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A Smaller Tree Doesn’t Necessarily Mean Reduced Yields: Analysis of Pedestrian Peach Orchard Systems and the Relationships Between Fruit Size, Crop Load, and Light Interception.

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A Smaller Tree Doesn't Necessarily Mean Reduced Yields: Analysis of Pedestrian Peach Orchard Systems and the Relationships Between Fruit Size, Crop Load, and Light Interception.

By

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THESIS

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ABSTRACT

Annual production costs for peaches (*Prunus persica*) grown in California are heavily dependent on the costs of labor for pruning, fruit thinning, and harvest, which is done from ladders because of large tree size (DeJong et al., 1999). To reduce production costs, dwarfing rootstocks have been developed which allow for the establishment of commercially viable orchards that eliminate need for ladders in orchard management. New dwarfing rootstocks for peach must reduce vigor, be graft compatible, and give good fruit production without reduction of fruit size and quality (Reighard, 2002). In April 2015, an orchard system trial was established at the University of California Kearney Agricultural Center, Parlier, CA. The research block consisted of two peach [*Prunus persica* (L.) Batsch] scion cultivars June Flame (early bearing cultivar) and August Flame (late bearing cultivar) grafted onto three different rootstock genotypes: HBOK 27(Controller 6, moderately dwarfing), P-30-135 (Controller 9, slightly dwarfing), and Nemaguard (CA commercial standard, vigorous). Controller 6 was used in two of four planting/pruning systems, each planting/pruning system had three replications per cultivar. Controller 6 systems were referred to as C-6 V and C-6 Quad. C-6 V was a high-density planting with an in-row spacing of 1.2m (1800 trees/hectare) and trained to the KAC-V perpendicular V system (DeJong et al., 1994). The C-6 Quad system was pruned to a Quad V with a larger in-row spacing of 2.4 m (895 trees/hectare). The Controller 9 Quad system (C-9 Quad) was identical to the C-6 Quad system with the only difference being their rootstock. Between-row spacing was 4.6m in all systems with size-controlling rootstocks. Nemaguard (Nema Quad) was used as the commercial standard rootstock with a planting density of 2.4m in-row spacing and 5.5m between-row spacing (750 trees/hectare). Systems with size-controlling rootstocks were topped to a height of 2.5m while the Nema Quad systems were topped at 3.5m. Harvest data were collected in the growing seasons 2017-2019. At harvest, fruit count per tree and total weight of fruit was recorded for each data tree. Results were analyzed to identify any significant differences in individual mean fruit weight, fruit produced per hectare, and the relationship between the two. Apart from the C-9 Quad system, yields per hectare and mean fruit size among systems were generally similar with both cultivars, during all three years. Since there were few performance differences among systems, and no consistent differences that occurred two or more years in a row, it appears that orchard systems with size-controlling rootstocks can produce yields on par with the current commercial standard systems. Further trials are necessary to determine long-term viability of these rootstocks and their production capabilities.

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INTRODUCTION

Overview

Annual production costs for peaches (*Prunus persica*) grown in California are heavily dependent on the costs of labor for pruning, fruit thinning, and harvest, which is done from ladders because of large tree size (DeJong et al., 1999). Expensive orchard management is not exclusive to peach and has been reported in other tree fruit crops such as apples, pear, plum, and cherry (Webster 2002, Weber 2001, Robinson and Lakso 1991). To counter these high management costs, size-controlling rootstocks have been developed to reduce tree size which permits the development of commercially viable orchards that eliminate the need for ladders. The elimination of ladders due to smaller tree size, combined with a high-density planting system, has been shown to decrease labor costs while simultaneously maintaining commercial standard yields (Webster 2002, DeJong et al., 1999). A concern has risen from previous rootstock studies that showed a trend for trees on size-controlling rootstocks to produce smaller fruit than trees on vigorous rootstocks (DeJong et al., 2011). Fruit size is vital for production and heavily influences, not only the price a grower will receive but, whether the crop is even acceptable for the fresh market.

Orchard yield is limited by the amount of photosynthetically active radiation (PAR) intercepted (Robinson and Lakso, 1991). These two factors are linearly related up to 50% light interception; after this light interception level, yield varies because other factors can become limiting (Wu¨nsche and Lakso 2000, Grossman and DeJong 1998). In peach, fruit size is negatively correlated with crop load and can be a limiting factor for obtaining marketable yields (Blanco et al., 1995, Johnson and Handley 1989, Rowe and Johnson 1990). Since size-controlling peach rootstocks are relatively new, few studies exist that analyze production capabilities such as the relationship between fruit size, fruit quantity, and light interception with pedestrian orchard systems using size-controlling rootstocks compared to conventional systems.

Rootstocks in Peach

In a fruit tree orchard system, individual trees are composed of two genetically different genotypes, one being the rootstock which includes the mass of the tree below the soil surface to a graft union about midway up the trunk. Rootstocks can be selected for pest resistance or tolerance towards adverse soil conditions, and they can also influence vigor and cropping (Webster 2002). The second portion of the tree is referred to as the scion and accounts for most of the above-ground mass, usually chosen for fruit production traits (late vs early harvest, clingstone vs freestone, fruit quality, etc.). Over the last 40+ years, the University of California has had a peach rootstock development program that has identified several promising size-controlling rootstocks which allow for the establishment of new commercially viable orchard systems (DeJong et al., 2011). New dwarfing rootstocks for peach must be graft compatible, reduce vigor, and not diminish marketable fruit production by reducing fruit size or quality (Reighard 2001). Previous peach rootstock trials monitored vigor control and grafting compatibility in conventional planting systems however, yield parameters such as fruit size and quantity have not been as thoroughly evaluated using these rootstocks in pedestrian orchard systems (DeJong et al., 1994, 2011). Fruit size is paramount in peach production as larger fruit, free of cosmetic imperfections, have a higher market demand and therefore higher market value (Day et al., 1990). It has been reported that peach fruit produced on trees with size-controlling rootstocks can tend to be smaller in size than fruit on trees with more vigorous rootstocks (DeJong et al., 2011).

Reduction in Hydraulic Conductance

Vascular tissue known as xylem is responsible for the movement of water and nutrients in all trees. In trees, every year a new ring of xylem forms surrounding the previous year's growth and water conduction in the xylem often occurs only in this outermost annual ring (Nobel 2020). It has been reported that size-controlling peach rootstocks contain a higher proportion of narrow diameter xylem vessels and fewer larger vessels when compared to more vigorous rootstocks in addition to having an increased axial diameter (Tombesi et al., 2009, 2011; Weibel and Reighard, 2009, Basile et al., 2007). Both characteristics create a reduction of hydraulic conductance in the size-controlling peach rootstocks compared to traditional, vigorous rootstocks. Reduced hydraulic conductance, as demonstrated by (Solari et al., 2006b) and (Solari and DeJong, 2006), can cause reductions in stem water potential during mid-day hours (Basile et al., 2003; Solari et al., 2006a) that can lead to a reduction in vegetative growth (Solari et al., 2006b, Weibel et at., 2003).

Potential Problems

An mean peach fruit's fresh weight is composed of over 80% water (Crisosto and Valero 2008). Thus, it is reasonable to assume a reduced hydraulic conductance created by size-controlling rootstocks could hinder fruit size. However, the relationship between fruit growth and water availability is dynamic and depends on the developmental stage of the fruit, the severity of water limitations, and the component of growth being considered (Berman and DeJong 1996). It has been reported that mild water stress applied during the intermediate developmental period of slow fruit growth has no effect on crop yields but significantly reduces vegetative growth in peach (Mitchell and Chalmers 1984). Fruit developmental stages may differ in time of initiation and duration among peach varieties, an example of this would be an early vs. late harvested cultivar as demonstrated by (Grossman and DeJong 1995). Fruit growth occurs in stages from fruit set to harvest, in all cultivars, and during the final growth phase of peach fruit is when 65% of a fruit's dry weight and 80% of a fruit's fresh weight are accumulated (Chalmers and Wilson 1978). Available water varies throughout the growing season, including diurnal fluctuations brought on by daily temperature fluctuations (Basile et al., 2003), day-to-day changes brought on by a shift in evapotranspiration (Ayars et al., 1999), and possible seasonal changes brought on by the formation of new xylem (Nobel 2020). Water conduction in the tree is largely dependent on newly formed xylem each spring and the new xylem cells are smaller in size-controlling rootstocks. It is thought that the spring flush of vegetative growth is limited in trees on size-controlling rootstocks compared to growth on vigorous rootstocks because of temporary reductions in root hydraulic conductance caused by smaller xylem vessels. A question that arises from these findings, does the reduction of water conductance in dwarfed peach trees also limit fruit growth?

Fruit Size vs. Crop Load

In peach production, fruit size is often manipulated with the use of a management practice known as fruit thinning. With fruit thinning, shortly after fruit set, a portion of immature fruit is removed from the tree to reduce carbohydrate competition among those remaining. It is widely recognized that fruit size is largely influenced by crop load, with larger fruit size obtained as the crop load is reduced (Reginato and Garcia de Cortazar 2007). Quality of fruit may also be affected by crop load, low-cropped trees have been shown to produce larger and firmer fruit than those from heavily cropped trees (Alcobendas et al., 2012). Although minor in comparison to carbohydrate demand, fruit size may also be diminished by inducing higher water stress with larger crop loads. An experiment by (Naor et al., 2001) found that larger crop loads were responsible for reducing midday stem water potential in nectarines. MacFayden et al.,(1996) concluded that an increased crop load also increased the fruit water deficit which may reduce fruit growth in peach. According to another study by (Inglese et al., 2002), rootstocks also influenced the crop load's effect on fruit size, and more vigorous rootstocks had larger fruits at specific crop loads. The forementioned findings relay the importance of better understanding the relationship between fruit size and crop load among vigorous and reduced-vigor rootstocks.

Light Interception and Total Yield

While crop load per tree is controlled by thinning, crop load per area (acre/hectare) is most influenced by planting density. The reduced vigor and overall size of trees on size-controlling rootstocks facilitates the establishment of high-density plantings (Webster 2002). The primary principle in establishing an appropriate planting density for an orchard using trees on size-controlling rootstocks is that total tree dry matter production and crop yield are related to total light interception (Agha and Buckley 1986, Hunter and Proctor 1986, Monteith 1977, Palmer, 1976, 1989, Palmer and Jackson 1974). This principle holds for essentially all crops (Monteith 1977). However, although higher light interception often leads to higher yields, yield may also vary significantly with other environmental stressors such as available water, nutrients, temperature, and amount of time the fruit has for growth (Lobell et al., 2007; Iannini et al., 2001; Layne and Bassi 2008, Jiménez and Diaz 2003). Orchard systems with increased planting densities have also been shown to reach maximum yield capacity earlier than conventional plantings since the trees are able to fill out their allotted space more quickly (DeJong et al., 2005). In a small trial using the 'Summer Bright" nectarine cultivar, trees that were pruned to a standard height of 12 to 13 feet or limited to heights of 8 or 9 feet produced similar sized fruit and crop yields. The reasoning for this was that, despite the height difference, both tree shapes had equal planar volume and therefore intercepted similar amounts of photosynthetically active radiation (PAR)(Day et al., 2005).

Purpose of Trial

The goal of this study was to address three production characteristics and their relationship with four different orchard systems. 1) Fruit size: can peach orchard systems using trees on size-controlling rootstocks produce fruit of equal size compared to orchard systems with trees on vigorous rootstocks? 2) Fruit count: if crop load per area is similar among size-controlling and vigorous systems is fruit size also similar? 3) PAR interception and yield: is there a difference in the relationship of fruit production vs light interception among orchard systems with vigorous rootstocks and those with size-controlling rootstocks? A better understanding of production capabilities will allow researchers and growers to better estimate the potential of an orchard system on size-controlling rootstocks as a commercially viable option.

MATERIALS AND METHODS

In April 2015, an orchard system trial was established at the University of California Kearney Agricultural Center, Parlier, CA. The research block consisted of two peach [*Prunus persica* (L.) Batsch] scion cultivars, June Flame (early bearing cultivar) and August Flame (late bearing cultivar) grafted onto three different rootstock genotypes: HBOK 27 (Controller 6, moderately dwarfing), P-30-135 (Controller 9, slightly dwarfing), and Nemaguard (CA vigorous commercial standard). Controller 6 was used in two of the four training systems (C-6 V and C-6 Quad). The C-6 V was a high-density planting system with an in-row spacing of 1.2m (1800 trees/hectare) and trained to the KAC-V perpendicular V pruning system (DeJong et al., 1994). The C-6 Quad system was pruned to a Quad V where four main scaffolds are selected in each tree and pruned to resemble an open vase, the system also had a larger in-row spacing of 2.4 m (895 trees/acre). The Controller 9 Quad system (C-9 Quad) was identical to the C-6 Quad system with the only difference being the rootstock. Between-row spacing was 4.6m in all systems using size-controlling rootstocks. Nemaguard was used as the commercial standard rootstock with a planting density of 2.4m in-row spacing and 5.5m between-row spacing (750 trees/hectare).

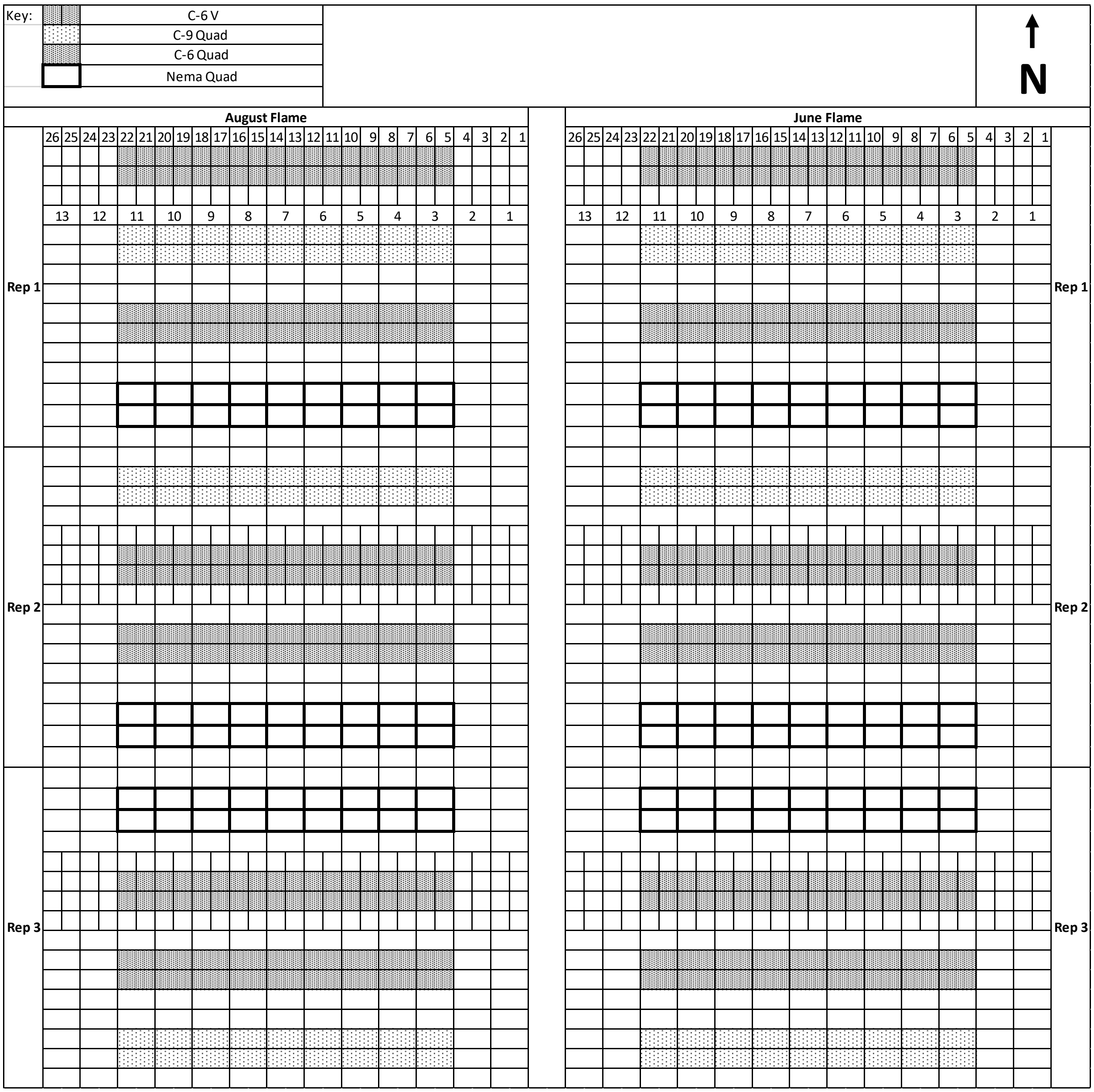
Shortly after harvest, orchard systems using size-controlling rootstocks were topped to a height of 2.5m while systems using the Nemaguard rootstock were topped at 3.5m. The four systems (C-6 V, C-6 Quad, C-9 Quad, and Nema Quad) were divided into three replications for each of the two scion cultivars making a total of eight unique orchard systems. Each replication consisted of four rows of trees with the northern and southern most rows used as guard rows, the first and last two trees in each data row (4 trees in the C-6 V systems) were also considered guard trees making nine trees in each of the two inner rows (18 trees in the C-6 V systems) the sample size per replication (Table 1). In total, each cultivar was represented by approximately 54 data trees (108 trees for the C-6V systems).

All systems with size-controlling rootstocks were irrigated and fertigated using sub-surface drip to maintain a soil moisture between -20 and -60 cbar throughout the growing season. Micro-sprinklers were used for irrigation and fertigation in the Nema Quad system. The soil at the site is a well-drained Hanford, fine sandy loam. Fertilizer and pesticides were applied according to standard horticultural practices. Weeds were controlled by mowing the row middles and applying herbicides to maintain a 1.5m wide weed-free strip down the tree rows. All systems received a light summer pruning and heavy dormant pruning to establish desired structure and improve light interception.

Approximately a week before harvest, total canopy light interception using a ACCUPAR LP-80 meter was measured in each plot. Harvest occurred on two or three separate days, depending on rootstock and cultivar, during the growing season due to variance in fruit maturity, as is common in stone fruit production. Each data tree was harvested individually, total quantity of fruit produced, and total fruit weight data were recorded which enabled calculation of mean fruit weight per tree. Harvest data were collected for growing seasons 2017-2019.

A linear model was created in R markdown for each season and cultivar's harvest. With each linear model, an ANOVA test was conducted using a 95% confidence level and Dunnett's method adjustments (Soetewey 2020) to identify significant differences among the four orchard systems for both scion cultivars. A true significant difference was concluded if the comparison between two systems had a p-value less than 0.05, a t-ratio greater than 1.68 (absolute), and a confidence level range that did not include 0.

Figure 1. Diagram of orchard layout and location of systems and replications within.



RESULTS

Fruit Size

During the 2017 harvest season for the June Flame cultivar, trees in all systems produced commercially acceptable mean fruit size, >200g per individual fruit (Table 2). The C-6 Quad system produced significantly larger fruit when compared to the Nema Quad system (Table 4). In the June Flame 2018 harvest, mean individual fruit weights in all systems were again > 200g, (Table 2). Although the C-9 Quad system produced large enough fruit for fresh market sale, the mean individual fruit weight was significantly less compared to fruit in the Nema Quad system (Table 4). The harvest season of 2019 for June Flame had individual fruit weight above 200g in all systems (Table 2). However, it should be noted that the C-6 V and C-9 Quad systems produced significantly smaller fruit compared to the Nema Quad system (Table 4). In all three seasons for the June Flame cultivar, the C-6 Quad system produced fruit of equal or larger size than the Nema Quad system.

In the 2017 harvest season for the August Flame cultivars, all systems with size-controlling rootstocks produced significantly larger fruit than the Nema Quad system (Table 5). In a few cases, fruit size exceeded 300g per fruit in systems with size controlling rootstocks, >50% larger than the minimum requirement for large sizing in the fresh market (Table 3). The harvest season of 2018 for August Flame may have been the most productive of all years for both cultivars, all systems exceeded 250g in mean individual fruit weight (Table 3). The C-6 Quad system had significantly larger fruit than the Nema Quad system while C-9 Quad had significantly smaller fruit (Table 5). In the 2019 harvest season all systems produced fruit sizes above 200g but were smaller than fruit from previous seasons (Table 3). Although the C-6 V and C-9 Quad systems did not differ significantly from the Nema Quad system, the C-6 Quad system produced significantly smaller fruit compared to the Nema Quad system (Table 5).

Fruit per Hectare

During the 2017 harvest season of the June Flame cultivar, the C-6 V and C-9 Quad systems produced significantly fewer fruit per hectare compared to the Nema Quad system. There was no significant difference between the C-6 Quad and Nema Quad systems (Table 2, Table 4). For June Flame in 2018 there were no significant differences in yield per hectare among the C-6 V, C-6 Quad and Nema Quad systems. The C-9 Quad system produced significantly fewer fruit per hectare compared to the Nema Quad system (Table 4). The 2019 June Flame harvest had close to identical fruit count per hectare between the C-6 Quad and Nema Quad systems (Table 2).Once again, the C-9 Quad was the only system that produced significantly fewer fruit per hectare compared to the Nema Quad system (Table 4).

In August Flame's harvest of 2017 there were no significant differences among systems using size-controlling rootstocks and the Nema Quad system for fruit produced per hectare (Table 5). In the 2018 harvest season for August Flame, the C-9 Quad system produced significantly fewer fruit per hectare compared to the Nema Quad system (Table 5). Meanwhile the C-6 V and C-6 Quad systems maintained similar fruit counts per hectare as the Nema Quad system. In the 2019 harvest for August Flame the C-6 V system produced significantly fewer fruit per hectare than the Nema Quad system. The C-6 Quad and C-9 Quad systems did not differ significantly for fruit count per hectare compared to the Nema Quad system (Table 5). It should be noted that during the 2019 harvest season some trees displayed signs of water stress in the field which may have hindered production and skewed results for that season.

Table 1. ANOVA results using a 95% confidence level for June Flame cultivar's mean individual fruit weight and fruit count per hectare. Results include estimated marginal mean (emmean), standard error (SE), degrees of freedom (df), lower confidence interval (Lower CL), upper confidence level (Upper CL) for each system.

June Flame 2017						
Mean Fruit Weight (g)	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	225	3.35	257	218	231
	C-6 V	210	2.37	257	205	214
	C-9 Quad	204	3.33	257	197	210
	Nema Quad	205	3.42	257	199	212
Fruit Count Per Hectare	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	90,635	6,336	257	78,157	103,112
	C-6 V	86,819	4,319	257	78,314	95,324
	C-9 Quad	70,504	6,027	257	58,635	82,373
	Nema Quad	110,997	6,125	257	98,935	123,059
June Flame 2018						
Mean Fruit Weight (g)	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	250	2.77	257	245	256
	C-6 V	245	1.99	257	241	249
	C-9 Quad	230	2.86	257	225	236
	Nema Quad	243	2.71	257	238	248
Fruit Count Per Hectare	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	101,026	5,627	257	89,947	112,106
	C-6 V	100,709	3,859	257	92,913	108,505
	C-9 Quad	55,404	5,592	257	44,392	66,415
	Nema Quad	91,257	5,467	257	80,491	102,022
June Flame 2019						
Mean Fruit Weight (g)	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	245	2.99	257	239	251
	C-6 V	228	2.15	257	224	232
	C-9 Quad	208	3.02	257	202	214
	Nema Quad	249	2.94	257	243	255
Fruit Count Per Hectare	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	151,452	5,082	257	141,444	161,459
	C-6 V	148,744	3,530	257	141,792	155,696
	C-9 Quad	116,406	5,289	257	105,990	126,822
	Nema Quad	150,950	5,126	257	140,859	161,044

Table 2. ANOVA results using a 95% confidence level for August Flame cultivar's mean individual fruit weight and fruit count per hectare. Results include estimated marginal mean (emmean), standard error (SE), degrees of freedom (df), lower confidence interval (Lower CL), upper confidence level (Upper CL) for each system.

August Flame 2017						
Mean Fruit Weight (g)	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	297	4.59	233	288	306
	C-6 V	282	3.24	233	276	289
	C-9 Quad	283	4.38	233	275	292
	Nema Quad	234	4.59	233	225	243
Fruit Count Per Hectare	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	83578	5,366	233	73,006	94,151
	C-6 V	85774	3,634	233	78,614	92,934
	C-9 Quad	66506	4,844	233	56,941	76,072
	Nema Quad	78136	5,932	233	66,450	89,823
August Flame 2018						
Mean Fruit Weight (g)	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	295	3.27	234	288	301
	C-6 V	289	2.36	234	284	294
	C-9 Quad	256	3.23	234	250	263
	Nema Quad	276	3.1	234	270	282
Fruit Count Per Hectare	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	115,034	4,925	234	105,331	124,738
	C-6 V	118,658	3,421	234	111,918	125,399
	C-9 Quad	64,125	4,504	234	55,252	72,999
	Nema Quad	112,410	4,510	234	103,525	121,296
August Flame 2019						
Mean Fruit Weight (g)	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	218	4.25	234	210	226
	C-6 V	238	3.09	234	232	244
	C-9 Quad	229	3.96	234	222	237
	Nema Quad	236	3.99	234	228	244
Fruit Count Per Hectare	Treatment	emmean	SE	df	Lower CL	Upper CL
	C-6 Quad	113,359	5,688	234	102,152	124,565
	C-6 V	105,800	4,017	234	97,886	113,714
	C-9 Quad	128,416	5,143	234	118,283	138,549
	Nema Quad	129,482	5,184	234	119,269	139,696

June Flame 2017								
Contrasted Fruit Mean Weight (g)	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	19.51	4.88	257	7.94	31.09	4.001	0.0002
	C-6V - Nema	4.43	4.17	257	-5.48	14.34	1.062	0.5728
	C-9Q - Nema	-1.72	4.88	257	-13.31	9.86	-0.354	0.9486
Contrasted Fruit Count Per Hectare	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	-20363	9092	257	-41945	1220	-2.24	0.0697
	C-6V - Nema	-24178	7490	257	-41957	-6399	-3.228	0.0041
	C-9Q - Nema	-40493	8547	257	-60783	-20203	-4.737	<.0001
June Flame 2018								
Contrasted Fruit Mean Weight (g)	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	7.43	3.87	257	-1.76	16.63	1.919	0.1432
	C-6V - Nema	1.94	3.36	257	-6.04	9.91	0.577	0.861
	C-9Q - Nema	-12.87	3.95	257	-22.26	-3.48	-3.255	0.0037
Contrasted Fruit Count Per Hectare	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	9770	7844	257	-8850	28390	1.246	0.4565
	C-6V - Nema	9453	6750	257	-6570	25475	1.4	0.3657
	C-9Q - Nema	-35853	7822	257	-54420	-17286	-4.584	<.0001
June Flame 2019								
Contrasted Fruit Mean Weight (g)	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	-4.1	4.2	257	-14.1	5.86	-0.976	0.628
	C-6V - Nema	-20.9	3.64	257	-29.5	-12.22	-5.729	<.0001
	C-9Q - Nema	-41.4	4.21	257	-51.4	-31.39	-9.826	<.0001
Contrasted Fruit Count Per Hectare	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	502	6910	257	-15902	16906	0.073	0.998
	C-6V - Nema	-2206	6356	257	-17294	12882	-0.347	0.9505
	C-9Q - Nema	-34544	7829	257	-53130	-15958	-4.412	<.0001

Table 3. Results of an ANOVA comparison between size-controlling systems and the Nema Quad system for the June Flame cultivar using a Dunettex method adjustment at a 95% confidence interval. Results include estimated marginal mean of the contrast (Estimate), standard error (SE), degrees of freedom (df), lower confidence interval (Lower CL), upper confidence level (Upper CL), t.ratio, and p.value.

August Flame 2017								
Contrasted Fruit Mean Weight (g)	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	63.3	6.69	233	47.4	79.2	9.467	<.0001
	C-6V - Nema	48.6	5.58	233	35.4	61.9	8.714	<.0001
	C-9Q - Nema	49.7	6.71	233	33.7	65.5	7.401	<.0001
Contrasted Fruit Count Per Hectare	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	5442	8777	233	-15407	26291	0.62	0.8396
	C-6V - Nema	7638	7155	233	-9357	24632	1.068	0.5692
	C-9Q - Nema	-11630	8288	233	-31317	8057	-1.402	0.3643
August Flame 2018								
Contrasted Fruit Mean Weight (g)	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	18.2	4.52	234	7.5	28.97	4.036	0.0002
	C-6V - Nema	12.7	3.84	234	3.61	21.85	3.315	0.0031
	C-9Q - Nema	-19.9	4.62	234	-30.9	-8.94	-4.308	0.0001
Contrasted Fruit Count Per Hectare	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	2624	6816	234	-13565	18813	0.385	0.9388
	C-6V - Nema	6248	5717	234	-7331	19828	1.093	0.5529
	C-9Q - Nema	-48285	6257	234	-63146	-33423	-7.717	<0.0001
August Flame 2019								
Contrasted Fruit Mean Weight (g)	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	-17.97	5.83	234	-31.8	-4.12	-3.082	0.0066
	C-6V - Nema	2.06	5.12	234	-10.1	14.22	0.402	0.9332
	C-9Q - Nema	-6.66	5.56	234	-19.9	6.55	-1.198	0.4862
Contrasted Fruit Count Per Hectare	Contrast	Estimate	SE	df	Lower CL	Upper CL	t. ratio	p. value
	C-6Q - Nema	-16124	7728	234	-34479	2231	-2.087	0.0998
	C-6V - Nema	-23682	6537	234	-39209	-8156	-3.623	0.001
	C-9Q - Nema	-1066	7313	234	-18437	16304	-0.146	0.9917

Table 3. Results of an ANOVA comparison between size-controlling systems and the Nema Quad system for the August Flame cultivar using a Dunettex method adjustment at a 95% confidence interval. Results include estimated marginal mean of the contrast (Estimate), standard error (SE), degrees of freedom (df), lower confidence interval (Lower CL), upper confidence level (Upper CL), t.ratio, and p.value.

Relationships between Fruit Size and Fruit per Hectare

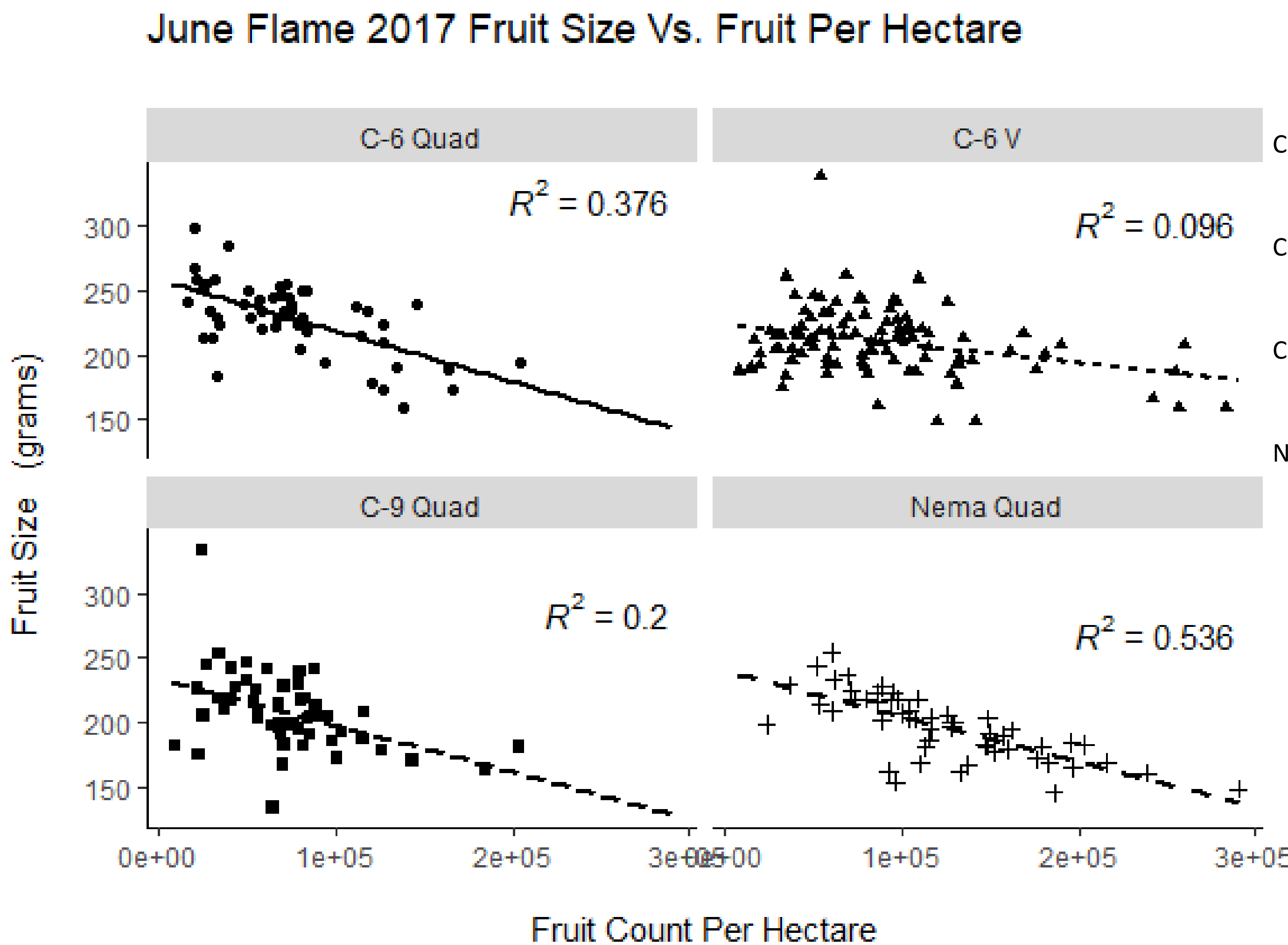
During the 2017 harvest of the June flame cultivar, there was a significant difference in the slope of the relationship between fruit size and fruit per hectare among the C-6 V and the Nema Quad systems (Table 6). Data from all systems fit a linear model that had a negative correlation between fruit size and fruit per hectare. Although a negative correlation was visible between fruit size and fruit per hectare in the C-6 V system, its magnitude was not as steep as with other systems in the same season (Figure 1). The following season, 2018, for June Flame there were significant differences in the fruit size vs. fruit per hectare relationship among systems. (Table 6). Even though no significant differences were detected with the ANOVA analysis, linear models were weak at representing the relationship between fruit size and fruit per hectare and all systems using size-controlling rootstocks had an R-squared value <0.15 (Figure 2). Continuing the trend from the previous season, in 2019 for June Flame, there were no significant differences in the slope of fruit size vs fruit per hectare relationship for any of the systems (Table 6). The contrast between the C-6 Quad system and Nema Quad system did have a t.ratio with a greater absolute value than 1.68, however the P.value for the same comparison was still greater than the designated alpha, > 0.05. In this same season the C-6 Quad system had the best fit for the linear model showing a negative correlation between fruit size and fruit per hectare. All other systems fit the model poorly and also did not indicate a clear negative correlation between fruit size and fruit count per hectare (Figure 3).

For the August Flame harvest of 2017, data from all systems fit linear models that showed a negative correlation between fruit size and fruit per hectare (Figure 4). Values for the t. ratio between the C-9 Quad and Nema Quad systems were beyond the absolute limit but had a P. value greater than the declared alpha, thus no significant differences were confirmed (Table 6).

For the 2018 harvest of August Flame there were no significant differences in the fruit size vs. fruit per hectare relationships detected among systems (Table 6). Linear models fit 2018 August Flame data better than other years and showed a clear negative correlation between fruit size and fruit per hectare (Figure 5). In 2019 there was a wide spread of mean fruit sizes per tree in the August Flame data and no significant differences occurred among systems for the relationship between fruit size and fruit per hectare (Table 6). Although the ANOVA analysis did not indicate differences among systems, linear models indicated a weak negative correlation between fruit size and fruit per hectare with all systems having near horizontal models accompanied by R-squared values <0.1 (Figure 6).

June Flame 2017						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	C-6Q - Nema	-0.091027	0.0817	254	-1.114	0.6814
	C-6V - Nema	-0.000408	0.088	254	-0.005	1
	C-9Q - Nema	-0.062763	0.091	254	-0.69	0.9009
June Flame 2018						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	C-6Q - Nema	0.0469	0.0788	254	0.596	0.9334
	C-6V - Nema	-0.0941	0.0852	254	-1.104	0.6872
	C-9Q - Nema	0.0981	0.1042	254	0.941	0.941
June Flame 2019						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	C-6Q - Nema	-0.2534	0.0897	254	-2.826	0.026
	C-6V - Nema	0.0136	0.1177	254	0.115	0.9994
	C-9Q - Nema	0.0919	0.0964	254	0.953	0.776
August Flame 2017						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	C-6Q - Nema	-0.179	0.117	230	-1.531	0.4207
	C-6V - Nema	-0.72	0.143	230	-5.036	<.0001
	C-9Q - Nema	-0.454	0.194	230	-2.341	0.0918
August Flame 2018						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	C-6Q - Nema	-0.2867	0.116	231	-2.472	0.067
	C-6V - Nema	-0.2184	0.108	231	-2.03	0.18
	C-9Q - Nema	-0.098	0.113	231	-0.866	-0.866
August Flame 2019						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	C-6Q - Nema	0.065	0.163	231	0.398	0.9785
	C-6V - Nema	-0.0691	0.152	231	-0.453	0.9689
	C-9Q - Nema	-0.0417	0.125	231	-0.333	0.9873

Table 5. Summary of comparison between dwarfing systems and Nemaguard for both cultivar's fruit size vs. fruit count per hectare linear slope.



C-6 Quad:
y = -0.0004x + 257.99

C-6 V:
y = -0.0001x + 222.95

C-9 Quad:
y = -0.0004x + 234.1

Nema Quad:
y = -0.0003x + 239.43

Figure 2. A scatterplot showing one method of determining efficiency by plotting the number of fruits harvested per hectare versus the mean weight of an individual fruit during the 2017 harvest season. As shown in crop load versus fruit weight, the more fruit produced by and orchard the smaller the mean weight of the fruit.

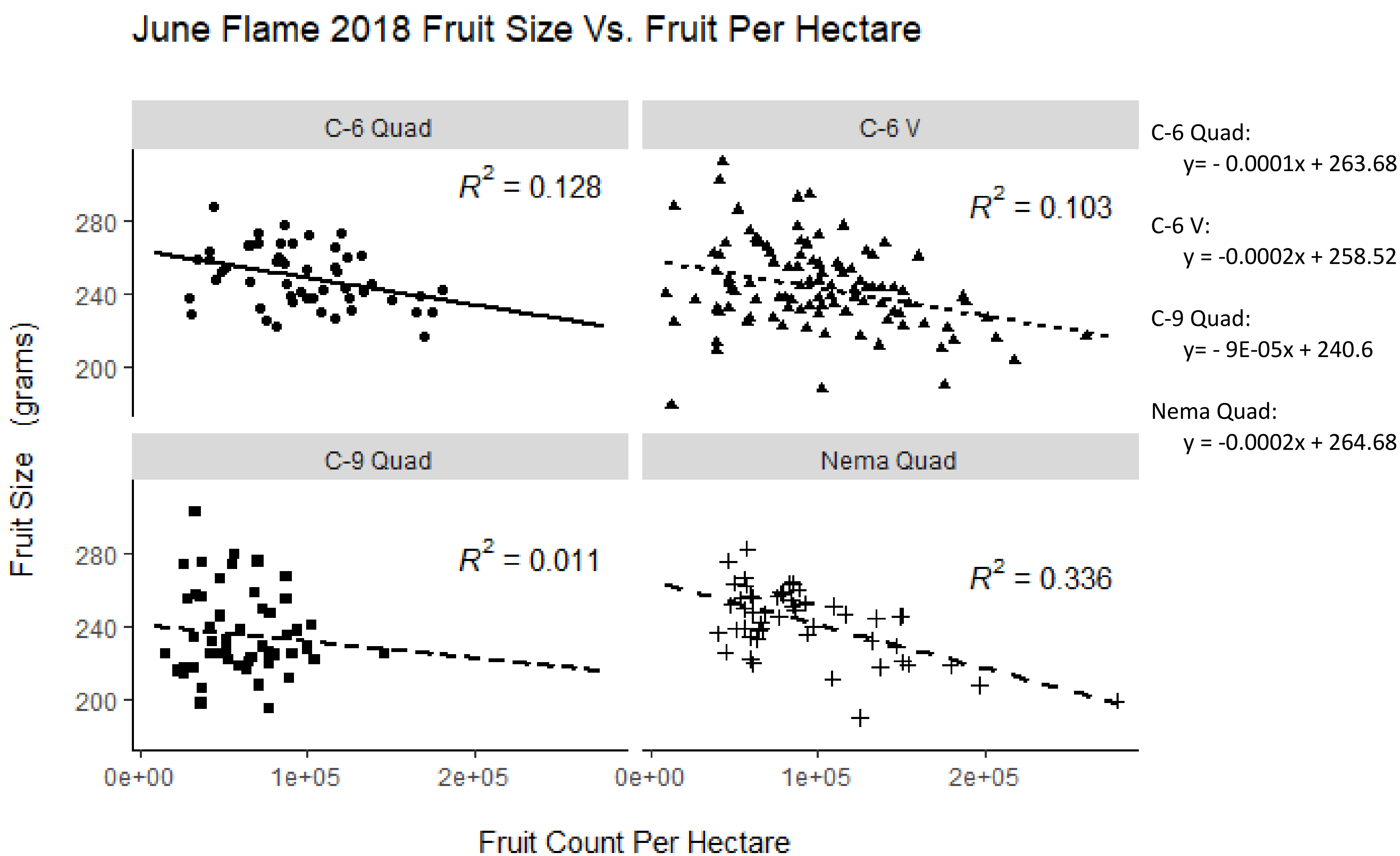


Figure 3. A scatterplot showing one method of determining efficiency by plotting the number of fruits harvested per hectare versus the mean weight of an individual fruit during the 2018 harvest season. As shown in crop load versus fruit weight, the more fruit produced by and orchard the smaller the mean weight of the fruit.

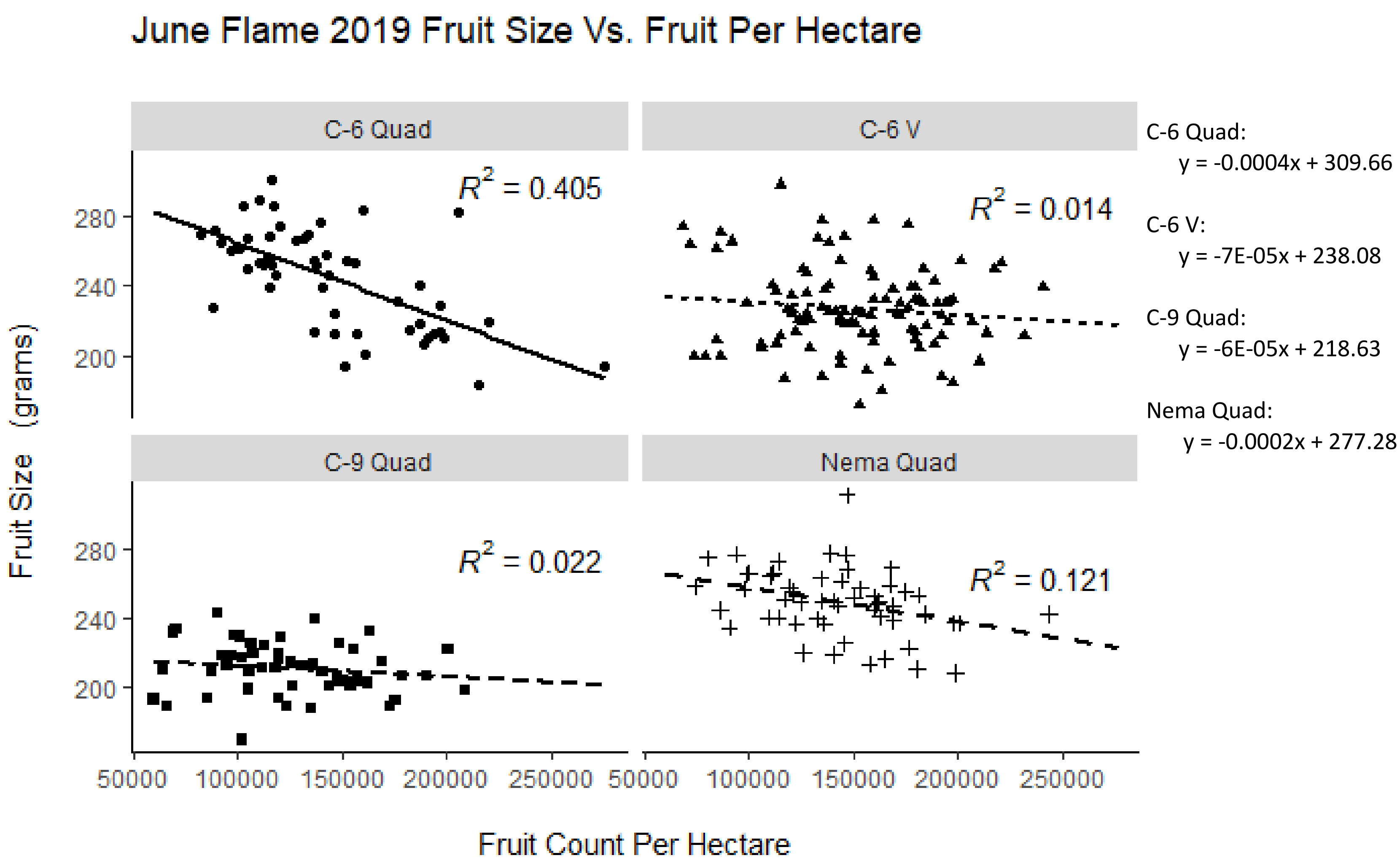
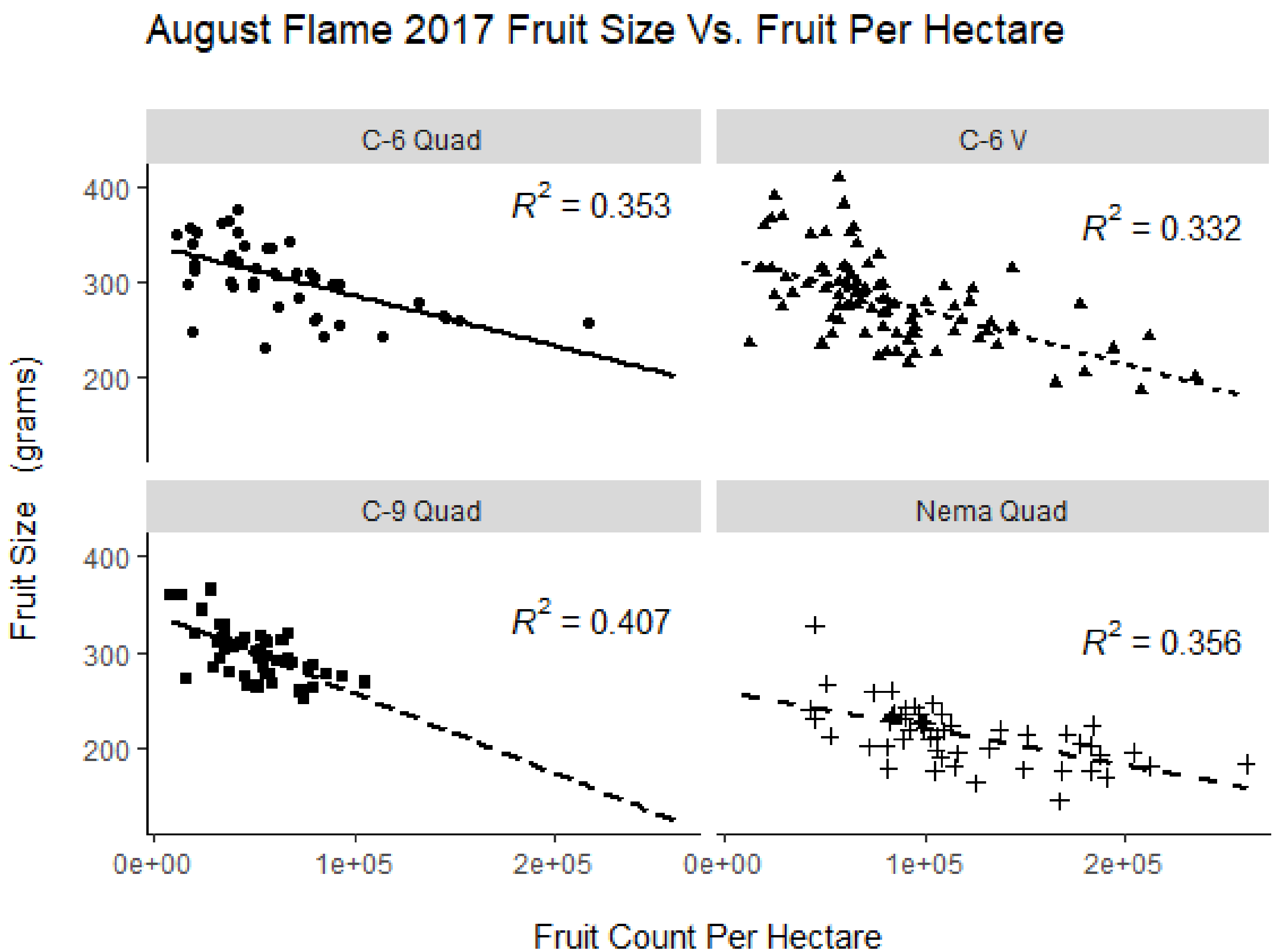


Figure 4. A scatterplot showing one method of determining efficiency by plotting the number of fruits harvested per hectare versus the mean weight of an individual fruit during the 2019 harvest season. As shown in crop load versus fruit weight, the more fruit produced by and orchard the smaller the mean weight of the fruit.



C-6 Quad:
y = -0.0005x + 338.32

C-6 V:
y = -0.0006x + 326.91

C-9 Quad:
y = -0.0006x + 326.91

Nema Quad:
y = -0.0004x + 259.22

Figure 5. A scatterplot showing one method of determining efficiency by plotting the number of fruits harvested per hectare versus the mean weight of an individual fruit during the 2017 harvest season. As shown in crop load versus fruit weight, the more fruit produced by and orchard the smaller the mean weight of the fruit.

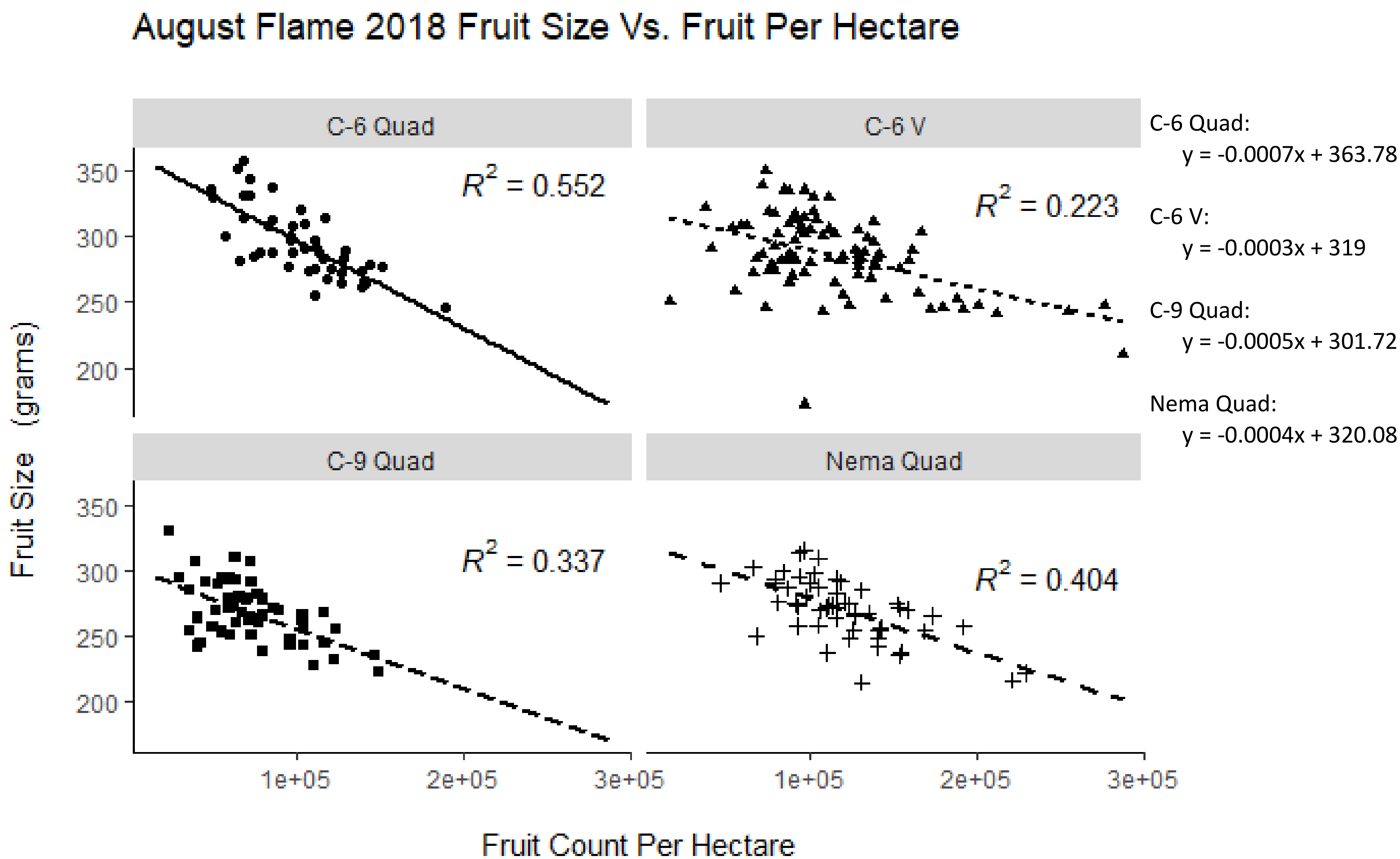


Figure 6. A scatterplot showing one method of determining efficiency by plotting the number of fruits harvested per hectare versus the mean weight of an individual fruit during the 2018 harvest season. As shown in crop load versus fruit weight, the more fruit produced by and orchard the smaller the mean weight of the fruit.

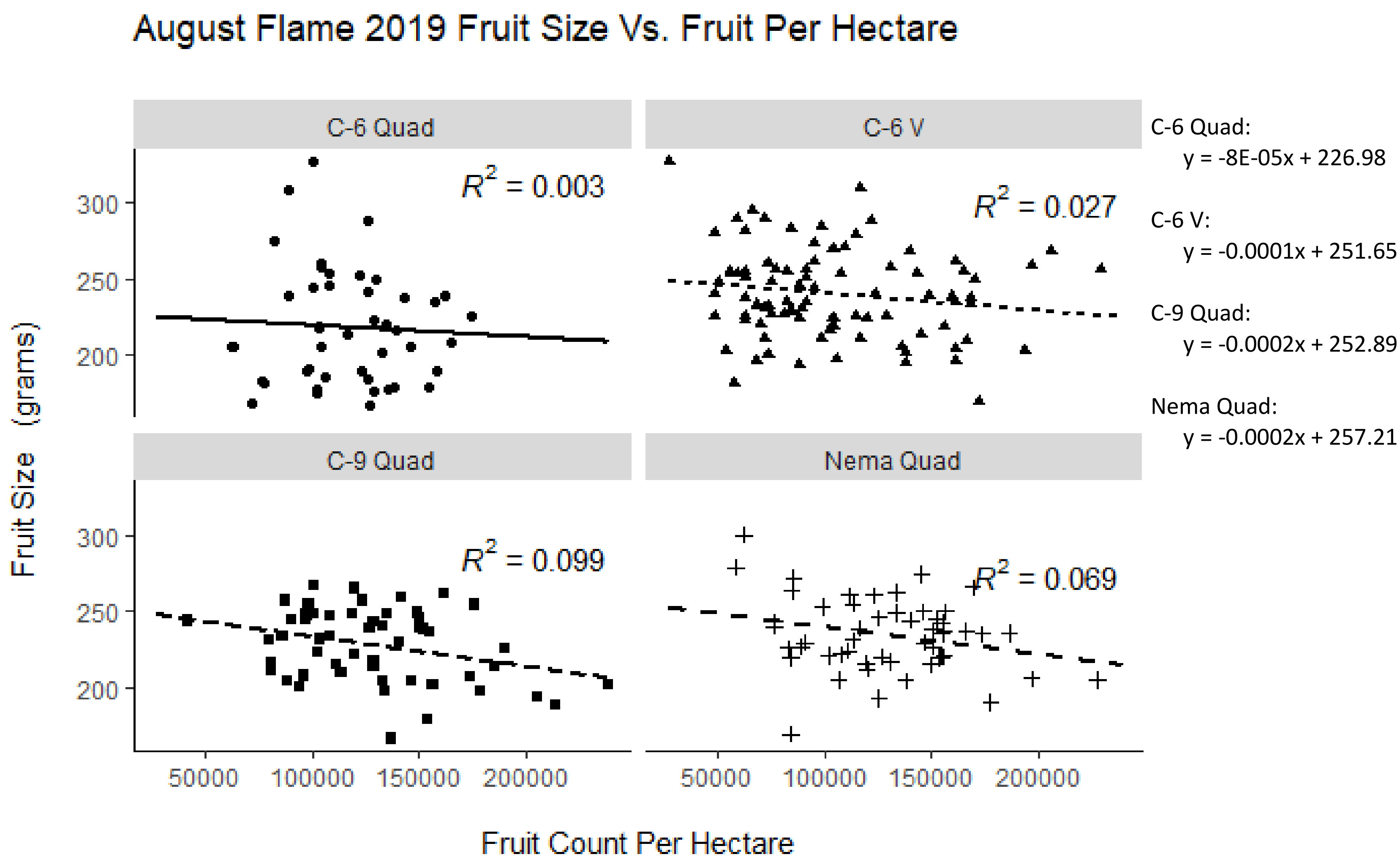


Figure 7. A scatterplot showing one method of determining efficiency by plotting the number of fruits harvested per hectare versus the mean weight of an individual fruit during the 2019 harvest season. As shown in crop load versus fruit weight, the more fruit produced by and orchard the smaller the mean weight of the fruit.

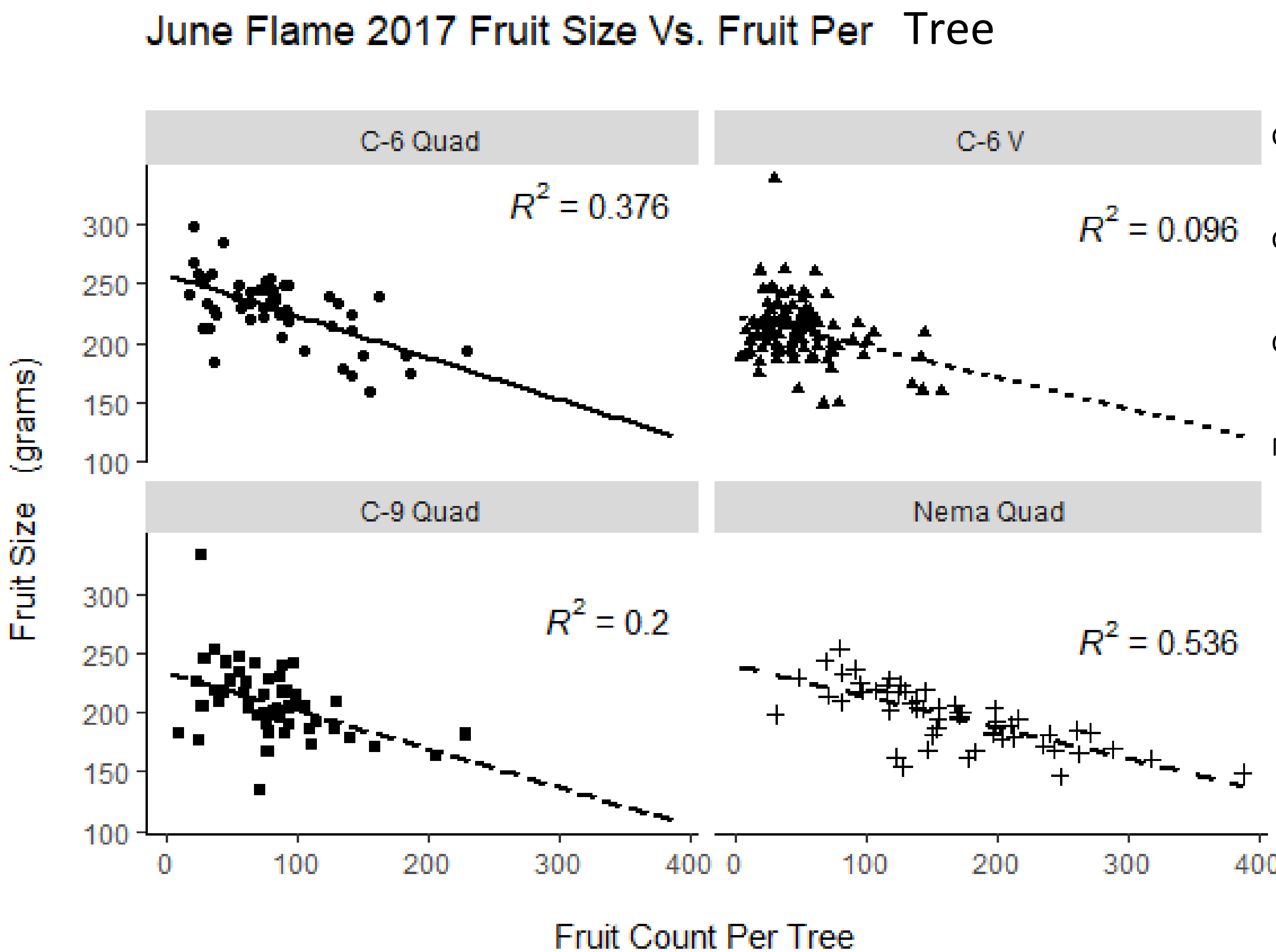
Relationships between Fruit Size and Fruit Per Tree

Although R-squared values for the linear models representing the relationship between fruit size and fruit per hectare were identical to those for fruit size and fruit per tree (Figures 1-12), there were differences detected in the contrast analysis for slopes (Table 7). Data for the June Flame 2017 and 2018 harvest seasons indicated no significant differences in the relationship for fruit size vs fruit count per tree among any of the systems (Table 7). In 2019 there was a significant difference in the data for the June Flame cultivar between the C-6 Quad system and the Nema Quad system (Table 7).

In the 2017 harvest data of August Flame there was a significant difference in the fruit size vs. fruit per tree relationship among C-6 V and Nema Quad systems (Table 7). The difference in 2017 data was visually apparent in the steeper slope indicated in the C-6 V system but that might be a result of the narrow range of fruit loads per tree in that system (Figure 10). No significant differences in the fruit size vs. crop load per tree relationship were detected in the harvest season of 2018, however both, C-6 Quad and C-6 V systems, had t. ratios indicating one may exist, but p-values remained above alpha, therefore a difference was not conclusive (Table 7). Data for the 2019 harvest of August Flame indicated no significant differences in this relationship between systems, and in fact, the fruit size vs. crop load per tree relationship were most similar among systems in this year compared to other years (Table 7).

June Flame 2017						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	6Q - N	-0.091027	0.0817	254	-1.114	0.6814
	6V - N	-0.000408	0.088	254	-0.005	1
	9 - N	-0.062763	0.091	254	-0.69	0.9009
June Flame 2018						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	6Q - N	0.0469	0.0788	254	0.596	0.9334
	6V - N	-0.0941	0.0852	254	-1.104	0.6872
	9 - N	0.0981	0.1042	254	0.941	0.941
June Flame 2019						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	6Q - N	-0.2534	0.0897	254	-2.826	0.026
	6V - N	0.0136	0.1177	254	0.115	0.9994
	9 - N	0.0919	0.0964	254	0.953	0.776
August Flame 2017						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	6Q - N	-0.179	0.117	230	-1.531	0.4207
	6V - N	-0.72	0.143	230	-5.036	<.0001
	9 - N	-0.454	0.194	230	-2.341	0.0918
August Flame 2018						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	6Q - N	-0.2867	0.116	231	-2.472	0.067
	6V - N	-0.2184	0.108	231	-2.03	0.18
	9 - N	-0.098	0.113	231	-0.866	-0.866
August Flame 2019						
Contrasted Slopes: Fruit Size Vs. Fruit per Tree	Contrast	Estimate	SE	df	t. ratio	p. value
	6Q - N	0.065	0.163	231	0.398	0.9785
	6V - N	-0.0691	0.152	231	-0.453	0.9689
	9 - N	-0.0417	0.125	231	-0.333	0.9873

Table 6. Summary of comparison between dwarfing systems and Nemaguard for both cultivar's fruit size vs fruit count per tree linear slope.



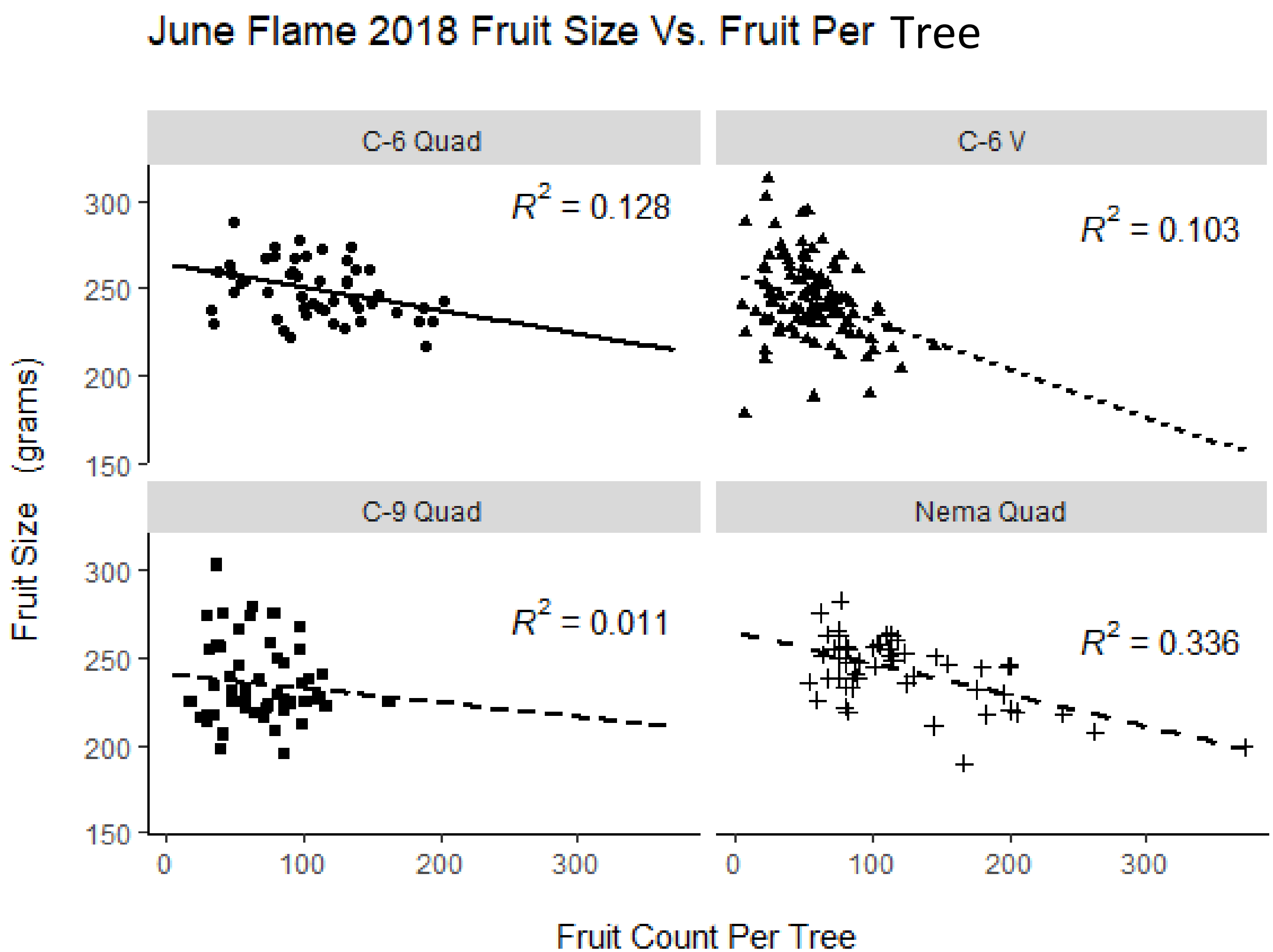
C-6 Quad:
$y = -0.352x + 257.99$

C-6 V:
$y = -0.2614x + 222.95$

C-9 Quad:
$y = -0.3237x + 234.1$

Nema Quad:
$y = -0.2609x + 239.43$

Figure 8. A scatterplot showing the more typical method of determining efficiency by plotting the number of fruits harvested per tree versus the mean weight of an individual fruit during the 2017 harvest season. As shown in crop load versus fruit weight, the more fruit on a tree, the smaller the mean weight of a fruit.



C-6 Quad:
y = -0.1331x + 263.68

C-6 V:
y = -0.2741x + 258.52

C-9 Quad:
y = -0.0819x + 240.6

Nema Quad:
y = -0.1331x + 263.68

Figure 9. A scatterplot showing the more typical method of determining efficiency by plotting the number of fruits harvested per tree versus the mean weight of an individual fruit during the 2018 harvest season. As shown in crop load versus fruit weight, the more fruit on a tree, the smaller the mean weight of a fruit.

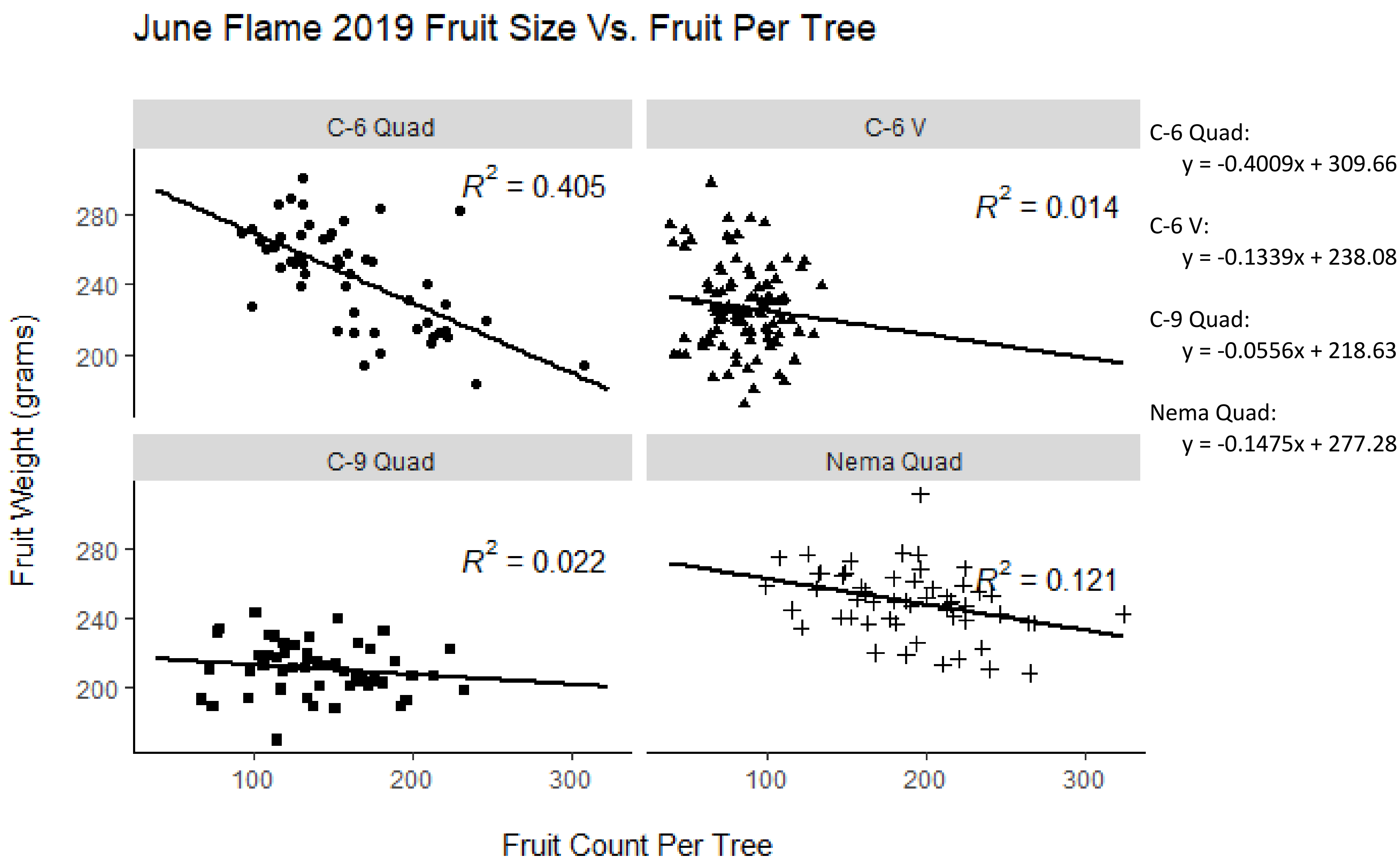
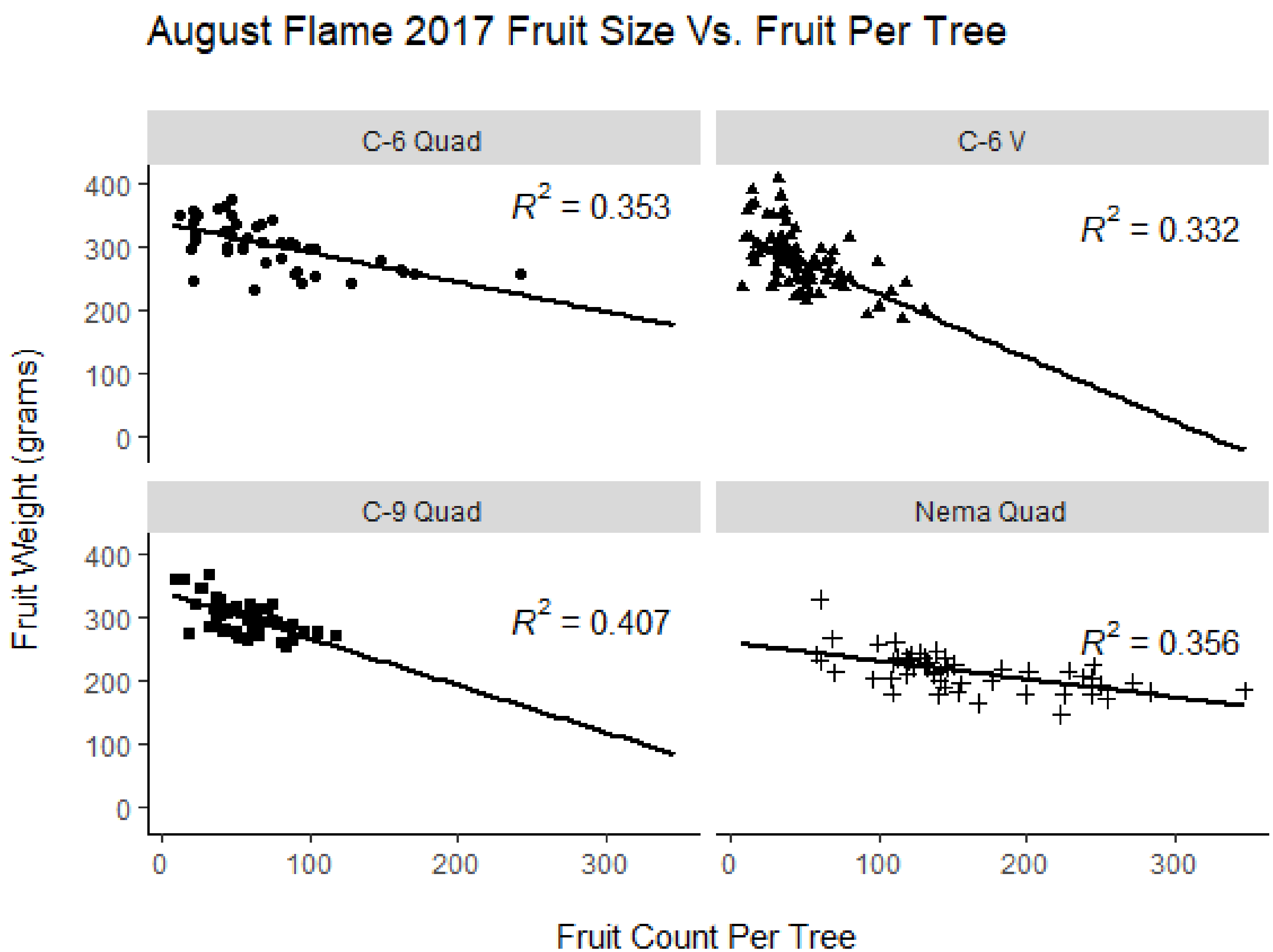


Figure 10. A scatterplot showing the more typical method of determining efficiency by plotting the number of fruits harvested per tree versus the mean weight of an individual fruit during the 2019 harvest season. As shown in crop load versus fruit weight, the more fruit on a tree, the smaller the mean weight of a fruit.



C-6 Quad:
$y = -0.1475x + 277.28$

C-6 V:
$y = -1.0094x + 326.91$

C-9 Quad:
$y = -0.7435x + 340.47$

Nema Quad:
$y = -0.4684x + 338.32$

Figure 11. A scatterplot showing the more typical method of determining efficiency by plotting the number of fruits harvested per tree versus the mean weight of an individual fruit during the 2017 harvest season. As shown in crop load versus fruit weight, the more fruit on a tree, the smaller the mean weight of a fruit.

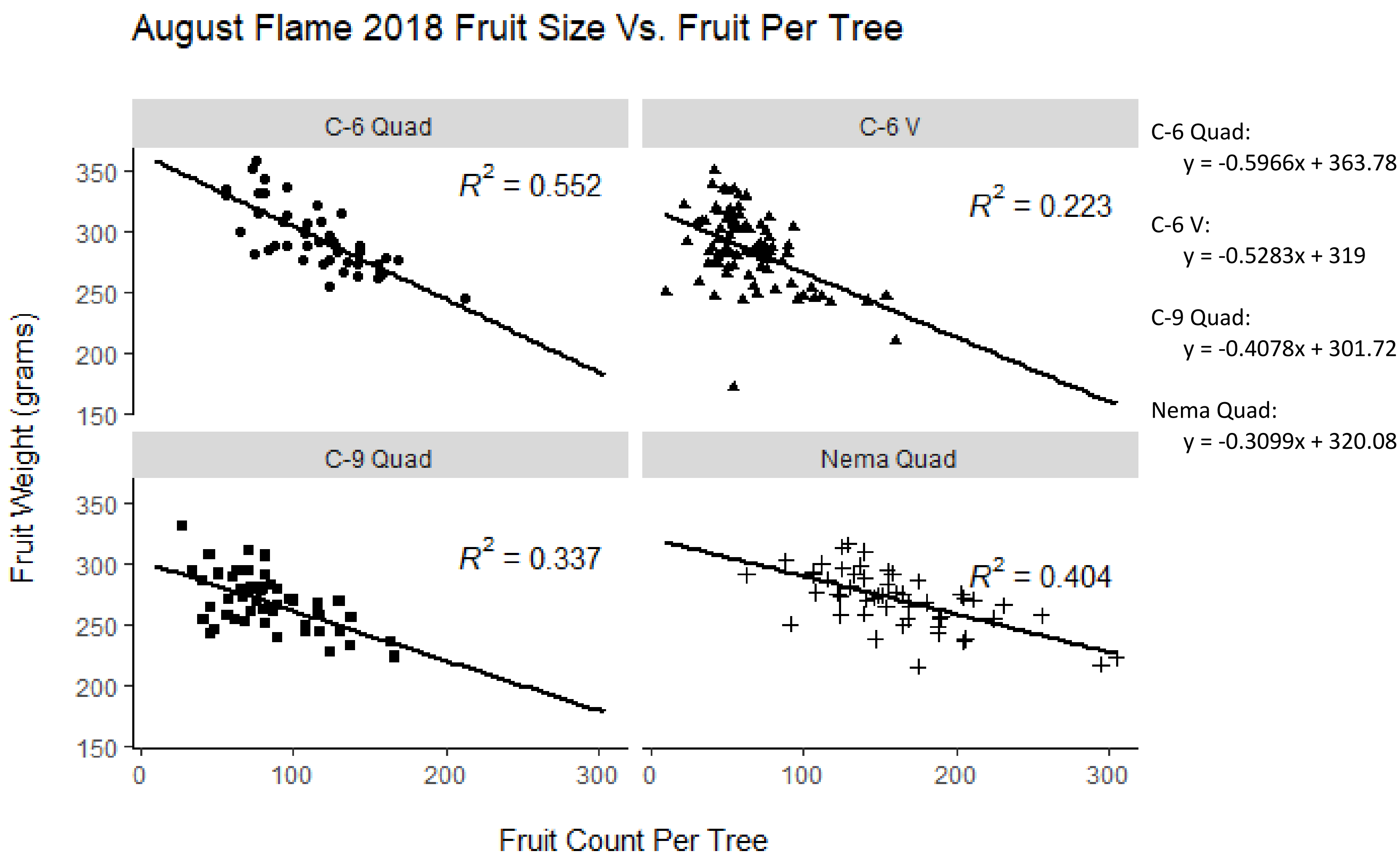
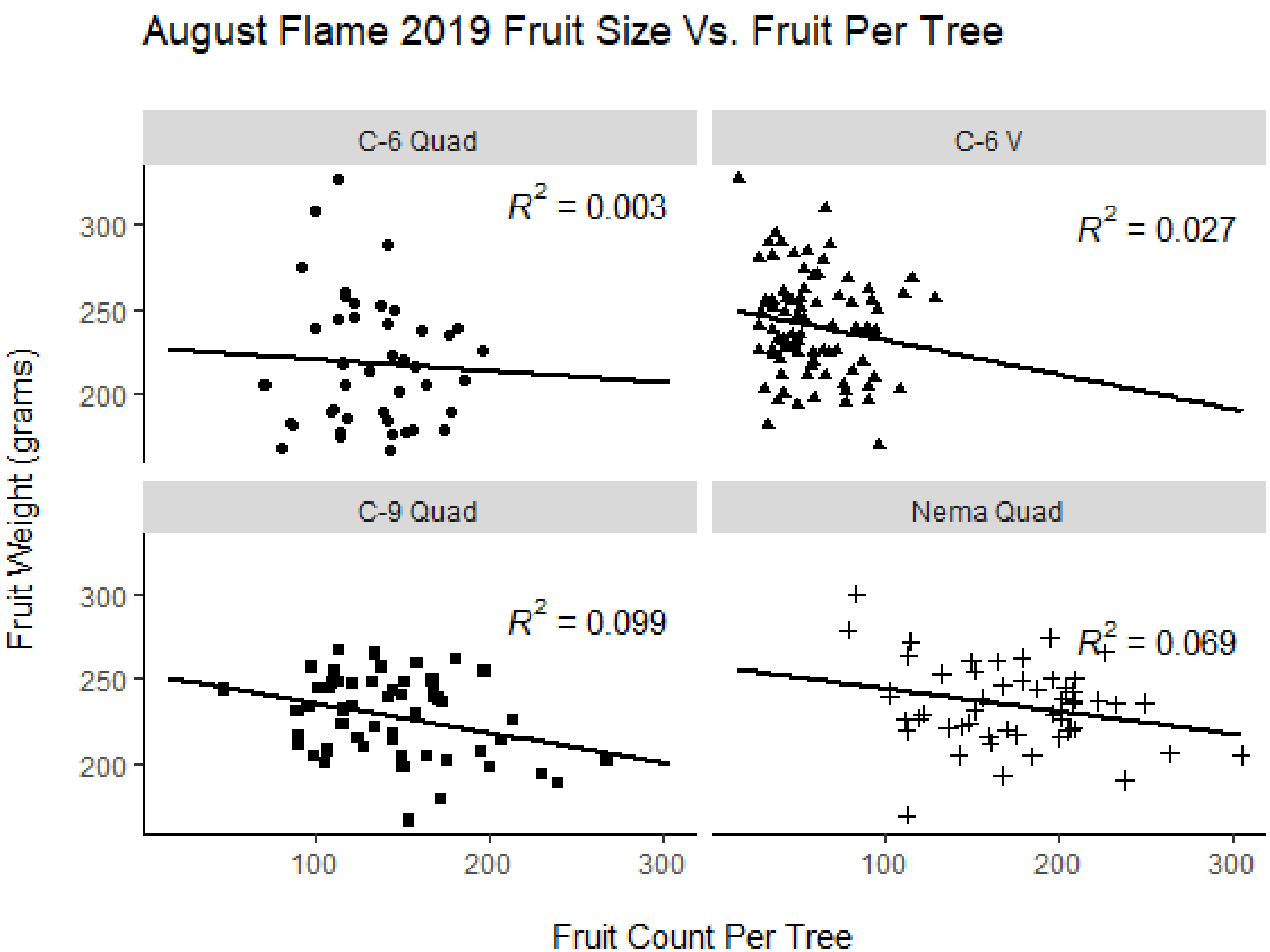


Figure 12. A scatterplot showing the more typical method of determining efficiency by plotting the number of fruits harvested per tree versus the mean weight of an individual fruit during the 2018 harvest season. As shown in crop load versus fruit weight, the more fruit on a tree, the smaller the mean weight of a fruit.



C-6 Quad:

y = -0.0676x + 226.98

C-6 V:

y = -0.2018x + 251.65

C-9 Quad:

y = -0.1743x + 252.89

Nema Quad:

y = -0.1326x + 257.21

Figure 13. A scatterplot showing the more typical method of determining efficiency by plotting the number of fruits harvested per tree versus the mean weight of an individual fruit during the 2019 harvest season. As shown in crop load versus fruit weight, the more fruit on a tree, the smaller the mean weight of a fruit.

PAR interception Vs. Yield per Area

A relationship between light (PAR) interception and yield was most apparent in the June Flame cultivar with the C-6 Quad and C-9 Quad systems which produced data that fit linear models with the highest R-squared values. The linear model for the Nema Quad system had the steepest slope but not a very strong R-squared value. Data from the C-6 V system had a poor fit with a linear model. Interestingly the systems with data that had a poor fit to the model also had the highest % light interception, often >50% (Figure 13). August Flame cultivars showed a similar pattern for the relationship between amount of light intercepted and yield. Data from the Nema Quad and C-6 V systems had poor fits to the linear models but also had the highest light interception. Data from the C-9 Quad system had a moderate correlation between PAR and yield, fit the model best. The C-6 Quad system is an apparent outlier, having a value of almost 5 Kg/m2 yield with only about 40% light interception, and a very slight negative correlation between the two parameters (Figure 14). Both of the C-6 V systems with the June and August flame cultivars had trends as shown in previous research, higher density systems were able to intercept a higher proportion of light during earlier years because the trees fill their allotted space more quickly, (Table 8) (DeJong et al., 2011).

June Flame						
2017	Treatment	PAR	Fruit Count	Yield (Kg)	Fruit Size (g)	Yield per Area (Kg/m2)
	C-6 Quad	49%	1462	317.7	225	3.17
	C-6 V	57%	1665	340	203	3.38
	C-9 Quad	31%	1439	282	197	2.81
	Nema Quad	47%	2947	554	189	4.60
2018	Treatment	PAR	Fruit Count	Yield (Kg)	Fruit Size (g)	Yield per Area (Kg/m2)
	C-6 Quad	39%	2193	418	193	3.70
	C-6 V	43%	2570	486	191	4.15
	C-9 Quad	41%	2382	452	192	3.93
	Nema Quad	56%	2188	520	239	4.32
2019	Treatment	PAR	Fruit Count	Yield (Kg)	Fruit Size (g)	Yield per Area (Kg/m2)
	C-6 Quad	63%	2809	673	242	6.71
	C-6 V	61%	2892	654	226	6.52
	C-9 Quad	60%	2503	526	210	5.24
	Nema Quad	59%	3414	846	248	7.02
August Flame						
2017	Treatment	PAR	Fruit Count	Yield (Kg)	Fruit Size (g)	Yield per Area (Kg/m2)
	C-6 Quad	65%	1073	312	297	3.11
	C-6 V	63%	1333	356	276	3.54
	C-9 Quad	53%	1019	296	293	2.95
	Nema Quad	55%	2710	560	209	4.65
2018	Treatment	PAR	Fruit Count	Yield (Kg)	Fruit Size (g)	Yield per Area (Kg/m2)
	C-6 Quad	60%	1723	499	290	4.97
	C-6 V	64%	1892	529	281	5.27
	C-9 Quad	64%	1458	384	264	3.82
	Nema Quad	57%	2779	739	267	6.14
2019	Treatment	PAR	Fruit Count	Yield (Kg)	Fruit Size (g)	Yield per Area (Kg/m2)
	C-6 Quad	56%	1955	426	218	4.24
	C-6 V	71%	1717	409	239	4.07
	C-9 Quad	71%	2555	576.22	227	5.74
	Nema Quad	57%	2979	693	234	5.76

Table 7. Breakdown of each system's mean amount of light interception, fruit count, total weight, fruit size, and yield per area for each plot

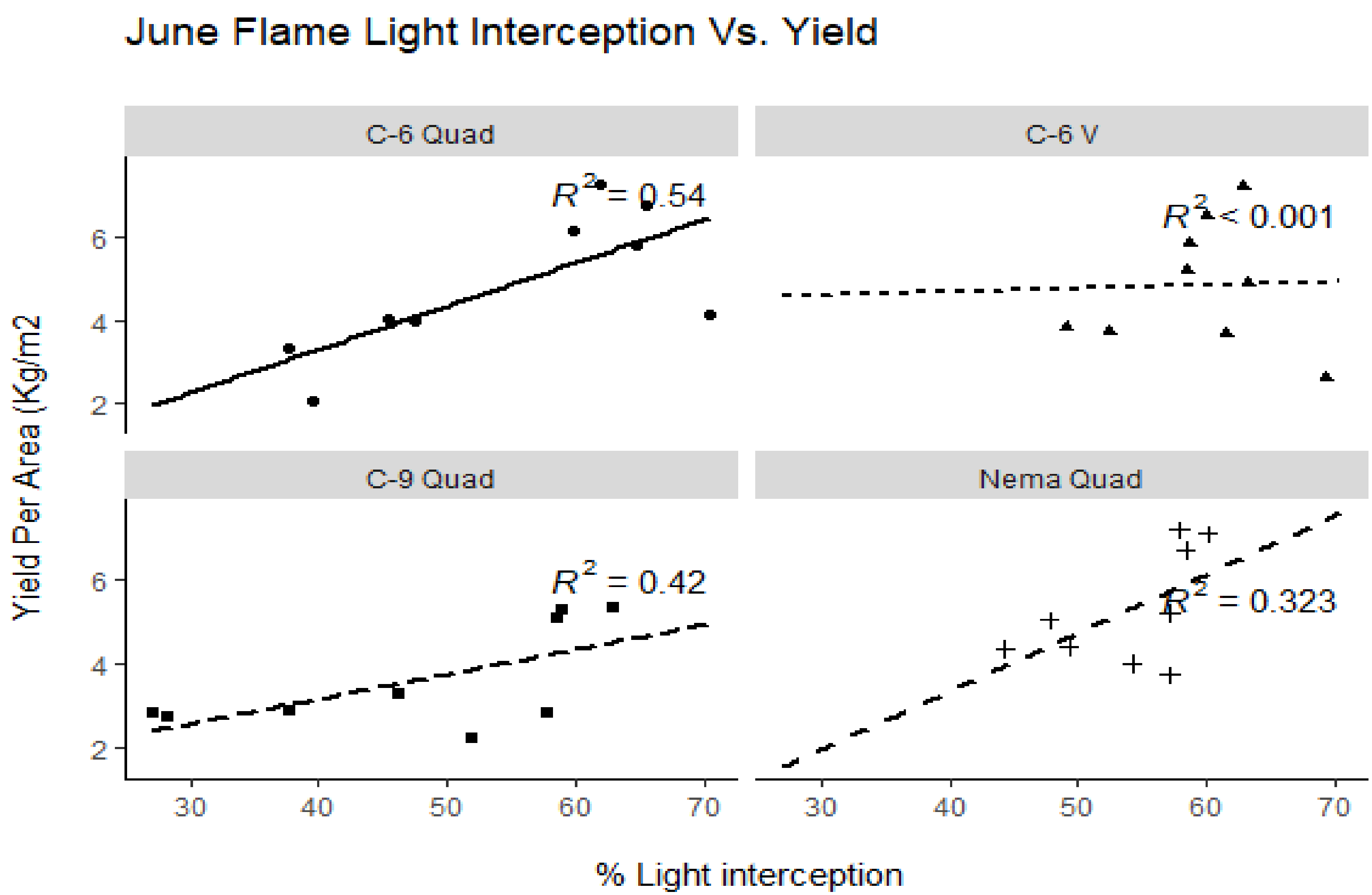


Figure 14. Mean canopy light interception vs yield per area (Kg/m2) for June Flame for all three seasons.

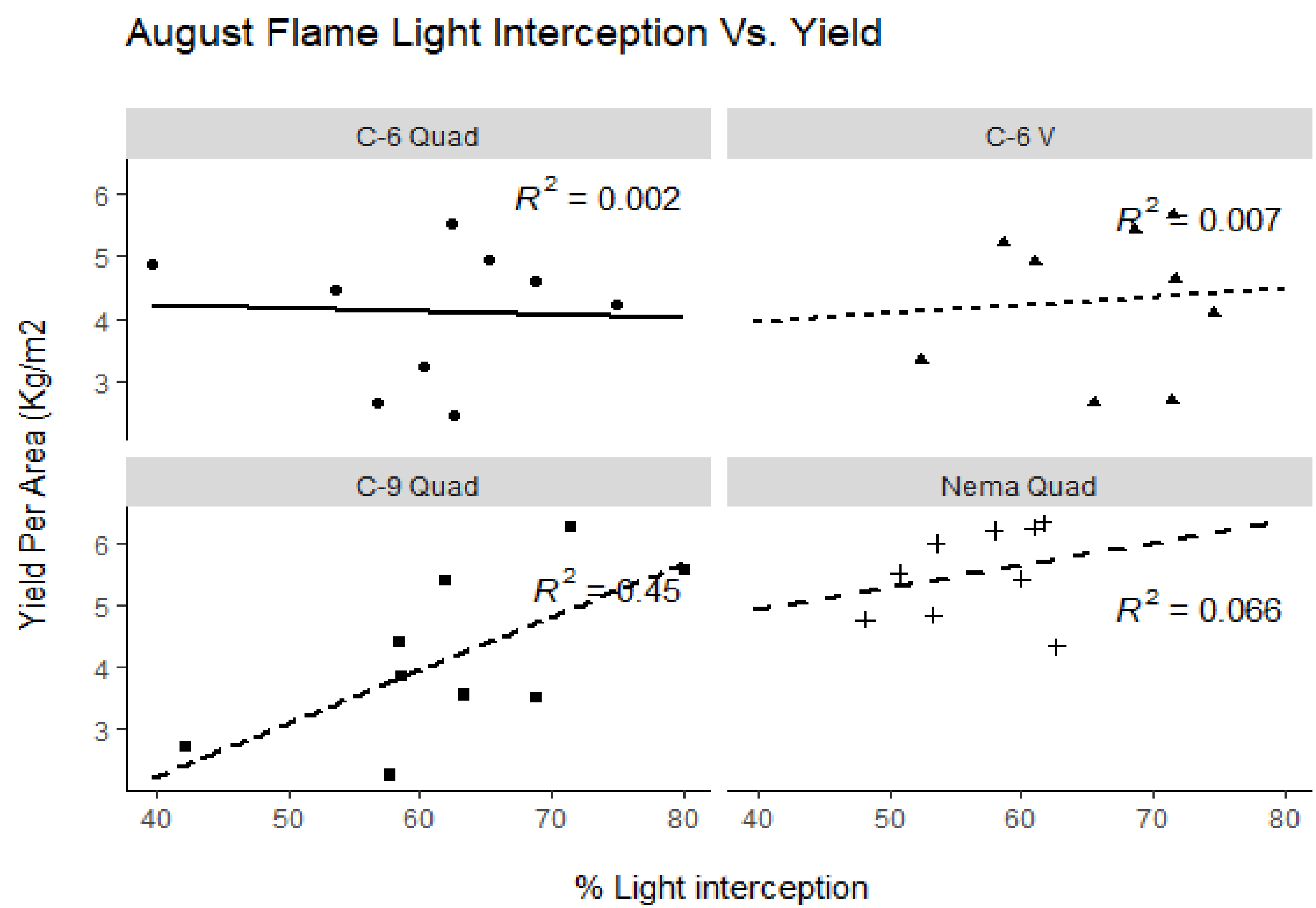


Figure 15. Mean canopy light interception vs yield per area (Kg/m2) for August Flame for all three seasons.

DISCUSSION

Fruit Size

The mean fruit size for the June Flame cultivar in 2017 was similar among all systems, most likely a result of consistent thinning resulting in the desired crop loads per tree. In 2018 the mean fruit size for June Flame systems was exceptionally large, especially for an early bearing cultivar. Considering that the C-6 Quad and C-6 V systems had some of the largest fruit sizes provides strong evidence that size-controlling rootstocks are not always associated with reductions in fruit size. The C-9 system had poor performance in the trial but, with its success in previous studies (DeJong et al., 1994, 1999, 2011) and how well systems with the more size controlling rootstocks performed in this trial, it is likely not due to the reduced hydraulic conductance associated with size controlling rootstocks (Solari et al., 2006b, Weibel et at., 2003). June Flame systems in 2019 closely mirrored fruit sizes from the previous season, providing more confidence that any reduction in fruit size compared to the Nema Quad system is unlikely a result of size controlling rootstocks.

The results from the June Flame cultivar are most promising because there were concerns that the size-controlling rootstocks may have the potential to have negative effects on fruit size in early maturing cultivars. With how quickly early bearing cultivars must set and mature fruit during the spring flush growth, there was concern that reduced hydraulic conductance associated with undeveloped xylem would influence fruit size (DeJong et al., 2011). However, this trial did not provide evidence that early maturing cultivars on the size-controlling rootstocks produce smaller sized fruit compared to those on more vigorous rootstocks.

With the August Flame cultivar, systems using size-controlling rootstocks also were not found to diminish fruit size in this later maturing cultivar. In 2017 all dwarfing systems performed beyond expectations. With fruit sizes reaching almost 300 grams, it is likely that thinning may have been excessive and crop load per tree could have been increased while still reaching above minimum fresh market size requirements. The strong yield for high density plantings of August Flame during the 2017 harvest supports reports of higher density plantings reaching full cropping sooner than low density systems (DeJong et al., 1999). By 2018 the Nema Quad systems were able to produce fruit of similar size compared to systems with size-controlling rootstocks, but fruit were still not the largest. Large fruit sizes indicate that the amount of thinning could, again, have been reduced. In 2019 there was noticeable water stress in the field due to some irrigation problems, but the magnitude of the problem was not documented. It is likely the water stress was a reason for some of the smaller fruit sizes compared to previous years. Most interesting about the 2019 season was the performance of the C-9 Quad system and how after producing significantly smaller and fewer fruit in both previous seasons, it now had the largest mean fruit size. Overall, systems with size-controlling rootstocks performed well and on par compared to the Nema Quad system giving confidence that reduced hydraulic conductance associated with size-controlling rootstocks does not necessarily reduce fruit size in either early or late bearing cultivars such as June and August Flame.

Fruit Per Hectare

In addition to fruit size, number of fruits produced was not diminished in systems using size-controlling rootstocks compared to the Nema Quad system. The 2017 harvest for the June Flame cultivar was the only harvest that the Nema Quad system produced significantly more fruit per hectare than all other systems. These results differ with previous studies where KAC_V plantings reached full cropping at the same time as trees on vigorous rootstocks but, systems with size-controlling rootstocks pruned to an open-vase lagged behind more vigorous rootstocks (DeJong 2005). By 2018 the C-6 Quad and C-6 V systems produced more fruit per hectare than the Nema Quad system while the C-9 system had a substantially reduced yield compared to all other systems. Fruit count could have been increased had thinning been more consistently managed but since fruit sizes were also similar, results would not likely have changed in terms of differences between systems. 2019 was by far the most productive harvest for June Flame, with strong yields in the C-6 Quad, C-6 V, and Nema Quad systems while the C-9 Quad was less productive. Due to the lack of significant differences among systems there is no evidence that a reduction in either fruit size or fruit count would be expected in an orchard system using size-controlling rootstocks compared to a system with more vigorous rootstocks, when using appropriate management practices and planting densities adjusted for the reduced tree size.

Results from the 2017 harvest of August Flame were much more aligned with previous studies where systems with high-density plantings reached maximum yield capacity earlier than in low-density systems (DeJong et al., 1999). It is possible that if the amount of thinning in the C-6 Quad and C-6 V systems had not been as severe, they could have produced significantly more fruit than the Nema Quad system. The C-9 Quad system had the lowest fruit count but, with such a large fruit size, could have potentially produced a fruit count similar to the Nema Quad system if thinning had been done more precisely. In 2018 the fruit count was similar in the C-6 Quad, C-6 V, and Nema Quad systems while the C-9 Quad system had half the crop load as the other systems. Since the most size-controlling rootstocks produced yields on par with the Nema Quad system, it is probable that the C-9 Quad system was under some stress that hindered production rather than its reduced fruit count being a result of reduced hydraulic conductance in the rootstock. It is likely in 2019 that all systems were under stress. Not only was fruit size significantly smaller than previous years, fruit count per hectare was also fewer than that of even the earlier bearing cultivar for all systems except the C-9 Quad.

Relationships between Fruit Size and Crop Load

It is widely accepted that as crop load increases fruit size diminishes (Reginato and Garcia de Cortazar 2007, Alcobendas et al., 2012, and MacFayden et al., 1996). In this study the relationship between crop load and fruit size was similar among systems with high density plantings on size-controlling rootstocks and the system with lower planting densities on a vigorous rootstock. Results were as expected, as crop load increased fruit size diminished. Although the relationship between fruit size and fruit produced per hectare was not significantly different among systems, appropriate crop load per tree and fruit size was influenced by planting density. The larger crop load that trees in the Nema Quad system could hold while maintaining similar fruit size as trees from other systems with significantly reduced crop load per tree indicate that trees with size-controlling rootstocks planted at a higher density may not be able to maintain as large of fruit size with larger crop loads compared to trees with more vigorous rootstocks at wider spaced plantings, this concurs with findings from Inglese et al., (2002). Results from this study also demonstrate that an increased number of trees per unit area compensate for the reduced crop load per tree, thus allowing high-density plantings on size-controlling rootstocks to be a viable option for commercial production, similar findings have been reported by Webster (2002) and DeJong et al., (1999).

PAR Vs. Yield per Area

It is well documented that an orchard's ability to intercept photosynthetically active radiation (PAR) influences yield and that the two are linearly related up to 50% light interception (Robinson and Lakso, 1991, Wu¨nsche and Lakso 2000, Grossman and DeJong 1998). Data from this trial had a similar trend for the relationship between light interception and yield. In the June Flame cultivar, yield measurements up to 50% light interception had little deviation from the linear model, above this point yield varied significantly. Above 50% light interception, differences in yield are likely caused by other limiting factors such as water or nutrients (Layne and Bassi 2008). This would also explain the poor fit for the model of the C-6 V system. With a canopy that intercepted >50% in all three seasons, yield variation was likely a result of environmental conditions. August Flame systems had more time in the first growing season to fill out their allotted space. This resulted in most systems having >50% light interception in all three seasons. Due to the higher light interception, all models had a poor fit and did not provide confident yield predictions.

CONCLUSION

The C-6 Quad system had an impressive performance throughout the trial. There were often significantly higher fruit counts and larger fruit compared to the Nema Quad system. In the June Flame 2019 harvest data there was a significant difference detected in slopes comparing fruit size vs fruit per hectare however the difference was related to the C-6 Quad system having the best fit to the model for that season. Overall, this system proved capable of producing yields on par with the current commercial systems.

The C-6 V system also proved to be a successful alternative to the current standard systems. Fruit sizes and crop loads matched the Nema Quad system in most seasons. High-density plantings may be more suitable for late-bearing cultivars and growers attempting to reach harvest a season earlier may find it difficult to do so with high-density plantings and an early-bearing cultivar. One drawback is the number of trees that must be managed in this kind of a system. With almost 1800 trees per hectare, initial costs are higher than a planting with half as many or fewer trees.

The C-9 Quad system performed poorly compared to all other systems. These results would suggest that the system is not capable of matching commercial production. However, systems using the C-9 rootstock and higher density plantings have been reported to be more productive than data from this trial suggest. With contrasting results from previous studies, nothing conclusive can be proposed.

The Nema Quad system did well as a representation of current commercial standards. The strong benchmark provided by this system highlights the impressive productivity of the C-6 V and C-6 Quad systems.

LITERATURE CITED

Agha NS, Buckley WR. Assessment of canopy efficiency of apple trees in beds. I. Canopy development assessed by direct light measurements. Journal of horticultural science. 1986 Jan 1;61(2):153-9.

Alcobendas R, Mirás-Avalos JM, Alarcón JJ, Pedrero F, Nicolás E. Combined effects of irrigation, crop load and fruit position on size, color, and firmness of fruits in an extra-early cultivar of peach. Scientia Horticulturae. 2012 Jul 13;142:128-35.

Ayars J, Trout T, Mead R, Phene C, Johnson RS. Crop coefficients for mature peach trees are well correlated with midday canopy light interception. InIII International Symposium on Irrigation of Horticultural Crops 537 1999 Jun 28 (pp. 455-460).

Basile B, Bryla DR, Salsman ML, Marsal J, Cirillo C, Johnson RS, DeJong TM. Growth patterns and morphology of fine roots of size-controlling and invigorating peach rootstocks. Tree Physiology. 2007 Feb 1;27(2):231-41.

Basile B, Marsal J, Solari LI, Tyree MT, Bryla DR, DeJong TM. Hydraulic conductance of peach trees grafted on rootstocks with differing size-controlling potentials. The Journal of Horticultural Science and Biotechnology. 2003 Jan 1;78(6):768-74.

Berman ME, DeJong TM. Water stress and crop load effects on fruit fresh and dry weights in peach (Prunus persica). Tree physiology. 1996 Oct 1;16(10):859-64.

Blanco A, Pequerul A, Val J, Monge E, Gomez Aparisi J. Crop-load effects on vegetative growth, mineral nutrient concentration and leaf water potential in ‘Catherine’peach. Journal of Horticultural Science. 1995 Jan 1;70(4):623-9.

Chalmers DJ, Mitchell PD, Jerie PH. The relation between irrigation, growth and productivity of peach trees. International Conference on Peach Growing 173 1984 Jul 9 (pp. 283-288).

Chalmers DJ, Wilson IB. Productivity of peach trees: tree growth and water stress in relation to fruit growth and assimilate demand. Annals of Botany. 1978 Mar 1;42(2):285-94.

Crisosto CH, Valero D. 22. Harvesting and Postharvest Handling of Peaches for the Fresh Market. The Peach: Botany, Production and Uses, CAB International, Wallingford. 2008:575-96.

Day KR, DeJong TM. Girdling of early season 'Mayfire'nectarine trees. Journal of Horticultural Science. 1990 Jan 1;65(5):529-34.

Day K, DeJong T, Johnson R. Orchard-system configurations increase efficiency, improve profits in peaches and nectarines. California agriculture. 2005 Apr 1;59(2):75-9.

DeJong TM, Johnson R, Ramming D, Doyle J, Day K. Evaluation of size controlling rootstocks for California peach, plum and nectarine production. Calif. Tree Fruit Agreement Rpt., Reedley. 1994.

DeJong TM, Tsuji W, Doyle JF, Grossman YL. Comparative economic efficiency of four peach production systems in California. HortScience. 1999 Feb 1;34(1):73-8.

DeJong TM, Johnson RS, Day KR. Controller 5, Controller 9 and Hiawatha peach rootstocks: their performance and physiology. Acta horticulturae. 2011(903):221-8.

Grossman YL, DeJong TM. Maximum fruit growth potential and seasonal patterns of resource dynamics during peach growth. Annals of Botany. 1995 Jun 1;75(6):553-60.

Grossman YL, DeJong TM. Training and pruning system effects on vegetative growth potential, light interception, and cropping efficiency in peach trees. Journal of the American Society for Horticultural Science. 1998 Nov 1;123(6):1058-64.

Hunter DM, Proctor JT. The correlation of light interception with yield and fruit color of McIntosh apple strains. Fruit varieties journal (USA). 1986.

Iannini C, Cirillo C, Basile B, Forlani M. Estimation of nectarine yield efficiency and light interception by the canopy in different training systems. InV International Peach Symposium 592 2001 Jul 8 (pp. 357-365).

Inglese P, Caruso T, Gugliuzza G, Pace LS. Crop load and rootstock influence on dry matter partitioning in trees of early and late ripening peach cultivars. Journal of the American Society for Horticultural Science. 2002 Sep 1;127(5):825-30.

Jackson DC, Palmer SE, Meadow WL. The effects of temperature and carbon dioxide breathing on ventilation and acid-base status of turtles. Respiration physiology. 1974 Mar 1;20(2):131-46.

Jiménez CM, Díaz JB. A statistical model to estimate potential yields in peach before bloom. Journal of the American Society for Horticultural Science. 2003 May 1;128(3):297-301.

Johnson RS, Handley DF. Thinning response of early, mid-, late-season peaches. Journal of the American Society for Horticultural Science (USA). 1989.

Layne DR, Bassi D, editors. The peach: botany, production and uses. CABI; 2008.

Lobell DB, Field CB. Global scale climate–crop yield relationships and the impacts of recent warming. Environmental research letters. 2007 Mar 16;2(1):014002.

McFadyen LM, Hutton RJ, Barlow EW. Effects of crop load on fruit water relations and fruit growth in peach. Journal of Horticultural Science. 1996 Jan 1;71(3):469-80.

Monteith JL. Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society of London. B, Biological Sciences. 1977 Nov 25;281(980):277-94.

Naor A, Hupert H, Greenblat Y, Peres M, Kaufman A, Klein I. The response of nectarine fruit size and midday stem water potential to irrigation level in stage III and crop load. Journal of the American Society for Horticultural Science. 2001 Jan 1;126(1):140-3.

Nobel PS. Physicochemical & environmental plant physiology. Academic press; 2020.

Palmer TP, Wynn-Williams RB. Relationships between density and yield of lucerne. New Zealand journal of experimental agriculture. 1976 Mar 1;4(1):71-7.

Palmer JW. The effects of row orientation, tree height, time of year and latitude on light interception and distribution in model apple hedgerow canopies. Journal of Horticultural Science. 1989 Jan 1;64(2):137-45.

Reginato GH, de Cortázar VG, Robinson TL. Predicted crop value for nectarines and cling peaches of different harvest season as a function of crop load. HortScience. 2007 Apr 1;42(2):239-45.

Reighard G. Current directions of peach rootstock programs worldwide. InV International Peach Symposium 592 2001 Jul 8 (pp. 421-427).

Robinson TL, Lakso AN. Bases of yield and production efficiency in apple orchard systems. Journal of the American Society for Horticultural Science. 1991 Mar 1;116(2):188-94.

Robinson TL, Lakso AN, Carpenter SG. Canopy Development, Yield, and Fruit Quality of Empire' and Delicious' Apple Trees Grown in Four Orchard Production Systems for Ten Years. Journal of the American Society for Horticultural Science. 1991 Mar 1;116(2):179-87.

Rowe RN, Johnson R. The interactions between fruit number, tree size and the yield and fruit size of Fantasia nectarine. Peach, XXIII IHC 315. 1990 Aug 27:171-6.

Soetewey A. Stats and R. https://statsandr.com/blog/anova-in-r/. 2020 Oct. 1.

Solari LI, Johnson S, DeJong TM. Relationship of water status to vegetative growth and leaf gas exchange of peach (Prunus persica) trees on different rootstocks. Tree Physiology. 2006a Oct 1;26(10):1333-41.

Solari LI, Johnson S, DeJong TM. Hydraulic conductance characteristics of peach (Prunus persica) trees on different rootstocks are related to biomass production and distribution. Tree Physiology. 2006b Oct 1;26(10):1343-50.

Solari LI, Pernice F, DeJong TM. The relationship of hydraulic conductance to root system characteristics of peach (Prunus persica) rootstocks. Physiologia Plantarum. 2006 Oct;128(2):324-33.

Tombesi S, Johnson RS, Day KR, DeJong TM. Relationships between xylem vessel characteristics, calculated axial hydraulic conductance and size-controlling capacity of peach rootstocks. Annals of Botany. 2009 Nov 24;105(2):327-31.

Tombesi S, Almehdi A, DeJong TM. Phenotyping vigour control capacity of new peach rootstocks by xylem vessel analysis. Scientia Horticulturae. 2011 Jan 10;127(3):353-7.

Tombesi S, Scalia R, Connell J, Lampinen B, DeJong TM. Fruit development in almond is influenced by early spring temperatures in California. The Journal of Horticultural Science and Biotechnology. 2010 Jan 1;85(4):317-22.

Weber M. Sweet cherry orchard management with dwarfing rootstocks in Germany. Compact Fruit Tree. 2001;34(1):20-2.

Webster T. Dwarfing rootstocks: past, present and future. Compact Fruit Tree. 2002;35(3):67-72.

Webster AD. Vigour mechanisms in dwarfing rootstocks for temperate fruit trees. InI International Symposium on Rootstocks for Deciduous Fruit Tree Species 658 2002 Jun 11 (pp. 29-41).

Weibel A, Johnson RS, DeJong TM. Comparative vegetative growth responses of two peach cultivars grown on size-controlling versus standard rootstocks. Journal of the American Society for Horticultural Science. 2003 Jul 1;128(4):463-71.

Weibel AM, Reighard GL. Dwarfing peach rootstocks generate scion water stress. InVII International Peach Symposium 962 2009 Jun 8 (pp. 633-639).

Wünsche JN, Lakso AN. Apple tree physiology-implications for orchard and tree management. Compact Fruit Tree. 2000 Feb;33(3):82-8.