
UFR-16	2015	N/A
US-812	2001	264,980
US-897	2007	285,459
US-942	2010	909,953

[z]Florida Department of Agricultural and Consumer Services (2020). N/A = not available. N/A rootstock propagations were not in the top 15, so their propagations numbers are not provided in the report.

The trials in Lake Placid and Babson Park included 144 trees per plot (12 rows wide and 12 trees in each row). However, the trial evaluation focused on a subplot within the 144-tree main plot. The subplots at those two sites consisted of 64 trees (eight rows wide and eight trees in each row). The site in Felda was bedded and the main plots consisted of 126 trees (seven rows wide and 18 trees in each row). The data were also collected from a subplot, which, in this case, consisted of 70 trees (five rows wide and 14 trees in each row). The tree planting density for each site was as follows: Lake Placid, 240 trees per acre (22 × 8.25 ft [between rows and in rows, respectively]); Babson Park, 303 trees per acre (18 × 8 ft); and Felda, 202 trees per acre (21.5 × 10 ft). Table 2 shows a summary of the site descriptions. All trees were budded with 'Valencia' sweet orange (clone 1-14-19). 'Valencia' is the predominant late orange cultivar produced in Florida and has accounted for ≈55% of the bearing area of oranges grown in the state during the past few years.

By having the same scion grafted on different rootstocks, we can make inferences regarding the tolerance of the rootstocks to HLB based on the differential yield and revenue they provide. However, the statistical analyses and comparisons we conducted were performed based on each individual site because groves at each site were managed by different growers who used different inputs and input levels (i.e., fertilizer, foliar nutritionals, insecticide sprays, etc.). Additionally, other sources of variability across sites included soil type, irrigation practices, tree density, weather, and level of asian citrus psyllid population, resulting in different HLB infection rates. By conducting our analyses by site, the only differing treatment across plots within a site was the rootstock because all other major sources of variability were kept constant. By performing our inferences in this way, we avoided the shortcomings that have been noted by Bowman et al. (2016), who pointed out that because the performance of citrus rootstocks is affected by many different factors, the relative rootstock field performance will often vary considerably between trials in different locations.

Throughout the duration of the trial, annual data regarding the CLas

Table 2. Description of the trial sites within Florida, evaluated citrus rootstocks, planting date of trees, tree spacing, tree density, and soil series. The acronyms UFR and US denote rootstocks developed by University of Florida and USDA, respectively.

		Evaluated rootstocks													
Site	Location (county within Florida)	Sour orange	Carrizo citrange	Swingle citrumelo	UFR 2	UFR 3	UFR 4	UFR 16	US 812	US 897	US 942	Planting date	Tree spacing [between-row × in-row (ft)]^z	Tree density (no./acre)^z	Soil series
Lake Placid	Highlands	X			X		X		X		X	July 2015	22 × 8.25	240	Paola sand and St. Lucie sand
Babson Park	Polk		X		X		X		X	X	X	Apr. 2015	18 × 8	303	Candler sand and Astatula sand
Felda	Hendry			X	X	X	X	X	X		X	Mar. 2015	21.5 × 10	202	Oldsmar sand, Pineda wet fine sand, Wabasso sand, limestone substrate, Winder fine sand, Wabasso sand

^z 1 ft = 0.3048 m; 1 tree/acre = 2.4711 trees/ha.

infection was also collected by conducting polymerase chain reaction (PCR) analyses of leaf samples from sentinel trees in each plot. There were eight sentinel trees per plot. The total number of plots was that for the full trial, which included the rootstocks we did not include in the statistical and economic analyses because of delayed planting. Therefore, there were 35 plots in Lake Placid and Felda and 40 plots in Babson Park. The cut-off cycle threshold (Ct) values used to determine whether a tree was *C*Las-negative was ≥36.

To analyze the yield data, we used regression analysis. In particular, we used ordinary least squares (OLS) with clustered SEs (by rootstock and plot) because, if there is a positive correlation of the errors within a cluster, then an additional observation in the cluster does not provide a completely independent piece of new information. Therefore, using default SEs can lead to using SEs that are too small, resulting in incorrect inferences by over-rejection of the true null hypotheses (Cameron and Miller, 2015). Instead, by using clustered SEs, we obtained robust estimates of correlations among errors of the same rootstock/plot and heteroscedasticity over time.

To determine differences in yield at each site based on the choice of rootstock, we performed a regression of yield (in pounds of solids per acre) for each plot i ($i = 1, 2, \ldots, 5$) during season t as a function of binary (dummy) variables representing the corresponding seasons for which we had data for each site as well as binary (dummy) variables interacting rootstock i and season t. Because the use of dummy variables in a regression requires excluding one category to avoid perfect collinearity, the control rootstock in each site does not explicitly appear in the regression. Conveniently, however, the control acts as the baseline against which the rootstocks undergoing evaluation are compared. In other words, the interaction dummy variables capture the differential yield per acre relative to the corresponding control through time. Because the independent variables in each regression varied according to the number of rootstocks evaluated at each site and the number of years harvested, the following equation denotes the generalized model specification:

$$Yield\ per\ Acre_{i,t} = \alpha_0 + \beta_t \sum_t Season_t + \gamma_{it} \sum_i \sum_t Rootstock_i \cdot Season_t + \varepsilon_{i,t}$$

where $\varepsilon_{i,t}$ represents the error term.

Results

Table 3 shows the progression of *C*Las infection by site and sampling date. In the first sampling, the percentage of infected trees was quite heterogeneous among the three sites. In Babson Park and Felda, the sampling was conducted ≈9 and 10 months after planting, and the levels of infection were 22% and 14%, respectively. In contrast, even though the sampling was performed 6 months after planting in Lake Placid, the percentage of infected trees was 51%. Such heterogeneity in infection rates across sites could be attributed to the differences in asian citrus psyllid spraying programs among the collaborating growers (as well as that of their neighbors). Importantly, however, in the fourth sampling, which occurred 43, 46, and 47 months after planting, the level of infection was more than 90% at all three sites. To the best of our knowledge, those field estimates are the first to show how quickly the disease progresses within a new grove in a commercial setting and provide evidence of how important it is for growers to find ways to optimize grove practices and management to manage the disease.

Table 4 shows the yield data by site and season. Table 5 shows the regression results by site. Importantly, the high R^2 (of at least 87%) in all three regressions indicate that most of the variations in yield are accounted for by the covariates included in the model. The regression coefficients of each of the intercepts denote the average yield during the first season across all rootstocks, and the coefficients for each season dummy represent the difference in yield of the control rootstock through time relative to that average. The coefficients of each of the interaction dummy variables represent the average differential yield of rootstock i with respect to the control in season t. For example, in Lake Placid, the coefficient for rootstock UFR-2 season 2018–19 denotes that such rootstock attained, on average across all replications, 229 lb/acre solids less relative to sour orange that season. All

Table 3. *Candidatus* Liberibacter asiaticus (*C*Las) date of sampling, number of sentinel 'Valencia' sweet orange trees sampled, and infection percentage of sentinel trees by site within Florida.

Site	Planting date	Date of tissue sample	Sampling timing (months after planting)	Sentinel trees sampled (no.)[z]	*C*Las-infected trees (%)[y]	Comments
Lake Placid	20 July 2015	19 Jan. 2016	6	243	51	Late planted trees not sampled
		15 Feb. 2017	19	280	70	All sentinel trees sampled
		9 Jan. 2018	30	280	85	All sentinel trees sampled
		30 Jan. 2019	43	279	91	One dead sentinel tree
		14 Jan. 2020	55	279	97	One dead sentinel tree
Babson Park	30 Apr. 2015	12 Jan. 2016	9	280	22	Late planted trees not sampled
		13 Feb. 2017	22	320	100	All sentinel trees sampled
		4 Jan. 2018	33	320	86	All sentinel trees sampled
		28 Jan. 2019	46	319	94	One dead sentinel tree
		15 Jan. 2020	57	318	94	Two dead sentinel trees
Felda	19 Mar. 2015	13 Jan. 2016	10	280	14	All sentinel trees sampled
		14 Feb. 2017	23	280	29	All sentinel trees sampled
		17 Jan. 2018	35	280	79	All sentinel trees sampled
		4 Feb. 2019	47	279	96	One dead sentinel tree
		30 Jan. 2020	59	279	98	One dead sentinel tree

[z]There were eight sentinel trees per plot. The total number of plots was for the full trial, which included the rootstocks that we did not include in the statistical and economic analysis because of delayed planting. Therefore, there were 35 plots in Lake Placid and Felda and 40 plots in Babson Park.
[y]The cut-off cycle threshold (Ct) value used to indicate whether a tree was *C*Las-negative was ≥36.

coefficients in the regression for Lake Placid were statistically significant either at the level of 1% or 5% level, except that for rootstock US-942 season 2019–20. In Babson Park, the only statistically significant coefficients were those for rootstock UFR-2 during both seasons and for rootstock UFR-4 season 2018–19 (all of which were negative). In Felda, the coefficients that were statistically significant were those for rootstock UFR-3 season 2019–20 (which was negative) and US-812 and US-942 during season 2018–19 (which were positive).

Figure 1 illustrates the results of the regressions for each site through time, which is useful to visualize the differential yields of the evaluated rootstocks through the different seasons. Figure 1 panels B and C evidence that the positive yield differentials of the U.S. rootstocks relative to the control observed during season 2018–19 became statistically nonsignificant in 2019–20. Such results could be attributable to decreased performance of the rootstocks or decreased input use by growers as a response to lower fruit prices (Singerman, 2020), or a combination of both. We were unable to determine the underlying cause of those yield changes with the data we had available. However, Table 4 shows that in Felda, the yield of US-812 and US-942 decreased in 2019–20 relative to that of the previous season, whereas that of Swingle citrumelo increased slightly. This would imply that if the cause was a decrease in input alone, then US-812 and US-942 were more sensitive to such change compared with Swingle citrumelo. Table 4 also shows that in Babson Park, the yield of all rootstocks increased relative to the previous season. Even though the yield of US-812 was still the highest among all rootstocks in that site in 2019–20, its increase in 2019–20 relative to the previous season was not as high as that of Carrizo citrange, thereby making the differential yield nonstatistically significant. This would suggest that US-812 is a rootstock that attains higher yields (and revenue) sooner but that Carrizo citrange catches up after a few seasons. Although these are inferences, they could be valuable considerations for growers to use to decide which rootstock to use. To be able to effectively establish the driver of the changes in yield during the last season, it is important to continue data collection for these (and other) trials.

Revenue differentials: Statistical significance and economic importance. Based on the yield data, we also computed the differential

Table 4. Annual 'Valencia' sweet orange yield data by site within Florida and harvest season. The treatments were the different citrus rootstocks at each site. The control citrus rootstocks in Lake Placid, Babson Park, and Felda were sour orange, Carrizo citrange, and Swingle citrumelo, respectively. The acronyms UFR and US denote rootstocks developed by University of Florida and USDA, respectively.

			Season				
			2016–17	2017–18	2018–19	2019–20	Total
Site	Control	Rootstock	Solids (lb/acre)[z]				
Lake Placid	Sour orange	Sour orange		32.02	435.66	638.31	1106.00
		UFR-2		13.89	206.28	434.41	654.58
		UFR-4		17.07	235.95	489.54	742.55
		US-812		31.18	562.89	798.83	1392.91
		US-942		45.78	585.30	689.02	1320.10
Babson Park	Carrizo citrange	Carrizo citrange		261.53	916.19	1224.48	2402.20
		UFR-2		147.03	533.92	813.23	1494.17
		UFR-4		205.14	627.16	1144.65	1976.95
		US-812		347.59	1160.06	1349.49	2857.14
		US-897		220.84	934.47	1037.83	2193.13
		US-942		290.57	1058.22	1279.19	2627.98
Felda	Swingle citrumelo	Swingle citrumelo	33.92	62.40	764.78	776.36	1637.46
		UFR-2	9.00	56.25	763.69	810.87	1639.82
		UFR-3	60.04	35.18	559.87	560.26	1215.35
		UFR-4	22.43	50.40	803.78	856.64	1733.24
		UFR-16	35.22	42.69	546.20	636.55	1260.65
		US-812	59.51	51.98	1013.30	870.05	1994.83
		US-942	61.92	54.47	1040.08	867.71	2024.18

[z] 1 lb/acre = 1.1209 $kg \cdot ha^{-1}$.

revenue by season of each of the rootstocks relative to the control at each site. Table 6 shows the differential revenue of each rootstock with respect to the control. The prices we used to calculate revenue were the actual average prices for 'Valencia' sweet oranges during each season as reported by the Florida Department of Citrus (Florida Department of Citrus, 2017, 2018, 2019, 2020). Therefore, the prices for 2016–17, 2017–18, 2018–19, and 2019–20 were \$2.85, \$3.09, \$2.42, and \$1.25 per pound of solids, respectively. By using the market prices for the seasons for which we had data, we were able to provide estimates of the actual revenue resulting from the yield attained by each rootstock during these trials. Using a 5-year average of prices instead, for example, would not change the ranking of the rootstock based on revenue; it would just provide a different revenue amount.

Table 6 shows the differential revenue for all rootstocks, not just those that we found to have statistically significant differences in yield relative to the control. The reason for doing so is because even though the differences in yield of some of the rootstocks were not statistically significant, the differences in revenue they attained relative to the control are large enough to have practical importance for growers. As argued by McCloskey (2005), statistical significance should not be used as an all-purpose way of judging whether a number is large enough to matter. As pointed out by Kirk (1996), "while statistical significance is concerned with whether a result is due to chance or sampling variability; practical significance is concerned with whether the result is useful in the real world" (p. 746).

Table 5. Regression results of the differential 'Valencia' sweet orange yields in pounds of solids per acre (1 lb/acre = 1.1209 kg·ha^{-1}) relative to the control by citrus rootstock, season, and site within Florida. The treatments were the different citrus rootstocks within each site. The control citrus rootstocks in Lake Placid, Babson Park, and Felda were sour orange, Carrizo citrange, Swingle citrumelo, respectively. The acronyms UFR and US denote rootstocks developed by University of Florida and USDA, respectively.

	Estimated coefficients (SE)[z]	
Variables	**Lake Placid**	**Babson Park**
Intercept	27.99*** (2.897)	245.4*** (20.95)
Season 2018–19	407.7*** (26.81)	670.7*** (69.98)
Season 2019–20	610.3*** (38.67)	979.0*** (153.0)
UFR-2 Season 2018–19	−229.4*** (36.79)	−382.3*** (112.8)
UFR-2 Season 2019–20	−203.9*** (57.36)	−411.3** (189.2)
UFR-4 Season 2018–19	−199.7*** (52.65)	−289.0** (105.0)
UFR-4 Season 2019–20	−148.8** (53.34)	−79.83 (186.4)
US-812 Season 2018–19	127.2*** (30.45)	243.9** (99.96)
US-812 Season 2019–20	160.5** (58.86)	125.0 (181.2)
US-942 Season 2018–19	149.6** (55.85)	142.0 (102.6)
US-942 Season 2019–20	50.72 (53.33)	54.71 (174.3)
US-897 Season 2018–19		18.29 (79.05)
US-897 Season 2019–20		−186.7 (176.9)
Observations	75	90
Clusters	25	30
R^2	0.949	0.868

	Estimated coefficients (SE)
Variables	**Felda**
Intercept	40.29*** (4.878)
Season 2017–18	22.11 (16.43)

(Continued on next page)

Table 6 illustrates the aforementioned point for UFR-16 in Felda. None of its coefficients attained a statistically significant difference in yield relative to the control (Table 5). However, as shown in Table 6, the cumulative revenue UFR-16 attained over the course of three seasons was −$761/acre compared with that of Swingle citrumelo. In contrast, rootstock US-812 in Felda attained a statistically significant difference in yield relative to the control only in 2018–19, but its cumulative revenue over the course of three seasons was $759/acre. Although none of the coefficients for UFR-16 was found to be statistically significant during all four seasons, and although only one coefficient was found to be statistically significant for US-812, there is still a meaningful economic difference between the two rootstocks that should not be ignored; a grower would not be indifferent between obtaining $760/acre more than the control as opposed to $760/acre less than it. Although the data available are only those of the first few seasons, early differences in yield and revenue are particularly important to growers' profitability and sustainability at a time when margins are becoming particularly narrow, if positive at all.

Table 6 shows that in Lake Placid, both UFR-2 and UFR-4 attained a lower level of revenue compared with sour orange during each of the seasons for which we had data; therefore, there was negative cumulative revenue over the course of three seasons of $866/acre and $715/acre. In contrast, US-812 and US-942 attained cumulative revenues of $506/acre and $468/acre more than the control, respectively. Despite the similar cumulative revenue, US-812 seems to be a better choice because, even though in 2019–20 both rootstocks attained a lower positive difference with respect to the control, that of US-812 was larger. It is also noteworthy that negative and positive revenue differences for all evaluated rootstocks decreased in 2019–20 compared with 2018–19 because of lower yield or lower fruit prices.

In Babson Park, rootstocks UFR-2 and UFR-4 attained negative revenues during all three seasons compared with Carrizo citrange, with cumulative revenues of −$1793/acre and −$974/acre, respectively. Therefore, it would be more beneficial if

Table 5. (*Continued*)

Variables	Estimated coefficients (SE)[z] Felda
Season 2018–19	724.5*** (79.31)
Season 2019–20	736.1*** (46.74)
UFR-2 Season 2017–18	−6.151 (22.43)
UFR-2 Season 2018–19	−1.082 (136.0)
UFR-2 Season 2019–20	34.51 (95.41)
UFR-3 Season 2017–18	−27.23 (18.39)
UFR-3 Season 2018–19	−204.9 (144.1)
UFR-3 Season 2019–20	−216.1** (84.82)
UFR-4 Season 2017–18	−12.01 (19.94)
UFR-4 Season 2018–19	39.01 (94.62)
UFR-4 Season 2019–20	80.28 (57.03)
UFR-16 Season 2017–18	−19.71 (23.17)
UFR-16 Season 2018–19	−218.6 (133.4)
UFR-16 Season 2019–20	−139.8 (111.0)
US-812 Season 2017–18	−10.43 (19.36)
US-812 Season 2018–19	248.5** (110.9)
US-812 Season 2019–20	93.69 (78.26)
US-942 Season 2017–18	−7.938 (20.01)
US-942 Season 2018–19	275.3** (122.9)
US-942 Season 2019–20	91.35 (77.63)
Observations	133
Clusters	35
R^2	0.907

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$, with robust SEs in parentheses.

growers used Carrizo citrange to graft 'Valencia' rather than UFR-2 or UFR-4 when using such a soil profile and management. Although US-897 performed somewhat better compared with the UFR rootstocks, it also attained negative cumulative revenue. Both US-812 and US-942 attained positive revenue differences compared with Carrizo citrange during all three seasons. However, at \$1012/acre, US-812 attained a cumulative revenue that doubled that of US-942.

In Felda, trees on rootstock UFR-2 showed performance similar to that of Swingle citrumelo, but with an intrinsic higher risk because its performance through time is still unknown. The cumulative revenue over the course of four seasons of trees on rootstocks UFR-3 and UFR-16 were similar; they obtained revenues of −\$776/acre and −\$761/acre relative to Swingle citrumelo, respectively. Therefore, it would benefit growers to use Swingle citrumelo to graft 'Valencia' when using such a soil profile and management. US-812 and US-942 resulted in the largest differences in yield and revenue compared with the control, but the differences decreased considerably in 2019–20 because of the combined decrease in yield differentials and prices. Although UFR-4 did not attain large differences, increases over the course of seasons would indicate that it is worthwhile to continue data collection to evaluate its performance over longer time periods.

Discussion

We compared 'Valencia' sweet orange yield data from side-by-side grower-run trials performed at three locations in Florida. The treatments consisted of scions grafted onto different rootstocks recently developed by the University of Florida and the USDA, as well as traditional rootstocks that were used as controls. Although the data were from trees during their first bearing years, the results of our analysis indicate that rootstocks can be a significant factor affecting yield and economic return. Moreover, finding rootstocks that yield returns (and revenue) sooner can be particularly valuable for growers to achieve breakeven (and profits) more quickly. Therefore, our estimates should prove useful to citrus growers during their decision-making process when determining which rootstock to use (and which not to use) in the current HLB-endemic environment in Florida.

The rootstocks that attained statistically positive differences in yield relative to the corresponding control included US-812 and US-942 in Lake Placid during two seasons and one season, respectively; rootstock US-812 in Babson Park during one season; and rootstocks US-812 and US-942 in Felda during one season. The rootstocks that attained statistically negative differences with respect to the corresponding control included rootstocks UFR-2 and UFR-4 in Lake Placid during two seasons; rootstocks UFR-2 and UFR-4 in Babson Park during two seasons and one season, respectively; and rootstock UFR-3 in Felda during one season. Importantly, some of the rootstocks attained meaningful positive and negative differences in revenue compared with traditional rootstocks even when none, or just one, of their coefficients attained a statistically significant difference in yield relative to the control. Those cases are illustrated by

Table 6. Differential 'Valencia' sweet orange revenue by citrus rootstock, season, and site within Florida relative to the control. The treatments were the different citrus rootstocks within each site. The control rootstocks in Lake Placid, Babson Park, and Felda were sour orange, Carrizo citrange, Swingle citrumelo, respectively. The acronyms UFR and US denote rootstocks developed by University of Florida and USDA, respectively. Estimates of revenue were obtained using actual average prices for 'Valencia' sweet oranges during each season as reported by the Florida Department of Citrus (2017, 2018, 2019, 2020). The prices for 2016–17, 2017–18, 2018–19, and 2019–20 were $2.85, $3.09, $2.42, and $1.25/lb solids, respectively ($1/lb = $2.2046/kg).

			Season					Season				
			2016–17	2017–18	2018–19	2019–20	Total	2016–17	2017–18	2018–19	2019–20	Total
Site	Control	Rootstock	Differential revenue ($/acre)[z]					Differential revenue (%/acre)[z]				
Lake Placid	Sour orange	UFR-2		−56.04	−555.12	−254.87	−866.03		−57%	−53%	−32%	−44%
		UFR-4		−46.22	−483.32	−185.96	−715.50		−47%	−46%	−23%	−37%
		US-812		−2.61	307.89	200.66	505.94		−3%	29%	25%	26%
		US-942		42.49	362.12	63.40	468.01		43%	34%	8%	24%
Babson Park	Carrizo citrange	UFR-2		−353.81	−925.09	−514.07	−1792.98		−45%	−42%	−34%	−39%
		UFR-4		−174.24	−699.45	−99.79	−973.48		−22%	−31%	−7%	−21%
		US-812		265.92	590.17	156.27	1012.36		33%	27%	10%	22%
		US-897		−125.75	44.25	−233.32	−314.81		−16%	2%	−15%	−7%
		US-942		89.73	343.73	68.39	501.84		11%	15%	4%	11%
Felda	Swingle citrumelo	UFR-2	−71.02	−19.01	−2.62	43.14	−49.50	−73%	−10%	0%	4%	−2%
		UFR-3	74.45	−84.13	−495.87	−270.12	−775.67	77%	−44%	−27%	−28%	−25%
		UFR-4	−32.76	−37.10	94.39	100.35	124.88	−34%	−19%	5%	10%	4%
		UFR-16	3.70	−60.92	−528.95	−174.76	−760.93	4%	−32%	−29%	−18%	−24%
		US-812	72.92	−32.22	601.42	117.12	759.24	75%	−17%	32%	12%	24%
		US-942	79.80	−24.53	666.24	114.19	835.71	83%	−13%	36%	12%	27%

[z]$1/acre = $2.4711/ha; 1acre = 0.4047 ha.

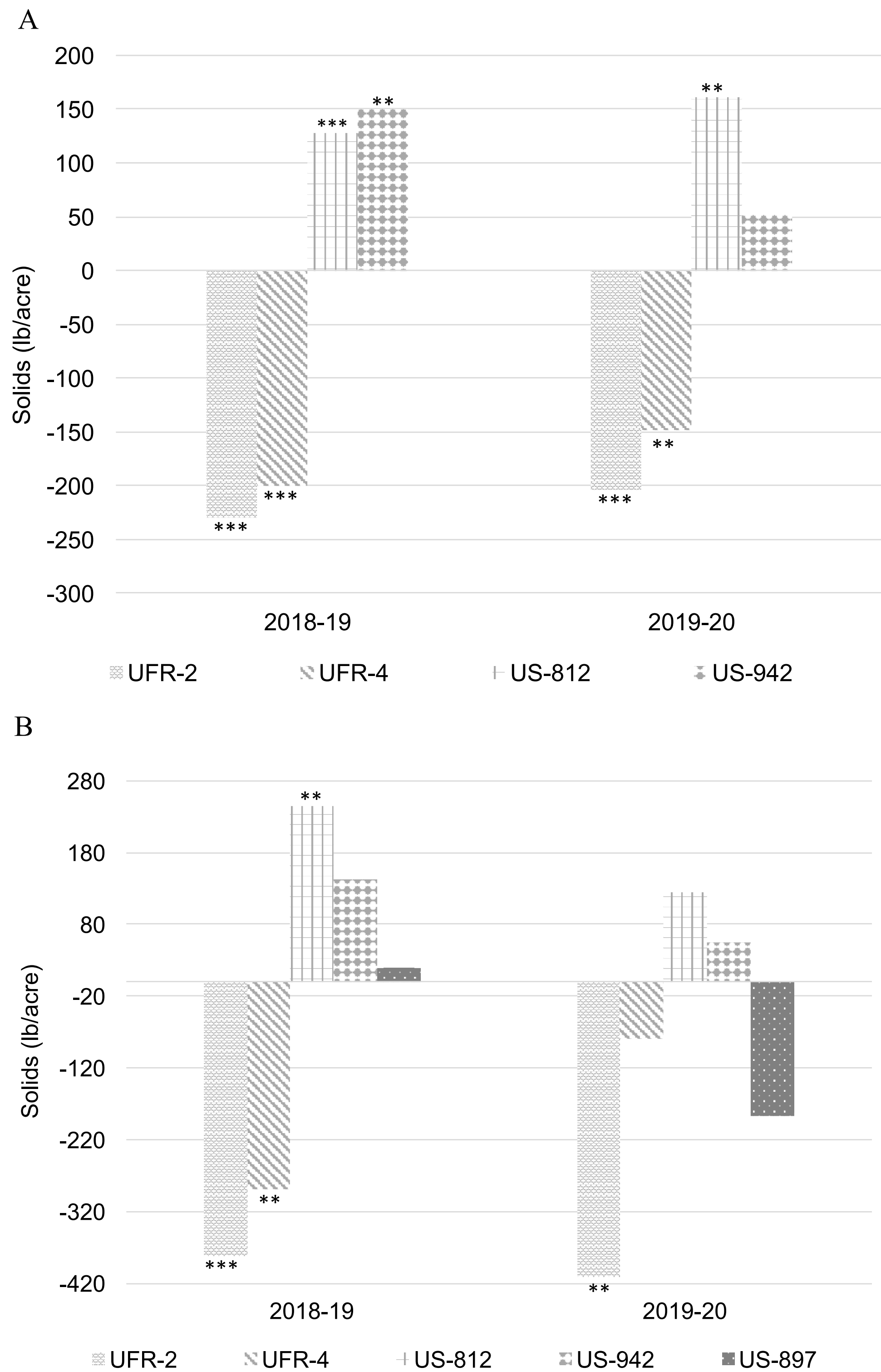

Fig. 1. Illustration of regression results of the differential 'Valencia' sweet orange yield in pounds of solids per acre relative to the control by citrus rootstock, season, and site within Florida: (A) Lake Placid, (B) Babson Park, and (C) Felda. The treatments were the different citrus rootstocks within each site. The control rootstocks at each site were sour orange, Carrizo citrange, and Swingle citrumelo, respectively. The acronyms UFR and US denote rootstocks developed by the University of Florida and USDA, respectively. Statistical significance: *** $P < 0.01$ and ** $P < 0.05$. 1 lb/acre = 1.1209 $kg \cdot ha^{-1}$.

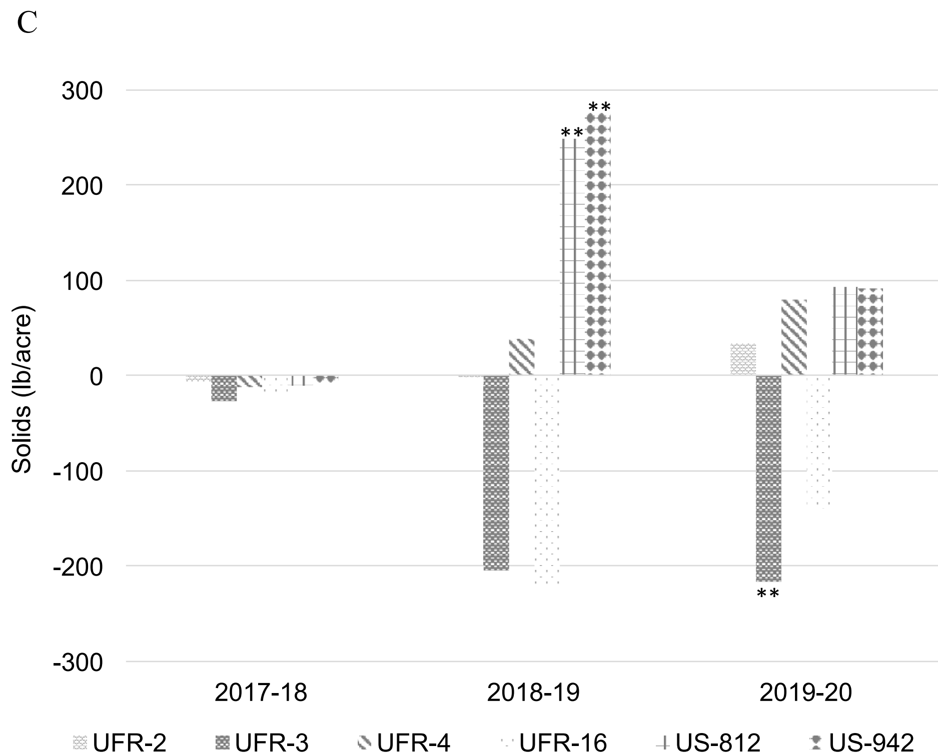

Fig. 1. ***(Continued)***

the positive (negative) differences in revenue attained by rootstock US-812 (UFR 4) in Babson Park and rootstocks US-812 and US-942 (UFR-3 and UFR-16) in Felda.

Our analysis had some limitations. The positive differences in performance attained by some of the evaluated rootstocks decreased during the last season for which we had data. Therefore, it remains to be seen whether the observed trend in performance will continue beyond the first few seasons. Follow-up studies that include more seasons are needed to address such an issue. It should also be clear that our findings have no implications for how well (or not) the rootstock evaluated would perform with other scions (e.g., early season and midseason) or in other locations. Even for the rootstocks/scion combinations evaluated here, our findings are the result of specific growing conditions (e.g., grower practices and weather) and should not be viewed as a guarantee of performance.

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