

Performance of Five High-Density Apple Orchard Systems over Eight Years

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Numerous training systems have been developed in apple orchards to increase light interception and maximize tree productivity in intensive production systems (Robinson, 2017). In New York, many apple growers use the Tall Spindle System as alternative systems may require more time in the nursery, additional labor for training, or are planted at higher densities, increasing the establishment cost (Lordan et al., 2019). Nonetheless, alternative training systems may allow for additional light capture and present an opportunity to increase yield. For example, two stem Bi-axis trees reduce the vigor of each leader and possibly reduce the number of trees needed during orchard establishment. Cordon systems rely on training many vertical shoots from trees as well as closer row spacing in an attempt to capture as much light as possible (Tustin et al., 2018). Fruiting Wall trees are trained to a single vertical axis and are maintained to a narrow fruiting space through pruning cuts which do not allow branches to extend more than 10 inches away from the center of the row. Tall Spindle trees have a wider canopy size and are normally pruned once during dormancy to a width of 3 ft. V-trellis trees are planted at much higher density and trained to a series of wires at a 70-degree angle from the ground and have high light interception (Robinson 1998).

In addition to improved horticultural performance some new high density planting systems are designed to incorporate future robotic pruning, thinning and harvest machines. We call such systems “robot ready” systems. In this paper we compare the performance of five robot ready training systems and two cultivars over the first 8 years of orchard development.

Materials and methods

A field trial was planted at Cornell's AgriTech Lucey Farm in Geneva, NY using 'Gala' and 'Honeycrisp' trees in 2017. The trees were trained to 5 systems (Bi-axis [Bi], planar cordon [C], fruiting wall [FW], tall spindle [TS], and V-Trellis [V]). The tree spacing for Bi-axis was 1.2m x 3.3m (2525 trees ha⁻¹), fruiting wall was 0.9m x 3m (3704 trees ha⁻¹), planar cordon was 3m x 2m (1667 trees ha⁻¹), tall spindle was 0.9m x 3.3m (3367 trees ha⁻¹), and V-trellis was 0.45m x 3.5m (6349 trees ha⁻¹). The Bi-axis, fruiting wall, tall spindle, and V-trellis trees were planted with G.41 rootstock, but the planar cordon trees were planted on G.890 with the assumption that planting at a wider in-row spacing would require more vigor to fill the canopy space. Each system was replicated 4 times and each replicate consisted of 3 rows sections of trees with each row section was 9 m long and containing between 3 and 20 trees depending on the in-row spacing of each system. There were 3 rows for each variety.

Light interception measurements were collected similarly to Gonzalez and Robinson (2023), using a modified ATV

which had three, 1m light bars (Li-191R Line Quantum Sensors, LICOR, Lincoln, Nebraska, USA) attached 0.2 m off the ground from the front of the vehicle and a single reference sensor (LI-190R quantum sensor, LICOR) at a height of 4m above the ATV. The ATV passed through each

replicate of the 5 training systems and occurred on cloudy days in 2018, 2019, 2020, and 2024. A local weather station measured daily radiation and photosynthetically active radiation intercepted (PARI) was estimated by dividing the total Gigajoules per hectare (GJ·ha⁻¹) of light received during May 1st and September 15th each year in half (Robinson and Lakso, 1991).

Yield data were collected each year by counting the total number of fruit per tree, the number of drops beneath each tree, and recording the total fruit weight (kg) of each tree. An average fruit weight was calculated for each tree by the number of fruit divided by the weight and this value was multiplied to the dropped fruit before adding the weight of the dropped fruit to the total yield. Cumulative yields were calculated by summing all yield data (harvested weight + estimated dropped fruit weight) over 7 years and converted to metric tons per hectare (t·ha⁻¹).

Tree size was calculated by measuring trunk circumference at 30cm above the graft union for each original tree and later estimating trunk cross sectional area (TCSA) using the area of the circle. TCSA increase was calculated by subtracting current year TCSA from the previous year.

The light capture data and traditional horticultural parameters of yield and TCSA were combined as light conversion efficiency (CE) and photosynthate partitioning index (PI) variables. Tree light CE was calculated for each tree by dividing yield (t/ha fruit harvested + dropped fruit) by the quantity of photosynthetically active radiation intercepted (PARI). The PI was calculated by dividing the amount of yield/tree (kg fruit harvested + g dropped fruit) by the increase of TCSA (cm²) from the same year. Crop load (CL) was calculated as the number of fruit from each m² of PARI similarly to Reginato et al., (2007). The average light interception (%) and CL across the study years was made by averaging all years of data. Cumulative PARI and yield were calculated by adding each year of data including estimated

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We have been evaluating 5 “robot ready” high-density planting systems with 'Gala' and 'Honeycrisp' apple trees. The super high-density V system had the highest cumulative yield over the first 8 years followed by the cordon, and fruiting wall, then the tall spindle while the bi-axis had the lowest cumulative yield.

years together. Cumulative CE was calculated by dividing cumulative yield (g fruit·ha⁻¹) of each block by cumulative PARi (MJ). Cumulative partitioning index was calculated using 5-year cumulative yield and 5-year increase of TCSA.

Statistical analysis was performed using analysis of variance (ANOVA) comparing the training systems as the main effect and replication as a random variable by year. No replant tree data was used for understanding yield or increasing TCSA. Light interception values were averaged by training system within each replication of the orchard, excluding sections which had a high number of replants. Data were analyzed using the Proc GLM function of SAS (SAS Institute, Cary, NC, USA).

Results

Annual yield among systems was the highest for the V-trellis due to higher planting density for both cultivars between 2019 and 2021 (Table 1). In 2022, yields of ‘Gala’ from the Cordon system and Tall Spindle were similar to the V-trellis and the Cordon continued to have similar yields to the V-trellis until 2024. For ‘Honeycrisp’, The V-trellis continued to have the highest yield until 2024, when the Cordon system had the highest. Nonetheless, cumulative yields showed the V-trellis was the highest for both cultivars, a direct result of higher planting density and higher average light interception (Robinson, 2017).

Light interception measurements taken in 2018, 2019, 2020, and 2024 did not always show the same relationship between systems or for both cultivars (Figure 1, A and B; Table 1). When expressed as PARi over a growing season (Figure 1, C and D; Table 1), in 2018 the highest light interception of ‘Gala’ was observed with V-trellis, while ‘Honeycrisp’ had the highest light interception for the Cordon system followed by V-trellis. In 2019, the ‘Gala’ again had the highest light interception in the V-trellis system while the Cordon system had the lowest light interception. The ‘Honeycrisp’ showed a similar trend, as the Cordon system had the least amount of light interception, and the V-trellis system was the highest. In 2020, the light interception of all systems except the V-trellis dropped compared to 2019. This was most likely the result of excessive pruning to combat an intense fire blight infection. In 2024, the V-trellis system had the highest light interception for both ‘Gala’ (80%) and ‘Honeycrisp’ (72%). The average of 80% for ‘Gala’ grown on the V-trellis was exceptionally high, and the cause of the high yield of the V-trellis (Robinson, 2017). Such high light interception was previously reported when reflective fabrics allowed additional light capture from light reflected back up to the canopy (Gonzalez and Robinson, 2023). Average light interception and cumulative PARi had similar patterns by cultivar. The V-trellis was highest for both cultivars, but the Cordon system had statistically higher interception and PARi than the Bi-Axis, Fruiting Wall, and Tall Spindle in the ‘Honeycrisp’ orchard.

There were differences in light conversion efficiency (CE) among systems and between years for both cultivars (Figure 1, E and F; Table 2). In 2019, the ‘Gala’ trees trained to the Cordon and V-Trellis systems had significantly lower CE than the other systems but in 2020 and 2021 there were no significant differences among systems. In 2022 and 2023, the V-Trellis system had the lowest CE compared to all other systems while in 2024, the Cordon system had the highest, followed by the Bi-axis, Tall Spindle, Fruiting Wall, and finally the V-Trellis. The ‘Honeycrisp’ trees showed few differences among systems between 2019 and

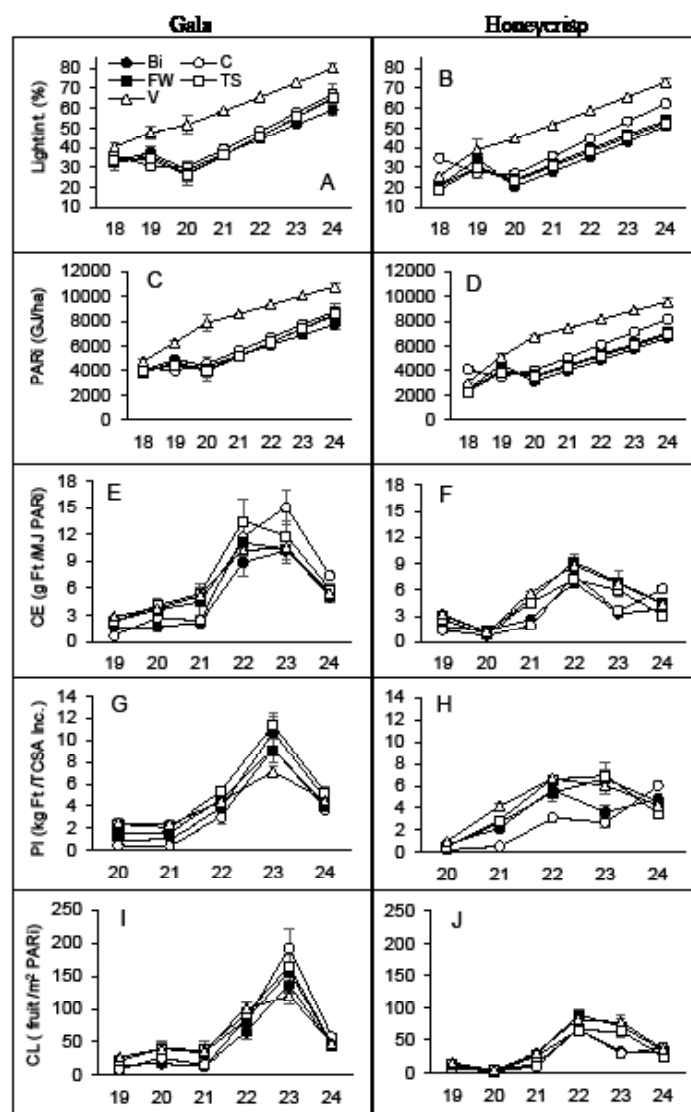


Figure 1. Average light interception (%), PAR intercepted (PARi, GJ·ha⁻¹), conversion efficiency (CE, g fruit·[MJ PARi]⁻¹), partitioning index (PI, kg fruit per TCSA [cm²] increase), and crop load (CL, Fruit number·[m² PARi]⁻¹) for ‘Gala’ (left) and ‘Honeycrisp’ (right) apples between Bi-axis (Bi), Cordon (C), Fruiting wall (FW), Tall Spindle (TS), and V-trellis (V) training systems between 2018 to 2024 (n = 4).

2021, with only the Bi-axis and Cordon systems having higher CE than Tall Spindle and V-Trellis in 2020. In 2022, the Cordon system had the highest CE, nearly 2.5x more than the V-Trellis. All ‘Honeycrisp’ training systems were similar in 2023, but the Cordon system had the highest CE in 2024 and was around 5x higher than the V-trellis. The drop in CE in 2024 on each of the ‘Gala’ systems, with an exception to the Cordon system, is also possibly a result of both overcropping in 2023 and a frost event which reduced overall fruit number in 2024. Regardless, the high values of the Cordon system was unexpected, as previous work showed the V-trellis had higher CE than other systems (Robinson and Lakso, 1991). Cumulative CE for ‘Gala’ was highest for the Cordon system and Tall Spindle, which were both higher than the Bi-Axis system. For ‘Honeycrisp’, the cumulative CE was highest for the FW and V-trellis, with the lowest CE calculated with Bi-Axis and Cordon.

There were also differences in partitioning index (PI) among systems for both ‘Gala’ and ‘Honeycrisp’. PI is a reflection of the efficiency of the rootstock. Thus, as expected with the

Table 1. Mean annual light interception (%), growing season (May 1 – Sept 15) photosynthetically active radiation intercepted (PARI, GJ·ha⁻¹), and yield (t·ha⁻¹) of ‘Gala’ and ‘Honeycrisp’ (HC) grown on five different training systems (n = 4). The final column shows either the average (\bar{x}) light interception or the cumulative (Cum.) PARI and yield over the study years.

Var.	Cult.	System	2018	2019	2020	2021	2022	2023	2024	\bar{x} or Cum.	
Light interception (%)	Gala	Bi	233.6	37.2 ab	29.1 b	y36.9 b	44.4 b	51.9 b	59.1 b	41.4 b	
		C	36.1	30.8 b	30.3 b	39.3 b	48.6 b	57.8 b	67.2 b	44.1 b	
		FW	32.5	35.7 ab	27.2 b	36.6 b	46.0 b	55.4 b	64.9 b	42.2 b	
		TS	33.6	34.2 b	26.5 b	36.1 b	45.9 b	55.7 b	65.6 b	42.2 b	
		V	40.1	47.6 a	51.8 a	58.7 a	65.8 a	72.9 a	80.1 a	60.1 a	
		P	n.s.	*	***	***	***	***	***	***	***
		LSD	10.9	9.4	9.2	3.7	6.1	5.5	8.2	5.4	
	HC	Bi	20.3 c	34	20.7 b	27.9 c	35.5 c	43.2 c	51.2 c	33.2 c	
		C	34.8 a	27.2	26.8 b	35.8 b	44.7 b	53.6 b	62.4 b	40.7 b	
		FW	20.5 c	30.2	23.9 b	31.9 bc	39.4 bc	46.9 c	53.9 c	34.6 c	
		TS	18.5 c	29.5	23.2 b	30.7 bc	38.1 c	45.5 c	52.7 c	33.0 c	
		V	25.5 b	38.8	44.4 a	51.4 a	58.5 a	65.6 a	72.8 a	49.7 a	
		P	***	n.s.	***	***	***	***	***	***	***
		LSD	3.6	11.5	2.2	6.5	6.8	7.6	3.8	5.2	
PARI (GJ·ha ⁻¹)	Gala	Bi	4000	4900 b	4400 b	5300 b	6100 b	6900 c	7800 b	39100 b	
		C	4300	4000 b	4600 b	5700 b	6700 b	7800 b	8800 b	42100 b	
		FW	3800	4700 b	4100 b	5200 b	6300 b	7400 bc	8500 b	39600 b	
		TS	4000	4500 b	4000 b	5200 b	6300 b	7500 bc	8600 b	39500 b	
		V	4700	6300 a	7900 a	8600 a	9300 a	10000 a	10800 a	57400 a	
		P	n.s.	**	***	***	***	***	***	***	***
		LSD	800	520	1500	1120	820	710	1070	5000	
	HC	Bi	2400 c	4500	3100 c	4000 c	4900 c	5800 c	6700 c	32000 c	
		C	4100 a	3600	4100 b	5100 b	6100 b	7200 b	8200 b	38400 b	
		FW	2400 c	4000	3600 bc	4500 bc	5400 bc	6200 bc	7100 c	32800 c	
		TS	2200 c	3900	3500 bc	4400 bc	5200 bc	6100 bc	6900 c	32500 c	
		V	3000 b	5100	6700 a	7400 a	8200 a	8900 a	9600 a	47600 a	
		P	***	n.s.	***	***	***	***	***	***	***
		LSD	260	640	1010	890	900	1020	500	4700	
Yield (t·ha ⁻¹)	Gala	Bi		7.7 b	7.4 b	8.4 d	43.2 c	59.0 c	39.0 c	184.5 c	
		C		2.7 c	12.4 b	12.2 c	71.2 ab	108.1 a	65.1 a	255.4 b	
		FW		10.1 b	13.7 b	20.0 bc	59.6 b	64.2 c	44.3 bc	198.2 c	
		TS		9.7 b	16.1 b	23.4 b	70.1 ab	71.8 bc	50.0 bc	228.7 bc	
		V		17.2 a	30.2 a	37.8 a	83.9 a	92.9 ab	58.0 ab	320.0 a	
		P		***	**	**	**	*	*	**	
		LSD		3.5	9.3	10.5	16.2	26.9	14.5	54.9	
	HC	Bi		7.8 c	4.0 b	10.5 c	33.1 d	19.1 d	25.1 cd	99.9 d	
		C		4.8 d	2.9 b	9.7 c	45.7 bc	26.4 cd	49.9 a	141.2 bc	
		FW		11.9 b	4.2 b	21.8 b	49.2 b	42.3 b	32.0 c	161.4 b	
		TS		9.5 c	3.5 b	19.5 b	37.3 cd	35.9 bc	21.0 d	126.9 cd	
		V		16.6 a	7.9 a	41.3 a	71.5 a	59.3 a	41.7 b	234.4 a	
		P		***	**	***	***	***	***	***	
		LSD		2.4	2	5.8	11.3	10.2	7.4	31.6	

^zLight measurements between 2018-2020, 2024 are compared statistically and letters show differences according to LSD test ($P \leq 0.05, 0.01, \text{ and } 0.001$ correspond to *, **, and *** respectively).

^yValues between 2020 and 2023 show estimates of light interception based on linear regression.

Cordon system often had the lowest index value due to the vigorous G.890 rootstock (Figure 1, G and H; Table 2). The PI was significantly lower on the Cordon system for ‘Gala’ in 2020 and 2021 compared to the Fruiting Wall, Tall Spindle, and V-Trellis. No differences were observed statistically in 2022, 2023 or 2024. The large PI value in 2023 across all systems corresponds with high number of fruit on the trees. The ‘Honeycrisp’ PI showed low values for the Cordon system until 2024, when it had the highest value compared to the other systems. The Fruiting Wall, Tall Spindle, and V-Trellis systems often had the highest values of PI for ‘Honeycrisp’ until 2024. The cumulative PI values for ‘Gala’ showed no differences, however the V-trellis, Tall Spindle, and Fruiting Wall had higher cumulative PI than the Cordon system for ‘Honeycrisp’.

CL based upon light interception was different among training system for both cultivars throughout the study, with both cultivars showing the highest CL in 2019 in the V-trellis system (Figure 1, I and J; Table 2). The highest CL values were observed on ‘Gala’ with the V-trellis, Tall Spindle, and Fruiting Wall, until 2023, when the Cordon system had the highest CL. The very high values for ‘Gala’ in 2023 across all systems was due to a high fruit set, yet sufficient rainfall to achieve good fruit size. A similar trend occurred in 2024 for ‘Gala’ CL, although no statistical differences were found. The ‘Honeycrisp’ trees generally had higher CL values on V-trellis, Tall Spindle, and Fruiting Wall with the lowest CL values on Bi-axis and

Table 2. Mean annual conversion efficiency (CE, g fruit·[MJ PARi]⁻¹), partitioning index (PI, kg·[cm² TCSA increase]⁻¹), and crop load based on light interception (fruit·[m² PARi]⁻¹) of ‘Gala’ and ‘Honeycrisp’ (HC) grown on five different training systems (n = 4). The final column shows either the cumulative (Cum.) CE and PI, or the average (\bar{x}) CL over the study years.

Var.	Cult.	System	2019	2020	2021	2022	2023	2024	Cum. or \bar{x}
CE (g fruit·[MJ PAR inc.]⁻¹)	Gala	Bi	3.2 a	3.9	4.8	15.3 ab	20.3 a	12.4 b	5.8 c
		C	2.2 b	9.1	7.5	19.9 a	24.6 a	22.7 a	7.7 a
		FW	3.0 a	5.6	7.8	14.3 ab	21.5 a	7.9 c	6.6 abc
		TS	3.2 a	7.2	9.7	16.7 a	23.5 a	8.8 c	7.5 ab
		V	2.1 b	3.5	4.6	8.8 b	9.7 b	4.6 d	6.5 bc
		P	*	n.s.	n.s.	*	**	***	*
		LSD	0.5	3.7	3.1	5.9	3.8	2.8	1.1
	HC	Bi	3.2	1.3 a	5.5	12.1 b	6.6	7.1 b	3.5 c
		C	4.0	1.4 a	6.4	17.0 a	9.2	16.4 a	4.1 c
		FW	4.0	0.7 ab	6.9	11.4 bc	8.9	6.1 b	5.3 a
		TS	3.2	0.5 b	6.5	9.5 c	8.3	4.6 c	4.3 bc
		V	2.4	0.4 b	4.9	7.0 d	5.4	3.1 d	5.2 ab
		P	n.s.	*	n.s.	***	n.s.	***	**
		LSD	1.3	0.7	2.5	4.0	2.5	2.5	2.2
PI (kg·[cm² TCSA inc.]⁻¹)	Gala	Bi		0.9 cd	21.0 bc	3.7	10.6	4.6	3.3
		C		0.5 d	0.4 c	3.1	9.1	3.7	3.1
		FW		1.5 bc	1.7 ab	4.6	9.1	4.0	3.2
		TS		2.4 ab	2.1 a	5.4	11.3	5.2	4.5
		V		2.5 a	2.4 a	4.3	7.1	4.5	4.0
		P		***	**	n.s.	n.s.	n.s.	n.s.
		LSD		1.0	1.1	1.7	2.2	2.2	1.2
	HC	Bi		0.7	2.2 b	5.6 a	3.6 bc	4.8 b	3.4 bc
		C		0.2	0.6 c	3.1 b	2.7 c	6.1 a	2.8 c
		FW		0.5	2.6 b	5.3 a	6.6 a	4.5 b	4.1 ab
		TS		0.5	2.8 b	6.6 ab	6.9 a	3.4 c	4.1 ab
		V		0.9	4.1 a	6.6 a	6.0 ab	4.2 b	4.3 a
		P		n.s.	***	**	**	***	**
		LSD		0.6	0.7	1.7	1.7	0.7	0.8
CL (Fruit·[m² PARi]⁻¹)	Gala	Bi	15.0 c	17.0 b	13.2 b	64.4 b	135.4 b	43.5	48.1 b
		C	8.7 d	25.5 b	15.6 b	81.3 ab	191.8 a	57.3	63.4 a
		FW	21.1 b	39.6 a	34.0 a	81.8 ab	155.5 ab	44.9	62.8 a
		TS	21.1 b	39.5 a	37.6 a	91.0 a	163.9 ab	44.9	66.3 a
		V	26.4 a	39.5 a	35.6 a	100.3 a	118.8 b	46.4	61.1 a
		P	***	**	*	*	*	n.s.	*
		LSD	2.7	13.6	16.2	20.8	45.9	11.8	12.9
	HC	Bi	7.6 c	4.8	13.3 b	65.5 b	32.2 b	29.8 bc	25.5 c
		C	6.8 c	2.6	9.5 b	65.5 b	28.8 b	39.4 a	25.5 c
		FW	14.3 a	4.2	25.8 a	88.2 a	70.7 a	33.5 ab	39.4 ab
		TS	11.6 b	3.0	24.5 a	65.1 b	63.2 a	23.8 c	31.9 bc
		V	14.8 a	3.8	30.2 a	81.2 ab	77.0 a	34.9 ab	40.3 a
		P	***	n.s.	***	*	**	**	**
		LSD	2.4	2.2	7.3	18.5	19.2	7.9	8.0

Cordon across the study. However, the Cordon system had the highest CL in 2024. Across all years the average CL of 'Gala' was lower for the Bi-Axis compared to all other systems. For 'Honeycrisp', the average CL was highest for the V-trellis and Fruiting Wall, which were both higher than the Cordon or Bi-Axis.

Plotting cumulative light interception by cumulative yield revealed a strong relationship between cumulative light interception and cumulative yield regardless of the systems for 'Gala' ($R^2 = 0.80$) and 'Honeycrisp' ($R^2 = 0.86$) (Figure 2). The V-trellis intercepted the most light over the first 8 years and had the highest cumulative yield per hectare. While the Cordon system intercepted the second highest cumulative light, yield was correspondingly the second highest for 'Gala' but not for 'Honeycrisp', as the Fruiting Wall had the second highest cumulative yield, performing better than expected based on light interception. The Bi-axis system for both cultivars had the lowest cumulative PARi and cumulative yield.

Discussion

We have previously shown that cumulative yield is related to cumulative light interception and planting density. Thus, as expected in the present study, after 8 years, the V-trellis system which had the highest planting density had the highest cumulative yield and the highest values of light interception, with 'Gala' trees averaging 80%, and the 'Honeycrisp' trees 70%. Surprisingly the Cordon system which had the lowest planting density had the second or third highest yield with Gala and Honeycrisp, respectively. It also had the second highest light interception. The Cordon system in this study achieved over 60% light capture for both 'Gala' and 'Honeycrisp' apples and surprisingly had higher CE and CL than other systems in recent years. However, the increased light capture of the Cordon system is a function of the very narrow row spacing (2m=6.5ft). Such a narrow spacing between rows would require different orchard machinery, possibly over the row machinery and thus is not likely to be adopted.

The tall spindle and the fruiting wall performed similarly as the cordon system while the bi-axis system had the lowest cumulative yield. The performance of each system needs to be explored over the lifetime of the orchard and additional years of data collection are needed as well as exploring CE and PI adjusted for annual crop load will allow a more comprehensive horticultural and economic understanding between the systems. This will also allow an economic evaluation of each system which will point the direction for future orchard design.

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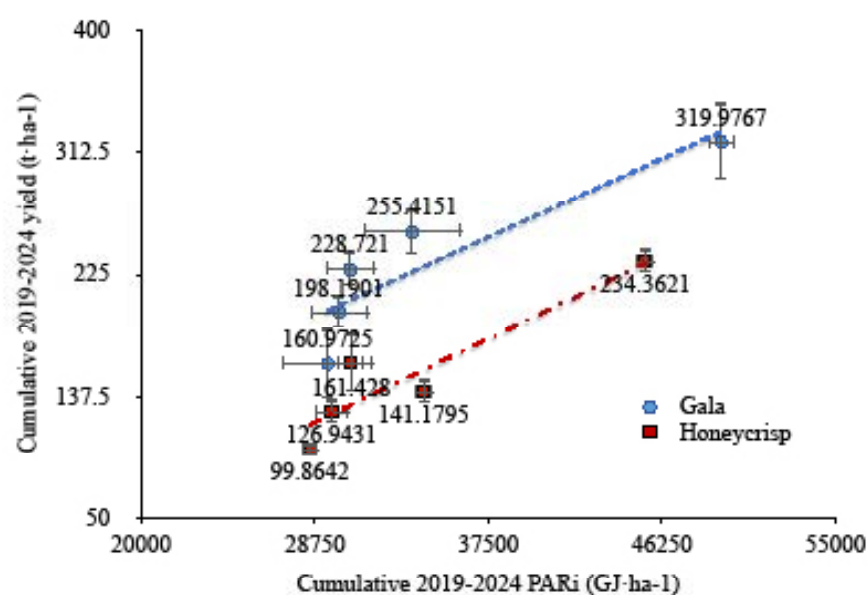


Figure 2. Cumulative light interception (PARi, GJ-ha-1) by cumulative yield (t-ha-1) measurements between 2019 and 2024 for 'Gala' (black circles, dashed line, $R^2 = 0.80$) and 'Honeycrisp' (white squares, dashed and dotted line, $R^2 = 0.86$) for Bi-axis (Bi), Cordon (C), Fruiting wall (FW), Tall Spindle (TS), and V-trellis (V) training systems.

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