Yield, Tree Size, and Fruit Quality of Mature ‘Owari’ and ‘Brown Select’ Satsuma on *Poncirus trifoliata* ‘Rubidoux’ and ‘Flying Dragon’ Rootstocks in North Florida

Peter C. Andersen¹ and Brent V. Brodbeck

North Florida Research and Education Center-Quincy, University of Florida, 155 Research Road, Quincy, FL 32351

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Abstract. There is increasing interest in the culture of satsuma citrus in the states bordering the northern Gulf of Mexico. Yield, tree size, and fruit quality of mature ‘Owari’ and ‘Brown Select’ satsuma (*Citrus unshiu* Marcovitch) on *Poncirus trifoliata* (L.) Raf. (‘Rubidoux’ and ‘Flying Dragon’) were evaluated in north Florida. Canopy area and volume, yield, and fruit quality data were analyzed as a 2 × 2 factorial design with scion and rootstock as the main effects. There were no scion × rootstock interactions. Overall average yield per tree was 16, 88, 91, 143, and 101 kg in 2010, 2011, 2012, 2013, and 2014, respectively. Yield was influenced by scion (higher for ‘Brown Select’) in three of five years, and by rootstock every year (higher for ‘Rubidoux’). Yield per tree was ≈2-fold greater for trees on ‘Rubidoux’ compared with ‘Flying Dragon’; the highest yield was recorded for ‘Brown Select’ on ‘Rubidoux’. Yield per m² canopy area was often similar since canopy area was often ≈2-fold greater for trees on ‘Rubidoux’. For three of the five years, fruit weight was greater for ‘Brown Select’ (average = 157 g) than ‘Owari’ (average = 146 g), with no rootstock effect. Soluble solids of juice averaged 10.0 °Brix and were higher for trees on ‘Flying Dragon’ than on ‘Rubidoux’ in three of five years. Juice pH averaged 3.67 and was unaffected by scion or rootstock. Trees were not subjected to freeze protection and were not damaged by minimum temperatures as low as –9.4 °C, except for 2014/15. A rating of defoliation after a freeze on 19 Nov. 2014 (–5.6 °C) indicated that cold hardiness varied by scion (greater for ‘Brown Select’) and rootstock (greater for ‘Rubidoux’). Differences in cold hardiness did not persist when assessed later in the winter. Successful satsumas production can be achieved in north Florida in the absence of a severe freeze event.

The satsuma (*C. unshiu* Marcovitch) originated in southeast Asia, but was first reported in Japan over 700 years ago (Andersen et al., 2012). The satsuma was introduced to St. Augustine, FL in 1876 from the province of “Satsuma” located in southern Japan. More than a million ‘Owari’ satsuma were subsequently imported from Japan and planted in the states bordering the Gulf of Mexico from Florida to Texas. In Alabama, there were over 8000 ha of satsumas in the early 1900s (Dozier, 1924), although severe freezes between 1925 and 1950 virtually eliminated this industry. Since 1950, there have been several attempts at orchard reestablishment, but once again, freeze events of 1984/85 and 1988/89, decimated the satsuma industry in the northern Gulf of Mexico region. There has been a resurgence of interest in satsuma orchard establishment due to the relatively mild winters

during the last two decades. Currently, there are several hundred hectares of satsumas in the northern Gulf of Mexico region. The use of soil mounding, commercial tree wraps, and microsprinkler freeze protection have facilitated successful orchard reestablishment (Ebel et al., 2004, 2005; Nesbitt et al., 2000, 2002).

The mandarins include satsumas [e.g. ‘Armstrong Early’, ‘Brown Select’, ‘Early St. Ann’, ‘Kimbrough’, ‘Owari’ (most popular), ‘Silverhill’, ‘Xie Shan’] and tangerines (e.g., ‘Clementine’, ‘Dancy’, ‘Ponkan’, ‘Sunburst’) (Andersen et al., 2012; McClendon, 2004; Powell and Williams, 1998). Satsuma mandarins, when grafted on trifoliate orange [*P. trifoliata* (L.) Raf.] rootstocks, are the most cold-hardy commercial citrus (Andersen et al., 2012; McClendon, 2004; Yelenosky, 1985). In laboratory studies, satsuma trees have survived temperatures of –9.4 °C (Yelenosky, 1985), –11 °C (Anderson et al., 1983), and –11.1 °C (Gerber and Hashemi, 1965). Cold hardiness of citrus (Yelenosky, 1978, 1985, 1991) including satsumas (Nesbitt et al., 2002) is largely impacted by the degree of cold acclimation. Field-grown satsumas in Mississippi survived –9.9 to –11.0 °C when fully cold acclimated (Ferris and Richardson, 1923); however, satsumas sustained significant injury in Alabama

when not fully cold acclimated at –6.7 °C (Wimberg, 1948).

In addition to cold hardiness, satsumas have other attributes for adaptation to the north Gulf of Mexico region. Fruit maturation occurs from 15 Oct. to 15 Dec., well before the onset of minimum winter temperatures (Andersen et al., 2012; Powell and Williams, 1998). Early fruit ripening is also desirable from a marketing perspective. The flavor of satsumas is sweet; fruit have no or very few seeds and are very easy to peel (Campbell et al., 2004). The satsuma is parthenocarpic (fruit set occurs without fertilization or seeds) and does not require a pollinizer cultivar. In addition, citrus greening, which has resulted in severe reductions in acreage and yield on citrus grown in the Florida peninsula, has not yet impacted satsuma production in the Florida panhandle.

The objective of this study was to quantify yield, tree size, and fruit quality of mature (7th to 11th growing season) ‘Brown Select’ and ‘Owari’ satsuma cultivars on trifoliate orange [*P. trifoliata* (L.) Raf.] (‘Rubidoux’ and ‘Flying Dragon’) rootstocks in north Florida (‘Flying Dragon’ is a dwarfing rootstock). We acknowledge a previous evaluation of young (fourth to sixth growing season) satsuma trees (Andersen and Brodbeck, 2010).

Materials and Methods

A 0.27-ha satsuma planting was established in June 2004 at the North Florida Research and Education Center (NFREC) in Quincy, FL. The experimental design was a 2 × 2 factorial with two satsuma (*C. unshiu* Marcovitch) cultivars (Owari and Brown Select) and two trifoliate orange [*P. trifoliata* (L.) Raf.] (‘Rubidoux’ and ‘Flying Dragon’) rootstocks arranged in a randomized complete block design. In this paper, we evaluated the performance of trees from the 7th to the 11th growing season. There were four adjacent trees of each scion rootstock combination in each of six rows. The experimental unit was the average of the four adjacent trees in each of six rows. Trees were spaced 4.6 and 6.1 m within and between rows, respectively. Soil type was an Orangeburg loamy fine sand (Typic Paleuduff, Silaceous). Trees were supplied with microjet irrigation and watered on an as needed basis. Fertilizer 10N–4.4P–8.3K plus micronutrients were applied at 0.9 kg/tree per application on or about 15 Mar., 1 May, 15 June, 1 Aug., and 15 Sept. The only freeze protection employed annually was by mounding the trunks of young trees with a pyramid or cone of soil to a height of 30–40 cm, although this was not performed after the Winter of 2008/09.

Satsumas were harvested on 12 to 16 Dec. 2010, 28 Nov. to 2 Dec. 2011, 6 to 10 Dec. 2012, 20 Nov. to 4 Dec. 2013, and 24 Nov. to 5 Dec. 2014. Harvest date was determined by the availability of labor after at least 90% of the fruit had a color change from green to yellow or orange. The color change was usually complete by late November. Tree height and average tree width (in north-south and east-west directions) were determined 7–9 May 2009, 9 Jan. 2012, and 4 Dec. 2014. Tree

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¹Corresponding author. E-mail: pcand@ufl.edu.

canopy area (cross-sectional area) was calculated as πr^2 . Yield/m² canopy area was calculated in 2010, 2012, and 2014 as yield/tree cross-sectional area. Tree canopy volume was calculated using the equation for one half of an oblate spheroid ($4/6 \pi r^2 h$) where r is the average tree cross-sectional radius and h is the height. Yield/m³ canopy volume was also calculated. Limbs that were in contact with the ground were pruned every year. Trees on *P. trifoliata* 'Rubidoux' were also pruned as necessary to maintain a 2.1-m alley to allow for the passage of farm equipment between rows. Trees were not pruned to control tree height.

Twenty representative fruit per tree were chosen from all fruit collected from each tree, and weighed as an estimate of average fruit weight. Five representative fruit per tree were juiced for measurements of soluble solids and pH. Soluble solids were measured with an Atago Model PAL-1 digital refractometer (www.atago.net Japan). The pH of juice was measured with an Orion Model 290A pH meter (Thermo Scientific, Beverly, MA).

Air temperatures were recorded at a height of 0.6 m every 15 min by the Florida Automated Weather Network located at the NFREC-Quincy within 0.5 km of the satsuma planting. There was no evidence of freeze damage for the duration of the experiment, except after an extremely early 19 Nov. 2014 freeze (−5.6 °C) and subsequent freeze events during 2015. On 4 Dec. 2014, cold injury was assessed for each tree as a visual estimate of defoliation from 1 to 10, with 1 corresponding to severe damage and 10 no damage. Several other freeze events occurred during the winter of 2014/15; the most noteworthy was on 8 Jan. 2015 (−7.0 °C). A visual estimate of defoliation was also conducted 24 Feb. and 17 Mar. to determine if differences in cold hardiness persisted at the end of the 2014/15 winter.

The planting was established as a 2 × 2 factorial design using combinations of two scions ('Brown Select' and 'Owari' satsuma) and two rootstocks ('Rubidoux' and 'Flying Dragon' trifoliolate orange) with six replications (rows) each containing four trees of each scion/rootstock combination randomized within rows. However, since there were no block effects for any of the variables measured, the block effect was dropped from the model. *P* values and least significant differences (*P* < 0.05) were presented.

Results and Discussion

Average yield for each scion rootstock combination was as follows: 'Brown Select'/'Flying Dragon' (66 kg/tree, 23.7 t·ha^{−1}); 'Brown Select'/'Rubidoux' (127 kg/tree, 45.3 t·ha^{−1}) 'Owari'/'Flying Dragon' (49 kg/tree, 17.6 t·ha^{−1}); 'Owari'/'Rubidoux' (109 kg/tree, 39.1 t·ha^{−1}) (Table 1). Overall average yield per tree varied from 88 to 143 kg for all years except for 2010, and the reason for a low yield in 2010 is not known. In a previous study of this planting, younger trees showed a tendency toward alternate bearing, and perhaps a very high yield

Table 1. Yield, canopy volume, and cross-sectional area of 'Brown Select' (BS) and 'Owari' (OW) satsuma scions on *Poncirus trifoliata* 'Flying Dragon' (FD) and 'Rubidoux' (RB) rootstocks.

Scion/rootstock	Yr				
	2010	2011	2012	2013	2014
Yield (kg/tree) ^a					
BS/FD	6.1	67.8	69.9	112.8	74.6
BS/RB	16.6	129.5	122.0	205.6	159.0
OW/FD	11.4	52.7	55.2	77.5	49.0
OW/RB	29.9	102.2	116.3	174.8	122.3
Statistics ^b					
LSD	10.0	27.1	21.1	31.4	24.7
Scion	0.013	0.031	NS	0.006	0.002
Rootstock	0.001	0.001	0.001	0.001	0.001
Tree canopy area (m ²)					
BS/FD	7.1	—	6.8	—	5.8
BS/RB	11.3	—	14.0	—	11.1
OW/FD	4.5	—	4.3	—	3.6
OW/RB	8.3	—	10.0	—	7.7
Statistics					
LSD	1.6	—	1.9	—	1.2
Scion	0.001	—	0.001	—	0.001
Rootstock	0.001	—	0.001	—	0.001
Tree canopy volume (m ³)					
BS/FD	10.5	—	16.1	—	12.2
BS/RB	19.7	—	44.2	—	30.2
OW/FD	4.77	—	8.2	—	5.9
OW/RB	13.3	—	27.8	—	18.5
Statistics					
LSD	3.2	—	15.2	—	8.3
Scion	0.001	—	0.001	—	0.001
Rootstock	0.001	—	0.001	—	0.001
Yield/tree canopy area (kg·m ^{−2})					
BS/FD	0.9	—	10.5	—	13.3
BS/RB	1.5	—	8.9	—	14.5
OW/FD	2.7	—	12.8	—	13.9
OW/RB	3.8	—	11.7	—	15.8
Statistics					
LSD	1.6	—	2.3	—	3.5
Scion	0.002	—	NS	—	NS
Rootstock	NS	—	0.004	—	NS
Yield/tree canopy volume (kg·m ^{−3})					
BS/FD	0.65	—	4.48	—	6.31
BS/RB	0.86	—	2.85	—	5.33
OW/FD	2.54	—	6.79	—	8.49
OW/RB	2.43	—	4.28	—	6.80
Statistics					
LSD	1.34	—	1.00	—	0.97
Scion	0.002	—	0.001	—	0.013
Rootstock	NS	—	0.001	—	0.052

^aTo calculate metric tons/ha, multiple kg/tree by 0.358.

^bThe statistics represent LSD at *P* = 0.05, and main effect *P* values.

recorded for 2009 (Andersen and Brodbeck, 2010) contributed, in part, to a low yield for 2010. Yield from 2011 to 2014 were fairly similar, with the exception of a ≈50% increase in 2013. The main effect of rootstock was significant (higher for 'Rubidoux') every year, and the scion main effect was significant from 2011 to 2014 (higher for 'Brown Select'). There were no significant scion × rootstock interactions for yield or any other variable measured in this study. 'Brown Select'/'Rubidoux' produced the highest yield in four of five years. Our yield data for satsumas on 'Rubidoux' were similar to that previously reported (Ebel et al., 2004; Nesbitt et al., 2000). For example, over an 11-year period 'Owari'/'Rubidoux' in Fairhope, AL produced an average yield of 116 kg/tree (Ebel et al., 2004), compared with our 109 kg/tree.

Tree canopy areas and canopy volumes were calculated in 2010, 2012, and 2014 to

assess yield efficiency on the basis of tree size (Table 1). Trees reached maximum size by 2010 to 2012, and differences in tree size reflect the pruning performed every year. Trees on 'Rubidoux' were pruned every year between rows to allow the passage of farm equipment. Also, satsumas have a prostrate growth habit and all limbs were removed that were contacting the ground. Main effects of scion and rootstock on canopy area were significant every year. 'Brown Select' was larger than 'Owari', and 'Rubidoux' produced larger trees than 'Flying Dragon'. There were main effects of scion and rootstock on canopy volume. Canopy volume was greater for 'Brown Select' than 'Owari', and higher for 'Rubidoux' than 'Flying Dragon'.

Yield per m² canopy was affected by scion in 2010 and by rootstock in 2012. In 2010 (a year with very low yield), yield per m² canopy was higher for 'Owari', and in 2012, yield efficiency was higher for 'Flying

Dragon'. There were no significant effects of scion or rootstock in 2014. There was much less disparity in yield per m² canopy compared with yield per tree. For example, yield per m² canopy in 2012 and 2014 varied only from 8.9 to 12.8 and from 13.3 to 15.8 kg·m⁻². Thus, satsumas on 'Flying Dragon' rootstocks when planted at a higher density can potentially produce similar yields per hectare to those on 'Rubidoux'. The main effects of scion and rootstock on canopy volume were significant in all three years ('Brown Select' was larger than 'Owari'). In 2012, there was also a rootstock effect with 'Flying Dragon' being higher than 'Rubidoux'. Yield per m³ canopy volume was higher for 'Brown Select' than 'Owari' for all three years, and was greater for 'Rubidoux' compared with 'Flying Dragon' in 2012. The significance for rootstock in 2014 was $P < 0.052$.

Interpretations of yield efficiency calculated on canopy area or canopy volume basis can lead to different management decisions by growers. Yield per hectare can be maximized by simply adjusting tree density at orchard establishment. Yield per canopy volume produced the opposite trend of yield per tree (or yield per hectare), indicating that the larger tree size of 'Brown Select' or 'Rubidoux' did not result in a proportional increase in yield. Thus, the density of fruit (yield per m³ canopy volume) was greater for 'Owari' than 'Brown Select', and greater for 'Flying Dragon' compared with 'Rubidoux'. These data provide justification to conduct additional research to determine the impacts of pruning to a maximum tree height on satsuma tree productivity.

Fruit weight was significantly greater for 'Brown Select' than 'Owari' in 2011, 2012, and 2014; there was no significant rootstock effect (Table 2). Average fruit weight was 157 and 146 g for 'Brown Select' and 'Owari', respectively. Fruit weight was greatest in 2010 (average = 205 g), most likely due to a very light crop load. Average fruit weight for 2011 to 2014 varied from 130 to 148 g. Ebel et al. (2004) reported that fruit weight of 'Owari' increased (perhaps 10%) from 1 Oct. to 24 Nov. They also reported that fruit weight varied considerably from year to year (i.e., 140 g in 2001 and 100 g in 2002).

The overall average soluble solids for the 5-year experiment were 10 °Brix. There was a scion effect in 2010 and 2011 (higher for 'Owari') and a rootstock effect in 2010, 2011, and 2012 (higher for 'Flying Dragon'). The °Brix of 'Brown Select' and 'Owari' in our study were slightly higher than that reported previously (Ebel et al., 2004) where the °Brix ranged from ≈8.0 (1 Oct.) to 9.5 (24 Nov.). The pH of juice ranged from 3.53 to 3.93. There was no scion or rootstock effect, although there was a trend for pH to decline slightly with tree age.

Satsuma genotypes did not sustain any visual symptoms of cold injury until the Fall/Winter of 2014/15 (Table 3). Microjet irrigation or other freeze protection methods were not employed from 2010 to 2015. Low temperatures recorded were as follows:

Table 2. Fruit weight, soluble solids, and pH of 'Brown Select' (BS) and 'Owari' (OW) satsuma scions on *Poncirus trifoliata* 'Flying Dragon' (FD) and 'Rubidoux' (RB) rootstocks.

Scion/rootstock	Yr				
	2010	2011	2012	2013	2014
Fruit weight (g)					
BS/FD	206	152	143	142	140
BS/RB	202	154	152	139	143
OW/FD	203	137	122	133	117
OW/RB	207	150	132	136	120
Statistics^z					
LSD	13	12	21	13	20
Scion	NS	0.03	0.009	NS	0.003
Rootstock	NS	NS	NS	NS	NS
Soluble solids (°Brix)					
BS/FD	10.6	8.8	9.7	10.3	11.7
BS/RB	8.9	8.1	9.0	10.2	11.8
OW/FD	11.0	9.5	9.7	9.9	11.1
OW/RB	10.1	8.8	9.1	9.9	11.2
Statistics					
LSD	0.5	0.6	0.5	0.5	0.9
Scion	0.038	0.004	NS	NS	k
Rootstock	0.002	0.002	0.002	NS	NS
pH					
BS/FD	3.86	3.75	3.63	3.61	3.63
BS/RB	3.88	3.72	3.59	3.57	3.56
OW/FD	3.93	3.70	3.59	3.56	3.54
OW/RB	3.82	3.73	3.54	3.53	3.56
Statistics					
LSD	0.08	0.05	0.07	0.08	0.08
Scion	NS	NS	NS	NS	NS
Rootstock	NS	NS	NS	NS	NS

^zThe statistics represent LSD at $P = 0.05$, and main effect P values.

11 Jan. 2010 (−9.4 °C), 14 Jan. 2011 (−7.4 °C), 4 Jan. 2012 (−7.0 °C), 17 Feb. 2013 (−4.3 °C), 7 Jan. 2014 (−7.4 °C), and 8 Jan. (−7.0 °C). On 19 Nov. 2014, a low temperature of −5.6 °C occurred at the NFREC-Quincy, which resulted in partial defoliation. This freeze event was noteworthy because trees were not yet acclimated to cold temperatures (Yelenosky, 1985, 1991). Cold hardiness was assessed on 4 Dec. 2014, 24 Feb. 2015, and 17 Mar. 2015 (Table 3). On 4 Dec., cold hardiness was greater for 'Brown Select' than 'Owari' and was greater for 'Rubidoux' than 'Flying Dragon'. This was followed by an advection freeze event on 8 Jan. 2015 (−7.0 °C), which resulted in slightly more defoliation. However, differences in the cold hardiness of scion or rootstock did not persist later that winter.

The degree of cold hardiness in citrus is strongly dependent on the acclimation to prior cold temperatures (Ebel et al., 2004, 2005; Yelenosky, 1985). An early freeze event or drastic fluctuations in temperature can exacerbate cold injury (Nesbitt et al., 2000; Yelenosky, 1985). The satsuma is generally acknowledged to be the most cold-tolerant commercial citrus (Andersen et al., 2012; McClendon, 2004; Yelenosky, 1985). Yelenosky (1991) reported that citrus trees begin the cold acclimation process at air temperatures ≤ 10 °C. Young and Peynado (1962) reported that satsumas cease the production of vegetative growth and become quiescent when temperatures fall below 15.5 °C. Under controlled conditions, satsumas have survived temperatures as low as −9.4 (Yelenosky, 1985) to −11.1 °C (Anderson et al., 1983; Gerber and Hashemi, 1965). In field studies, cold-acclimated satsuma trees have withstood −11.0 °C (Ferris and Richardson,

Table 3. Cold hardiness (visual rating of defoliation) of 'Brown Select' (BS) and 'Owari' (OW) satsumas on *Poncirus trifoliata* 'Flying Dragon' (FD) and 'Rubidoux' rootstocks.

Scion/rootstock	Date		
	4 Dec. 2014	24 Feb. 2015	17 Mar. 2015
BS/FD	8.5 ^z	7.6	6.3
BS/RB	9.3	7.9	7.7
OW/FD	7.7	6.8	5.7
OW/RB	8.4	7.7	7.3
Statistics^y			
LSD	0.7	0.8	1.1
Scion	0.018	NS	NS
Rootstock	0.031	NS	NS

^zThe statistics represent LSD at $P = 0.05$, and main effect P values.

^yCold hardiness rated on a scale from 1 to 10 with 1 corresponding to severe damage and 10 corresponding to no damage.

1923), but have sustained damage at −6.7 °C (Wimberg, 1948) when not sufficiently exposed to cold preconditions. Ebel et al. (2005) summarized freeze events in Fairhope, AL to satsumas over a 56-year period and reported that defoliation and a moderate level of limb dieback occurred at −7.1 to −10.5 °C, while severe damage and tree death occurred at −11.0 to −14.9 °C.

In conclusion, tree size was greater for 'Brown Select' compared with 'Owari', and for 'Rubidoux' compared with 'Flying Dragon'. Yield per tree (and yield per hectare) was much higher on 'Rubidoux' than 'Flying Dragon'; however, yields on a canopy area basis were usually fairly similar. Thus, yield differences can largely be mitigated by adjusting planting density at orchard establishment. The use of 'Flying Dragon' also offered the

advantage of increased harvest efficiency since trees were easily harvested without ladders. A more efficient planting density for trees on 'Flying Dragon' would be perhaps 3.0 and 4.6 m within and between rows, respectively. Ostensibly, freeze control by microjet irrigation can also be deployed in a more efficient manor for high-density trees. Fruit of 'Brown Select' were larger than 'Owari' for all years except 2010, a year of very low yield. Fruit size was unaffected by rootstock. The soluble solids were higher for trees on 'Flying Dragon' in three of five years, and for 'Owari' in two of five years. Cold injury was not observed in this study until a 19 Nov. 2014 freeze event (-5.6°C), and subsequent Jan. 2015 freezes (-7.0°C) resulted in partial defoliation. Cold hardiness when evaluated on 4 Dec. 2014 was greater for 'Brown Select' and 'Rubidoux'; however, there were no significant scion or rootstock effects when evaluated later in the winter.

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