Digital Technologies for Precision Apple Crop Load Management (PACMAN) Part I: Experiences with Tools for Predicting Fruit Set Based on the Fruit Growth Rate Model

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We are working with several companies to evaluate methods to streamline the use of the fruit growth rate model to manage crop load more precisely. In this article we report on our evaluations of a smart phone camera system of measuring fruit size distribution to determine fruit set after a thinning spray that was developed by Pometa company. We also evaluated their method of yield estimation.

Decades of work have demonstrated that PACMAN (Precision Apple Crop load MANagement) is an extremely effective method for successfully managing crop load. Effective crop load management has a direct effect on yield, quality, size, and return bloom, and ultimately an orchard's profitability. The process involves three management practices: 1) pruning, 2) chemical thinning, and 3) hand thinning, which have been described in detail in previous articles (Robinson et al., 2014a,b). We are continuing to refine recommendations for PACMAN, on a regional basis, as part of a 4-year national project, funded by the USDA-NIFA SCRI. This article is a follow-up to our previous article summarizing earlier work on this project (Robinson et al., 2022).

A key element of precision crop load management is the fruit growth rate model (Greene et al., 2013). Despite the successes of many research and pilot projects, commercial adoption of the model has been slow. The model requires tedious hand counting and measuring of fruitlets during the thinning window, which some growers view as time prohibitive. Even after successfully using the approach and seeing the payoff, many farmers report that they simply do not have the time during this busy period of the season.

As part of the PACMAN SCRI project, we are working to alleviate this challenge by developing robotic and digital technologies that offer practical implementation of PACMAN. In addition, in the past few years, a multitude of companies have emerged from the private sector with tools to accomplish these tasks. In 2021 and 2022, our team began identifying, advising, and evaluating these companies and their technologies on commercial and research orchards. Efforts to date have included field days, demonstrations, and data collection to verify information provided by these technologies. This will be an ongoing process, as the landscape of digital and robotic technologies is changing rapidly.

In 2022, we conducted trials to evaluate the accuracy of several technologies for predicting fruit set following a chemical thinning spray. The objective was to evaluate and compare three methods of predicting fruit set – Malusim app (Malusim), Ferri Fruit Growth Model app (Ferri), and Farm Vision scans (Farm Vision) – all of which are based on the fruitlet growth rate model. Farm Vision was a company founded by Patrick Plonski, University of Minnesota graduate, offering a technology for counting and measuring fruitlets to make fruit set and harvest estimations. In January 2023, Farm Vision was purchased by Meter Group and renamed Pometa. Pometa is referred to here as Farm Vision, reflecting the name at the time the work was conducted.

The trials presented here represent a ground truthing effort of one of the new AI technologies, as compared to the previously validated hand measurement methods of fruit set predictions. The results and experiences from the 2022 season will be used to guide further evaluations of more technologies in the future.

For the latest updates, please visit the PACMAN website: pacman.extension.org

Methods

Trials were carried out in 11 orchard blocks in Massachusetts, Michigan, New York, and North Carolina (Table 1). In each location, fruit set following a chemical thinning spray was evaluated according to the protocol of predicting fruit set using the fruitlet growth

Figure 1. Scanning of an orchard using Farm Vision equipment, including cellphone, RTK GPS, and battery pack, affixed to stabilizing device (3 ft pole). This equipment will no longer be used in 2023. Harvest scans were conducted with two people using an ATV. One person drove the ATV and a cell phone operator scanned full rows (both sides) as shown in the cell phone screen. Photo: Mario Miranda Sazo.

Table 1. Characteristics of commercial orchard blocks in Massachusetts, Michigan, and North Carolina for evaluation of fruit growth rate model prediction tools.

#	Block	Rootstock	System	Spacing	Target Crop
1	UMO 'Gala' (MA)	M.9	Tall Spindle	3x12'	60
2	UMO 'Fuji' (MA)	M.9	Tall Spindle	3x12'	80
3	UMO 'Honeycrisp' (MA)	G.11	Tall Spindle	3x12'	60
4	TFF 'Gala' (MA)	G.41	Tall Spindle	3x12'	100
5	TFF 'Honeycrisp' (MA)	G.41	Tall Spindle	3x12'	75
6	Vinton 'Honeycrisp' (MI)	Nic.29	Super Spindle	2x11'	150
7	Vinton 'Gala' (MI)	G.11	Super Spindle	2x11'	200
8	Thome 'Fuji' (MI)	B.9337	Vertical Axe	5x12'	90
9	Thome 'Gala' (MI)	Nic.29	Tall Spindle	4x12'	250
10	Cornell 'Honeycrisp' (NY)	M.9	Tall Spindle	3x11'	140
11	NCSU 'Gala' (NC)	M.9	Tall Spindle	3x13'	130

rate model" available at https://ag.umass.edu/fruit/fact-sheets/hrt-recipe-predicting-fruit-set-using-fruitlet-growth-rate-model. Five representative trees were selected per block, the number of flower clusters were counted on each tree (for potential fruit set), and then fourteen (MA) or fifteen (MI, NC, NY) flower clusters were tagged on each of the five trees for data collection. Fruitlets were measured using calipers beginning at approximately 6-7 mm fruitlet size and then at 4–7-day intervals; for Michigan, New York, and North Carolina, this corresponded with approximately 3 and 7 days after the first thinning application was made. Final fruit set was counted after June drop and/or at harvest.

In all four states (MA, MI, NY, NC), the Malusim app was evaluated using hand caliper measurements which were then entered into the Malusim app to generate predictions of fruit set. In MA, the Ferri app was also evaluated using the same trees and the same caliper measurements, entered into this app. In addition to the caliper measurements of fruitlets as described in the online protocol, the Farm Vision scanning technology was evaluated at all three states, using the company's directions and equipment: smart phone, stereo video camera, and enhanced GPS location identifier. The scans with the Farm Vision systems were carried out using the same trees where manual fruitlet measurements were being made. A final Farm Vision scan was also conducted in MA to determine the final fruit set in August. Because the objective was to evaluate and compare predicted fruit set using the fruitlet growth rate model, the chemical thinner applications are noted, but not further discussed. The specific details of each location are:

Massachusetts: The trials evaluating all three methods (Malusim, Ferri, and Farm Vision) were conducted at two orchards – the UMass Orchard in Belchertown and Tougas Family Farm in Northborough, using three varieties – 'Gala', 'Fuji' (UMass Orchard only), and 'Honeycrisp'. At the UMass Orchard (UMO), five adjacent 'Gala' and 'Fuji' trees in two orchard blocks with uniform bloom were selected. In the 'Honeycrisp' block, five individual, non-adjacent trees were selected in another block. Measurements were taken when fruitlets were approx. 6-7 mm in size on 23-May and continuing subsequently on 26-May, 29-May, and lastly on 3-June, 2022. Although chemical thinners were applied at the UMass Orchard, the details are not available.

At Tougas Family Farm (TFF) we evaluated 'Gala' and 'Honeycrisp'. Fruitlet measurement dates were 21-May, 25-May, and 27-May, 2022. Chemical thinner applications were made to the 'Gala' at bloom on 12-May of Promalin + AmidThin, and 20-May of 6-BA. Chemical thinner applications made to the 'Honeycrisp' included NAA (10 ppm) at bloom on 12-May, NAA (10 ppm) + carbaryl (1 pt) on 18-May, and NAA (5 ppm) on 27-May.

Michigan: The Malusim app and Farm Vision technology were evaluated in four mature, bearing, high-density, commercial orchard blocks in Sparta, MI. These included a 'Buckeye Gala'/G.11 and 'Honeycrisp'/Nic.29 planting at Schwallier's Country Basket (Vinton) and a 'Aztec Fuji'/M.9337 and 'Gale Gala'/Nic.29 planting at Bernard Thome Orchards (Thome). At the Vinton orchard, thinning applications were made on May 23 to 'Gala' of 6-BA (150 ppm) + carbaryl (1 pt), and to 'Honeycrisp' of NAA (10 ppm). At the Thome orchard, a thinning application was made on May 28. Fruitlet caliper measurements and scans were made on 23-May, 27-May, and 31-May at Vinton, and 28-May, 30-May, and 3-June at Thome. A final fruitlet count was made after June drop on 27-June.

New York: In New York, the Malusim app and Farm Vision technology were evaluated in a mature 'Honeycrisp'/M.9 block at the Cornell AgriTech Campus in Geneva. A thinning application was made on 21-May at approximately 9.5 mm fruitlet diameter, of 6-BA (150 ppm) + carbaryl (1 pt). Caliper measurements and scans were conducted on 21-May, 23-May, 27-May, and 31-May. Final fruit counts were conducted at harvest on 20-Sept.

North Carolina: In North Carolina, the Malusim app and Farm Vision technology were evaluated in a mature tall spindle 'Ultima Gala'/M.9 planting at the Mountain Horticultural Crops Research and Extension Center, Mills River NC. Flower cluster counts were recorded at bloom. Thinning application of 6-BA (75 ppm) + carbaryl (1 pt) was made on 2-May, and subsequent caliper measurements and scans were made on 5-May, 9-May, 11-May, 15-May, and 18-May. Final fruit count was recorded after June drop.

Results and Discussion

Results from individual trials are presented in Table 2 and Figure 2 (A-J), and a summary of percent accuracy for all of the trials are presented in Table 3 and Figure 3. Scans and caliper measurements were taken on four or five dates in all trials. In all cases, predicted fruit set is based on the change in fruitlet size between two subsequent measurements. Therefore, no prediction is made or presented on the first measurement date. In addition, these model and algorithms are optimized for predicting fruit set after taking measurements 3 and 7 days after a thinning application. Therefore, the first predicted fruit set estimate were made after the 7-day or second date for measurements and or scanning following a thinning treatment

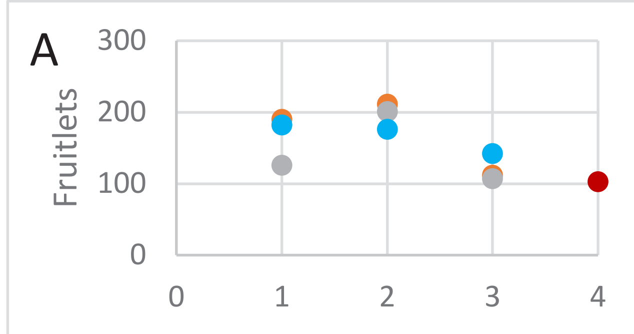
In general, both the Malusim and the Ferri apps, predicted fruit set reasonably well in comparison to the actual fruit set, but not exactly equal. Compared to final fruit set counted by hand after June drop or near harvest, Malusim predictions (made approx. 7 days after thinning application or 6-7 mm fruitlet size) ranged from 43-352% of actual fruit set with median 137%, and Ferri predictions ranged from 107-258% with median 161%. Both apps were most frequently within 20-30% accuracy.

Some discrepancy is to be expected, as the exact implementation of the fruit growth model in each app may be slightly different. In addition, both apps use some form of error correction, where measurements are discarded if deemed to be out of "range." For example, in Malusim when the growth rate is more than 1.5 mm per day or is an outlier (more than 2 standard deviations of all growth rates) it is discarded. Also, some human error is expected. It is recommended to have the same person measure fruitlets on each measurement date. Some of the error in MA measurements may be attributed to different people doing the measurements on different dates (for example when

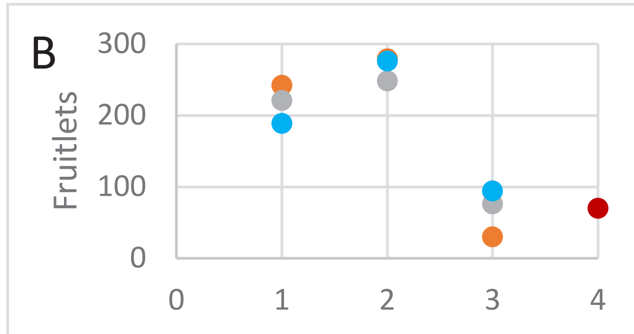
Table 2 (A-J). Actual and predicted fruit set (per tree) using Malusim, Ferri, or Farm Vision technologies for orchard blocks in MA, MI, NY, and NC in 2022.

A. UMO Gala (MA)					
		1	2	3	4
Actual Count					103
Malusim	predicted[z] %	190	211	112	
	of actual[y]	(184%)	(205%)	(109%)	
Ferri	predicted %	126	201	107	
	of actual	122%	195%	104%	
Farm Vision	predicted %	182	176	142	
	of actual	177%	171%	138%	

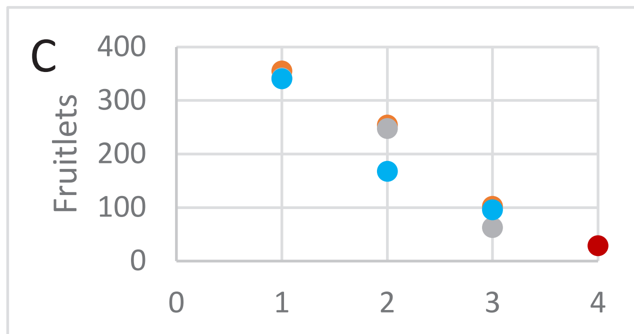
[z]predicted fruit set per tree | [y]percent accuracy = predicted fruit set / actual fruit set



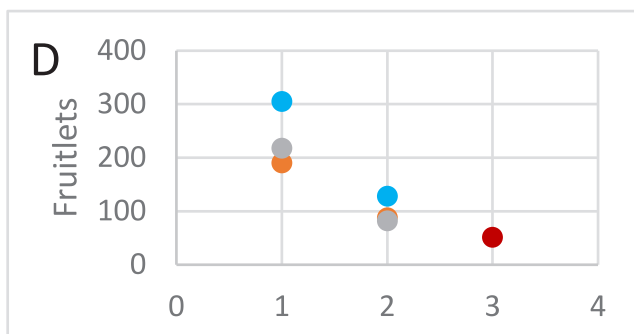
B. UMO Fuji (MA)					
		1	2	3	4
Actual Count					70
Malusim	predicted	242	279	30	
	% of actual	346%	399%	43%	
Ferri	predicted	221	248	76	
	% of actual	316%	354%	109%	
Farm Vision	predicted	189	276	94	
	% of actual	270%	394%	134%	



C. UMO Honeycrisp (MA)					
		1	2	3	4
Actual Count					29
Malusim	predicted	355	254	102	
	% of actual	1224%	876%	352%	
Ferri	predicted	342	248	63	
	% of actual	1179%	855%	217%	
Farm Vision	predicted	341	168	96	
	% of actual	1176%	579%	331%	



D. TFF Gala (MA)				
		1	2	3
Actual Count				51
Malusim	predicted	190	88	
	% of actual	373%	173%	
Ferri	predicted	218	82	
	% of actual	427%	161%	
Farm Vision	predicted	305	128	
	% of actual	598%	251%	



E. Vinton Honeycrisp (MI)					
		20-May	27-May	31-May	27-Jun
Actual Count		822			148
Malusim	predicted		206	80	
	% of actual		139%	54%	
Farm Vision	predicted		276	128	
	% of actual		186%	86%	

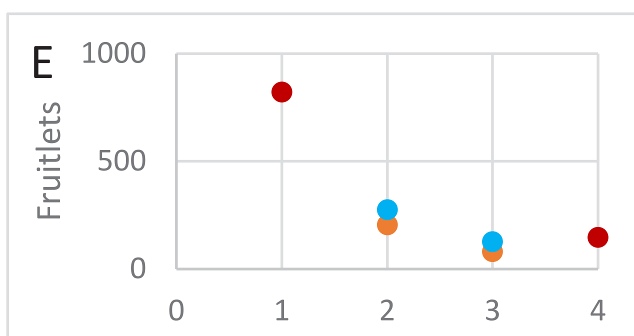
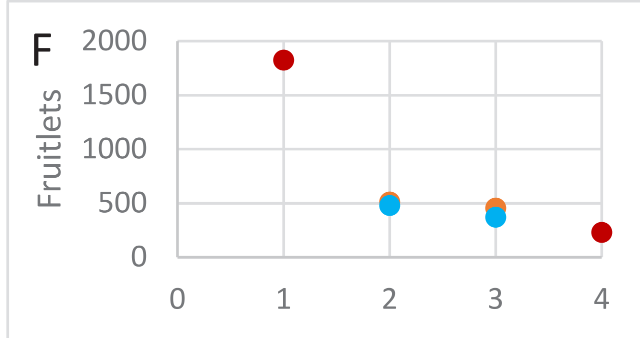
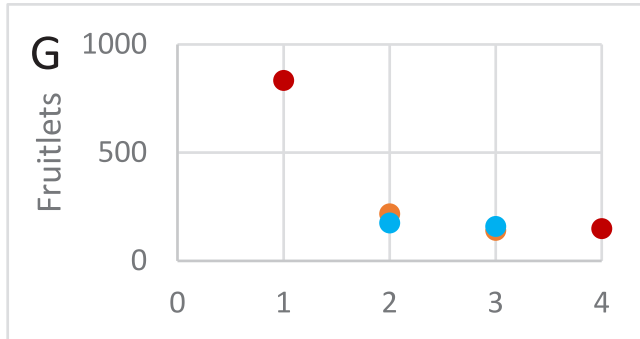


Figure 2 (A-J). Actual and predicted fruit set (per tree) using Malusim, Ferri, or Farm Vision technologies for orchard blocks in MA, MI, NY, and NC in 2022.

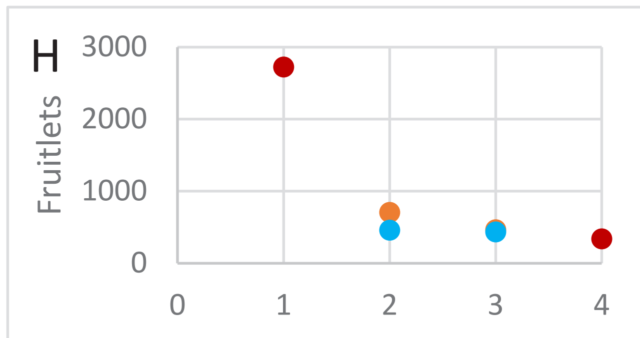
F. Vinton Gala (MI)					
		20-May	27-May	31-May	27-Jun
Actual Count		1824			229
Malusim	predicted		511	456	
	% of actual		223%	199%	
Farm Vision	predicted		479	372	
	% of actual		209%	162%	



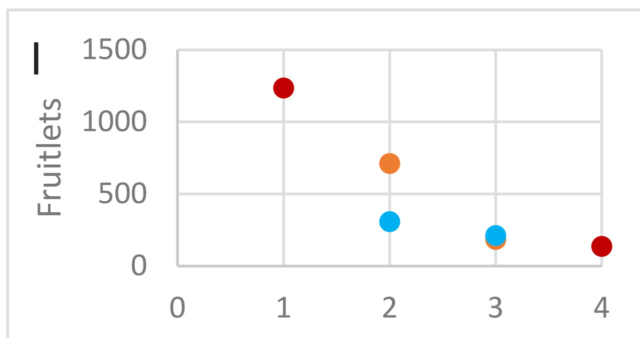
G. Thome Fuji (MI)					
		20-May	30-May	3-Jun	27-Jun
Actual Count		833			150
Malusim	predicted		217	142	
	% of actual		145%	95%	
Farm Vision	predicted		175	159	
	% of actual		117%	106%	



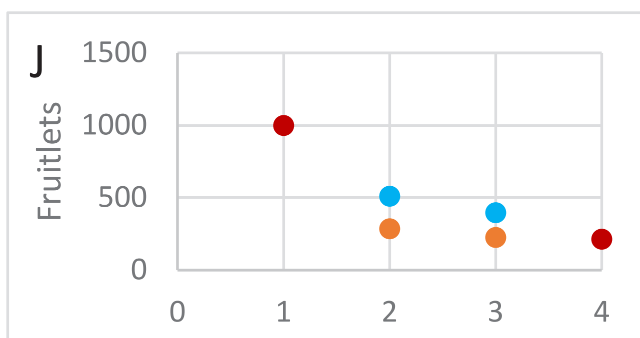
G. Thome Fuji (MI)					
		20-May	30-May	3-Jun	27-Jun
Actual Count		2722			337
Malusim	predicted		708	463	
	% of actual		210%	137%	
Farm Vision	predicted		460	435	
	% of actual		136%	129%	



I. Cornell AgriTech Honeycrisp (NY)					
		21-May	23-May	27-May	27-Oct
Actual Count		1235			135
Malusim	predicted		712	186	
	% of actual		527%	138%	
Farm Vision	predicted		308	212	
	% of actual		228%	157%	



J. NCSU Gala (NC)					
			9-May	11-May	
Actual Count		998			213
Malusim	predicted		287	226	
	% of actual		135%	106%	
Farm Vision	predicted		510	396	
	% of actual		239%	186%	



the predicted fruit set actually increased (UMO 'Gala' and 'Fuji'). In conclusion, the two apps were comparable in their results, they gave similar predictions of fruit set, and were fairly accurate in relation to the actual fruit set.

With the Farm Vision technology there was also variability in prediction of final fruit set compared to other models, and in accuracy compared to actual fruit set. Compared to the final fruit set counted after June drop or near harvest, the final prediction of fruit set by Farm Vision ranged from 86-331% of final fruit set with median 152%. Like the Malusim and Ferri apps, most frequently predictions were within 20-30% of actual fruit set.

A few blocks appear to have been outliers, with gross over or under predictions compared to actual fruit set. In the UMO 'Fuji' block, Malusim greatly under predicted fruit set (43% of actual), but Ferri and Farm Vision methods did not (109% and 134% respectively). In the Vinton 'Honeycrisp' block, Malusim under predicted fruit set (54%) but Farm Vision only slightly under predicted (86%). This was most likely due to the placement of flagged clusters in these trees. A large portion of the clusters were in the lower part of the canopy, which experienced some over thinning compared to the tops of the trees. This is an excellent illustration of the importance of flagging clusters throughout the canopy in order to reflect thinning and fruit set of the entire tree. In the UMO 'Honeycrisp' block, all three methods significantly over predicted fruit set (Malusim 352%, Ferri 217%, Farm Vision 331%). This indicates that more thinning occurred after the measurements and scans were complete and predictions made. Additional thinners may have been applied to this block, or other environmental conditions may have imposed additional stress that resulted in further fruitlet abscission (i.e., carbohydrate deficits induced by low sunlight and excessive heat).

When comparing the Farm Vision to the Malusim and Ferri apps, all three showed similar trends in fruit set predictions, but Malusim and Ferri were much more similar than Farm Vision. This is mostly as expected. We might consider it a bit like comparing "apples to oranges". The Malusim and Ferri apps use a similar method of data collection, measuring by hand with calipers a known number of fruitlets, with slightly different models for making fruit set predictions. On the other hand, Farm Vision introduces a different technology for "seeing" and measuring fruitlets (cameras and computer vision) and algorithms for determining the actual number of fruitlets present based on occlusion models calibrated to a given planting. In addition, Malusim and Ferri make predictions on fruit set on a per tree basis, whereas at the time of this work, Farm Vision was estimating set on a linear basis (i.e., predicted fruit set per meter). In the future Farm Vision will be changing its models to operate on a per tree basis, and they will continue to ground truth results. In general, less data used in the Malusim and Ferri apps than in the Farm Vision method could have led to some of this variation.

Table 3. Accuracy of fruit set predictions by Malusim, Ferri , or Farm Vision scanning technology compared to actual fruit set. Reported as percent (%).

Block	Malusim	Farm Vision	Ferri
UMO 'Gala'	109%	138%	104%
UMO 'Fuji'	43%	134%	109%
UMO 'Honeycrisp'	352%	331%	217%
TFF 'Gala'	173%	251%	161%
TFF 'Honeycrisp'	183%	.	258%
Vinton 'Honeycrisp'	54%	86%	.
Vinton 'Gala'	199%	162%	.
Thome 'Fuji'	95%	106%	.
Thome 'Gala'	137%	129%	.
Cornell 'Honeycrisp'	138%	157%	.
NCSU 'Gala'	106%	186%	.
Average	144%	168%	170%
Max	352%	331%	258%
Min	43%	86%	104%
Median	137%	148%	161%

There were a few concerns with the Farm Vision hardware during our work. These were primarily related to the QR code signs needed to geo-locate the trees, which were easily obscured. Also, RTK GPS connectivity was a challenge in some locations. In 2023, Farm Vision (Pometa) is eliminating and/or changing several aspects of their hardware and data presentations. For example, QR code signs are being reimagined and the app can now be used without an external RTK GPS device, eliminating connectivity issues. These are examples of how Farm Vision, and other technologies, are rapidly responding to user experiences and improving their output going forward. In general, we found Farm Vision support very easy to work with and responsive to our concerns.

Farm Vision offers some advantages to the Malusim and Ferri apps. The time for data collection is drastically reduced. Data collection for either Malusim or Ferri from a single block typically took us the greater part of an hour, and it is difficult to accomplish alone. Farm Vision took less than five minutes per block to complete the scans, once the hardware was set up and GPS was connected, plus walking time between trees. In addition, Farm Vision uses a much larger sample size of fruitlets to make predictions (all visible fruitlets), whereas the Malusim and Ferri apps are limited by a small sample size. In these apps, only 70-75 clusters were measured (14 or 15 clusters on each of 5 trees). If these clusters were an inaccurate representation of the total tree or block, they would have provided poor fruit set predictions. Based on our personal experiences, even one aberrant tree or flower cluster(s) can seriously skew the results.

Overall, all methods tended to over-predict fruit set. This means they are conservative by nature, and the risk of over-thinning is minimal. All three followed similar trends in nearly all situations and provide similar predictions of fruit set and corresponding recom-

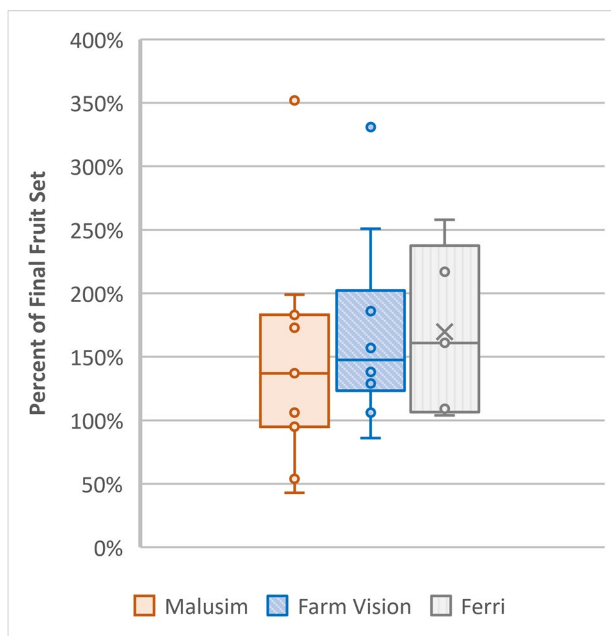


Figure 3. Accuracy of fruit set predictions by Malusim, Ferri, or Farm Vision, compared to actual fruit set.

Table 4. Actual yields and yield estimations with a cell phone camera at two mature WNY orchard sites in the fall of 2022.

Site	Number of rows and scanned acreage	Yield (bins)		
		Actual Yield	Predicted (cell phone camera)	
			With Occlusion Model	Without Occlusion model
'Fuji'/B.9 (2x11ft)	12 rows (2.87acres)	127	154 (Overpredicted by 21%)	114.5 (Under-predicted by 10%)
'Evercrisp'/ B.9(3x12ft)	8 rows (1.5acres)	83	80.1 (Slightly under-predicted by 3%)	NA

mendations for thinning.

Yield Estimation Studies with Farm Vision in New York

As a follow up to our work in the spring to estimate fruit set, in the fall of 2022, we conducted two yield estimation studies with Farm Vision in the Lake Ontario Fruit region of New York. Orchard scans were conducted at two locations. The first was a commercial five-year old 'Fuji'/B.9 planting at 2x11 ft (Fish Creek Orchards, Orleans County, NY) on September 14, 2022. A second trial was conducted at a commercial six-year-old 'Evercrisp'/B.9 planting at 3x12 ft (Cherry Lawn Farm, Wayne County, NY) on October 13, 2022.

Calibrations for occlusion were conducted prior to full scanning of rows for yield estimation. At each of the two sites, five 3-tree plots which were randomly distributed in the orchard were used for calibration of occlusion. Calibration plots had uniform crop load, tree height, canopy width, and trunk diameter. Fruit counts/tree were conducted for each of the calibration plots before the scanning of full rows. Setting up of calibration plots and ground-truth work took one hour for two people at each of the orchard sites.

Full row scans were conducted with two people. One person drove an ATV at approximately 10 miles/hour and a cell phone operator scanned full rows (both sides) that contained the five calibration plots. Entire tree canopies and trunks were scanned by the cell phone operator. Scanning with the cell phone camera took less than 10-12 mins with one ATV and two people at each of the orchard sites.

At Fish Creek Orchards we scanned 12 rows or 2.87 acres. The Farm Vision technology estimated 2,926 bushels or 154 bins (19 bushels/bin) from the 12 rows (Table 4). The actual yield from the 12 rows was 2,413 bushels or 127 bins recorded on October 12, 2022. At Cherry Lawn Farms we scanned 8 rows or 1.5 acres. The Farm Vision technology estimated 1,602 bushels or 80.1 bins (20 bushels/bin) from the 8 rows (Table 4). The actual yield from the 8 rows was 1,658 bushels or 82.9 bins recorded on October 26, 2022. The Farm Vision yield estimates overpredicted the yield of 'Fuji' by 21% and slightly underpredicted the yield of 'Evercrisp' by 3%. The large overestimation of 'Fuji' fruit seemed to be associated with the occlusion model when scanning both sides of the Fuji trees were scanned. The Super Spindle Fuji orchard had a very narrow 2-dimensional canopy with almost all fruit visible to the camera from one side. In this case, the Farm Vision technology had some double-counting of fruit, even though the system attempts to compensate. When the scanning results for Fuji were re-run by Farm Vision and the occlusion model was turned off for the analysis, the new Fuji yield estimate was 114.5 bins and only 10% lower than the actual Fuji yield at harvest. This result showed that the Farm Vision technology can be used to scan very thin, 2-D fruitful canopies, from a single side of a row, without the use of an occlusion model. This took less time than other yield estimation models.

Conclusions

Many tools utilizing computer vision, AI, and ML are rapidly becoming available to assist with PACMAN, specifically to improve and expedite the process of fruitlet measuring to predict fruit set according to the fruit growth rate model, as well as to make harvest predictions. The tools tested here, including the Malusim app, Ferri app, and Farm Vision (Pometa) scanning, varied in accuracy in our 2022 trials. This and other tools are continuing to be updated and improved, both in terms of accuracy of predictions and user friendliness. We are optimistic about the accuracy and efficiency with which computer vision tools will accomplish this task in the future. As with all models or tools, they are not perfect, they are an excellent "decision aid." As always, grower experience should be a factor in making chemical thinning decisions, don't rely on the models alone.

Acknowledgments

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