Precision Crop Load Management of Apple Using Digital Technology

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Abstract

Precision crop load management is a suite of strategies and machines to manage the number of fruits per tree to exactly the economic optimum. We have developed a series of strategies that include precision pruning guided by computer vision, blossom thinning guided by a pollen tube growth model, post bloom chemical thinning guided by a carbohydrate balance model and a fruit growth rate model aided by computer vision and finally hand thinning guided by computer vision. At each step in the process of reducing fruit bud load, flower load or fruitlet load, we are developing computer vision and other digital technologies to streamline the counting of buds, flowers and fruitlets. Our preliminary results show that: 1) we can digitally count fruit buds and use the information to guide precision pruning to leave a pre-determined flower bud load; 2) we can apply sequential chemical thinning sprays guided by the use of computer models to adjust the dose and timing of chemical application and to assess the effect of the chemical sprays shortly after application to inform re-application; and 3) we can digitally count fruitlets to guide human workers to leave an exact number of fruits per tree when hand thinning.

Keywords: *Malus* × *domestica,* fruit size, crop value, chemical thinning, pruning, computer vision, hand thinning

INTRODUCTION

Precision crop load management is a strategy that seek to manage the number of fruits per tree to a pre-determined economic optimum utilizing three management practices that have a large effect on crop load: 1) pruning, 2) chemical thinning and 3) hand thinning (Robinson et al., 2021). It begins with precision pruning to leave a preset number of floral buds per tree, followed by precision chemical thinning to reduce initial flower number per tree to a preset fruit number per tree and ends with precision hand thinning to leave a precise final number of fruits per tree (Robinson et al., 2013). The number of fruits that remain on a tree directly affects yield, fruit size and the quality of fruit that are harvested, which largely determines crop value (Robinson et al., 2023.)

We have previously developed manual methods of managing flower bud load and fruit number per tree (Robinson et al., 2013); however, those methods require manual counting of buds or fruitlets at various times throughout the season. The tedious nature of manual counting has limited the commercial adoption of these methods.

In September of 2020 we began a 4-year national USA project on precision crop load management of apples that includes university researchers, extension educators and commercial company engineers that seeks to bring digital solutions to manage crop load in apples. The project is funded by the federal US government through the USDA-NIFA Specialty Crops Research Initiative (SCRI). The project has horticultural objectives, engineering objectives and economic objectives. Among the horticultural objectives are to 1) assess the optimum crop load for two important apple cultivars: 'Gala' (number one in USA production) and 'Honeycrisp' (number three in production) (US Apple Association, 2022) in different growing regions of the USA and 2) improve the three models used in chemical thinning (carbohydrate balance model, pollen tube growth model and the fruit growth rate model) to

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provide more precision and greater confidence in their use. The engineering objectives are to 1) develop computer vision approaches and machines to count dormant fruit buds, flowers, and then fruitlets per tree and also geo-reference the tree's location and 2) process the information and communicate actionable information to human workers. The economic objectives are to 1) assess the economic effects of thinning and 2) determine the economic feasibility of automated methods of assessing crop load and managing crop load. The project also seeks to extend to growers and tech companies the results of the research project to guide grower adoption of digital technology to manage crop load. We have published several reports on aspects of this project including comparing the optimum crop load across 4 distinct climates in the USA (Robinson et al., 2023), use of computer vision to count fruitlets, measure trunk cross-sectional area and estimate yield with computer vision (Gonzalez, et al, 2023a; Jiang et al., 2023; Wallis et al., 2023) and a new model to predict fruit set after chemical thinning sprays (Hillman, et al., 2022) and a spectroscopic method to predict fruitlet abscission (Larson et al., 2023a, b).

In this paper we report on the progress on precision pruning and precision hand thinning using computer vision to access crop load. Precision pruning is a strategy to reduce the flower bud number per tree to a pre-defined flower bud number through pruning (Robinson, et al., 2013). The process involves defining a target number of flower buds per tree, and then removing excess fruit buds via pruning and keeping only those needed to set an adequate crop (Robinson et al., 2014). By pruning to a specified bud number, growers can start the process of fruit thinning early to reduce competition among flowers and fruitlets resulting in increased resources for the remaining fruit and improved fruit size and quality.

Determining the proper bud number per tree depends both on the desired yield and fruit size but also on the level of risk the grower is willing to accept (Francescatto et al., 2020). Counting the number of buds for each tree can be done either manually (which is tedious and costly) or with computer vision.

As an example of this process, in 2023 we used a commercial camera system from Orchard Robotics Inc. to counting fruit bud number of mature 'Gala' trees to assess the variability and then through pruning adjusted the bud number to a constant bud load based on trunk cross-sectional area. This was done in the dormant season just before bud break in the spring.

MATERIALS AND METHODS

Geneva precision pruning trial.

A single row of 15-year old 'Brookfield Gala' trees on M.9T337 rootstock composed of 97 trees was used for this trial. The trees were trained as Tall Spindles with a planting spacing of 1m X 3.5m (2,857 trees/ha). The entire row was scanned with the Orchard Robotics camera system which utilizes a proprietary camera and proprietary algorithms to measure trunk diameter of each tree and count the number of dormant buds. After the scan with the camera system, we calculated a target bud number based on trunk cross-sectional area (TCSA) and by pruning reduced the bud load to the target number. For these relatively old trees we selected a bud load of 5.9 buds/cm^2 TCSA based on our previous work that the number of buds should be 150% of the final desired (target) fruit number. For this orchard we estimated that the final fruit load should be 3.93 fruits/cm^2 TCSA which would result in 304 fruits per tree.

Geneva precision hand thinning trial.

We did the precision hand thinning trial on the same row of 'Gala'/M.9 trees used in the precision pruning trial. After the precision dormant pruning was completed, we applied several chemical thinning sprays using the precision chemical thinning protocol we have previously published (Robinson et al., 2021). This protocol uses sequential thinning sprays guided by three computer-based models (the Pollen Tube Growth Model to guide blossom thinning, the MaluSim Carbohydrate Model and the Fruit Growth Rate Model to guide small fruitlet thinning) (Rufato et al., 2017). The results of the precision chemical thinning sprays are not presented here.

For the hand thinning trial, we compared two methods of counting the number of fruits per tree: the Orchard Robotics proprietary camera system and the Pometa system which uses video images taken with an iPhone 14 camera along with its proprietary algorithms to count the number of fruits per tree. We scanned the entire row to count the number of fruits/tree. After the scan with the camera systems, we calculated a target fruit number per tree based on trunk cross-sectional area. We then hand thinned each tree to the target number of fruitlets using commercial hand thinning personnel which we instructed on the number of fruitlets to remove from each tree. Following the hand thinning we scanned the row again with both camera system.

Hudson Valley precision hand thinning trial.

A second precision hand thinning was conducted in the Hudson Valley region of NY State (Eastern part of New York State) on a commercial apple farm. A single row of 'Gala'/G.41 trained as Tall Spindles with a planting spacing of 0.9 m X 3.5m (3,175 trees/ha) was used for the trial. The trees had previously been pruned to in a consistent manner along the row by a commercial crew of farm personnel. The row had also received 2 chemical thinning sprays (one at petal fall and one at 12mm fruit size. At hand thinning time it was apparent that most tree had too many fruits and required hand thinning. To implement a precision hand thinning strategy on the entire row, we scanned the entire row of trees with the Orchard Robotics camera system and the Pometa camera system to count the number of fruitlets on each tree in the row. After the scans with the camera systems, we calculated a target fruit number per tree based on trunk cross-sectional area. We then hand thinned each tree to the target number of fruitlets using commercial hand thinning personnel which we instructed on the number of fruitlets to remove from each tree (using data from the Orchard Robotics scan). Following the hand thinning we scanned the row again with both camera system.

RESULTS

Geneva precision pruning trial.

The number of dormant buds for each tree in the row counted with the camera systems varied considerably from 779-342 buds per tree with an average bud number of 524 (Figure 1). Based on trunk cross-sectional area measured with the camera system we targeted a bud load of 5.9 fruits/cm^2 TCA. The resulting target number of fruit for each tree also varied considerably from 147-425 fruits per tree (Figure 1). The average target fruit number was 304 fruits per tree. Following the scans and the processing of the data we pruned each tree in the row to the target bud number before bloom and before any chemical thinning sprays. Post pruning, we were unable to use the camera system to count the number of remaining buds due to technical problems.

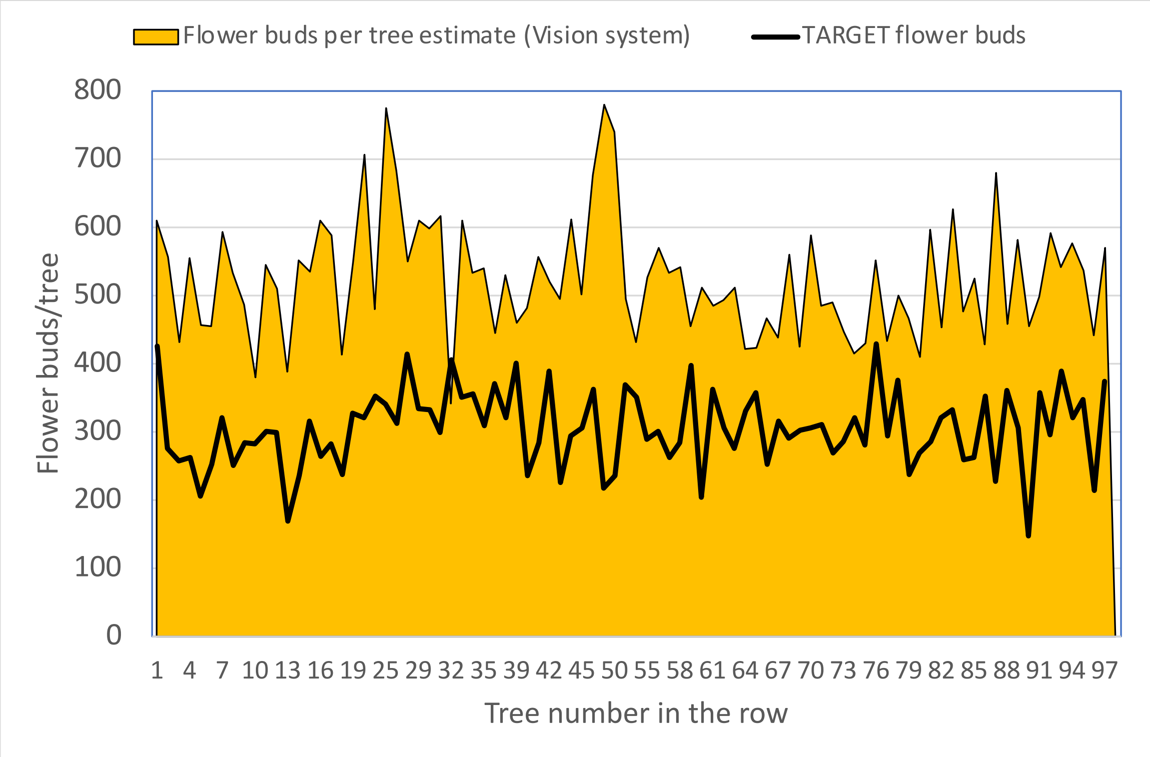

Figure 1. Estimated flower buds per tree of 'Gala'/M.9 apple trees measured using a proprietary camera vision system to measure trunk cross-sectional area and count bud numbers at Geneva, NY State. Yellow line is the bud number per tree and the Black line is the desired (target) number of flower buds based on trunk cross-sectional area with a target of 5.9 flower buds /cm² TCSA.

Geneva precision hand thinning trial

It was apparent that even after the precision pruning and the precision chemical thinning there were too many fruits on most of the 'Gala' trees. A scan of the entire row with the Orchard Robotics camera system showed that the number of fruitlets per tree varied considerably (77-605) with some trees having fewer fruits than the target (overthinned by chemical thinning) but most trees had more fruits than the target (Figure 2). After the hand thinning we again used the camera system to scan the number of fruits per tree. The final number of fruits per tree was closer to the target number of fruits per tree but there was still considerable variability in fruit number 63-443). In relation to the target fruit number the pre-hand thinning fruit numbers per tree were generally greater than the target number while the post-hand thinning fruit number per tree were both above and below the target number of fruit per tree (Figure 3). This illustrates the significant error in the hand thinning process. In Figure 3 the vertical distance between the trees pre-hand thinning fruit number and the post-hand thinning fruit number represents the number of fruits removed by hand thinning. Where trees had been overthinned by chemical thinning, the hand thinning was skipped while those trees with an excessive crop load were hand thinned according to the data from the camera scan which brought them closer to the target fruit number.

When comparing the Pometa fruit counting system using a cell phone with the Orchard Robotics camera system, the Pometa system counted fewer fruits than the Orchard Robotics system (Figure 4). A final scan was conducted just before harvest and the larger count per tree with the Orchard Robotics system than the Pometa system persisted.

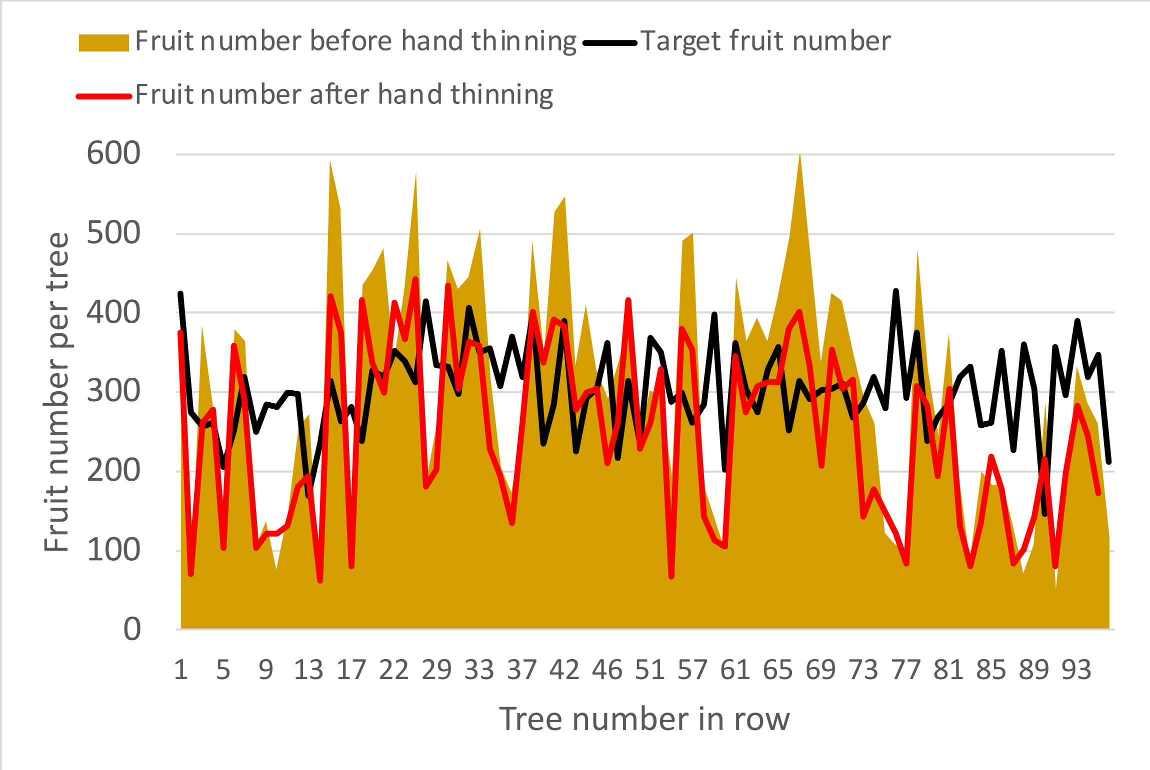

Figure 2. Estimated fruitlet number per tree of 'Gala'/M.9 apple trees measured using a proprietary camera vision system to count fruitlet number before hand-thinning at Geneva, NY State. Yellow line is the fruitlet number per tree before hand thinning, the Black line is the desired (target) number of flower buds based on trunk cross-sectional area with a target of 5.9 flower buds /cm^2 TCSA and the red line is the final number of fruitlets per tree after hand thinning.

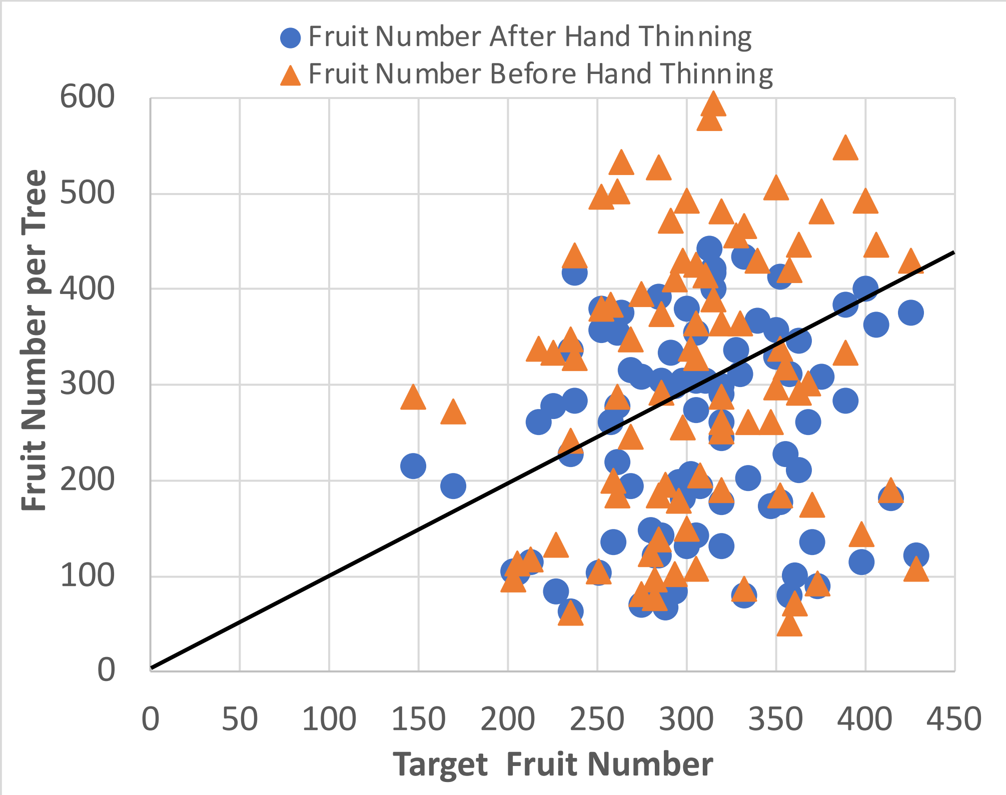

Figure 3. Relationship of the target fruit number per tree and the fruitlets per tree counted with the Orchard Robotics system before and after hand thinning at Geneva, NY.

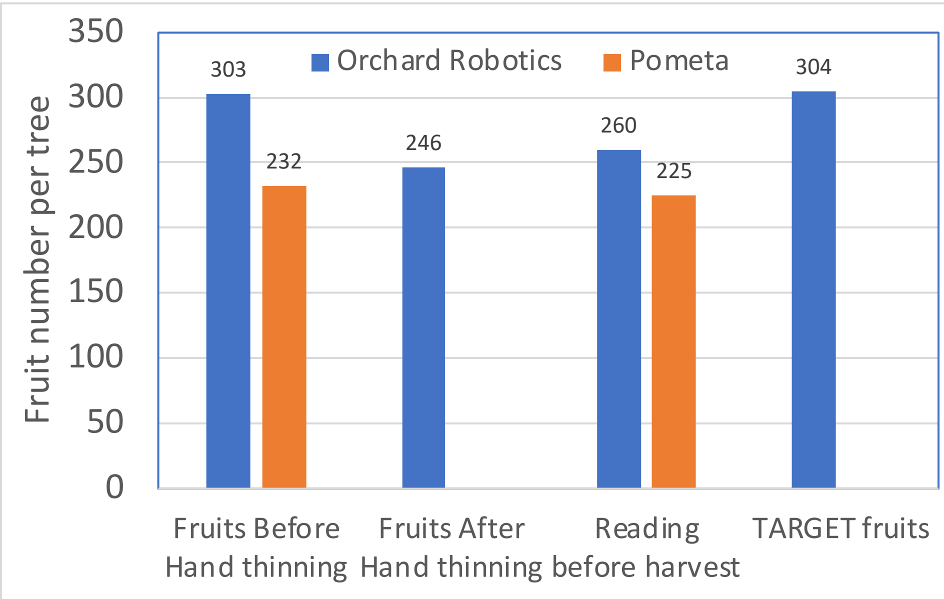

Figure 4. Comparison of the scan results before and after hand thinning using the Orchard Robotics camera system and the Pometa cell phone camera system at Geneva, NY.

Hudson Valley hand thinning trial.

The scanning of the row of 'Gala' trees in the commercial orchard in Hudson Valley with the Orchard Robotics camera systems showed considerable variation in fruitlet number per tree (Figure 6). Following the scan and the processing of the data we hand thinned each tree in the row to the target fruit number. After the hand thinning we again used the camera Orchard Robotics system to scan the number of fruits per tree. The final number of fruits per tree was close to the target number of fruits per tree but there was still considerable error in the hand thinning process (Figure 6). Similar to the Geneva hand thinning trial, there was a general agreement between the final fruit number and the target fruit number but some trees were overthinned (Figure 6). In Figure 6 the vertical distance between each trees' pre-hand thinning fruit number and the post-hand thinning fruit number represents the number of fruits removed by hand thinning.

When comparing the Pometa fruit counting system using a cell phone with the Orchard Robotics camera system, the Pometa system counted more fruits than the Orchard Robotics system both before hand thinning and after hand thinning (Figure 7).

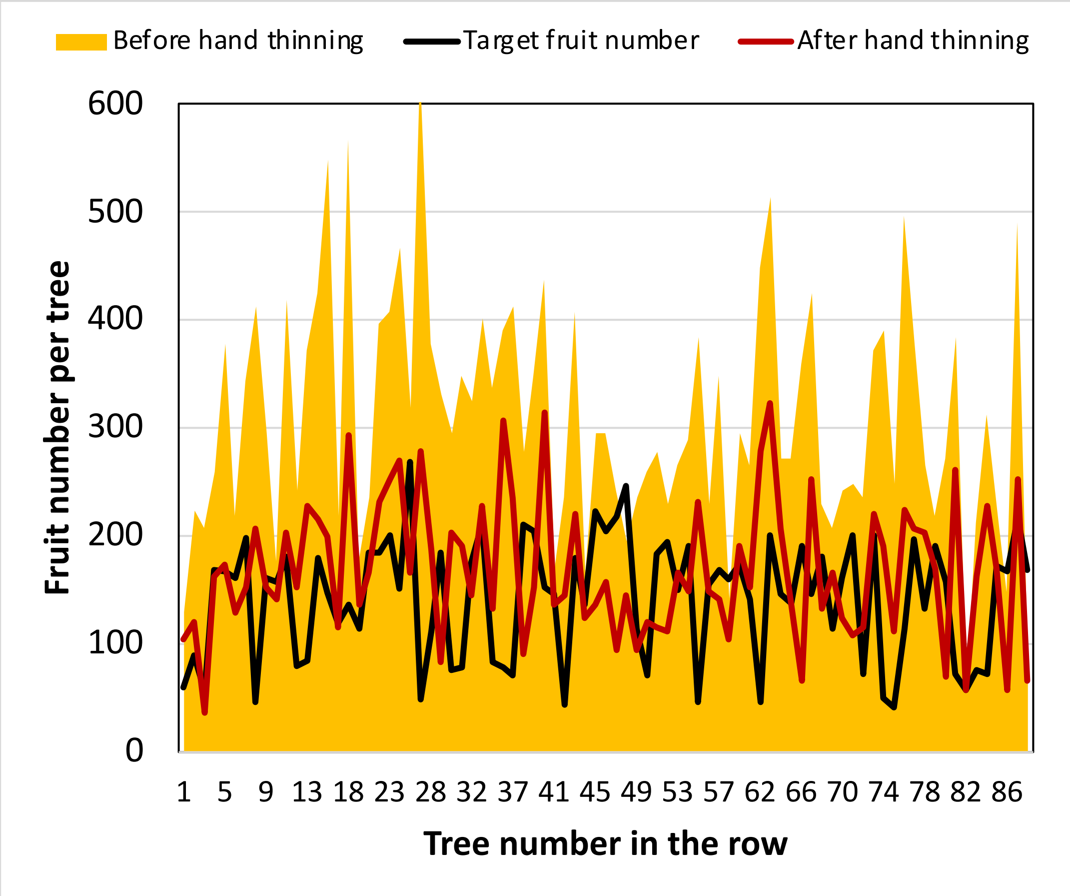

Figure 5. Estimated fruitlet number per tree of 'Gala'/G.41 apple trees measured using a proprietary camera vision system to count fruitlet number before hand-thinning at the Hudson Valley in NY State. The yellow line is the fruitlet number per tree before hand-thinning, The black line is the desired (target) number of flower buds based on trunk cross-sectional area with a target of 5.9 flower buds /cm^2 TCSA and the red line is the final number of fruitlets per tree after hand thinning.

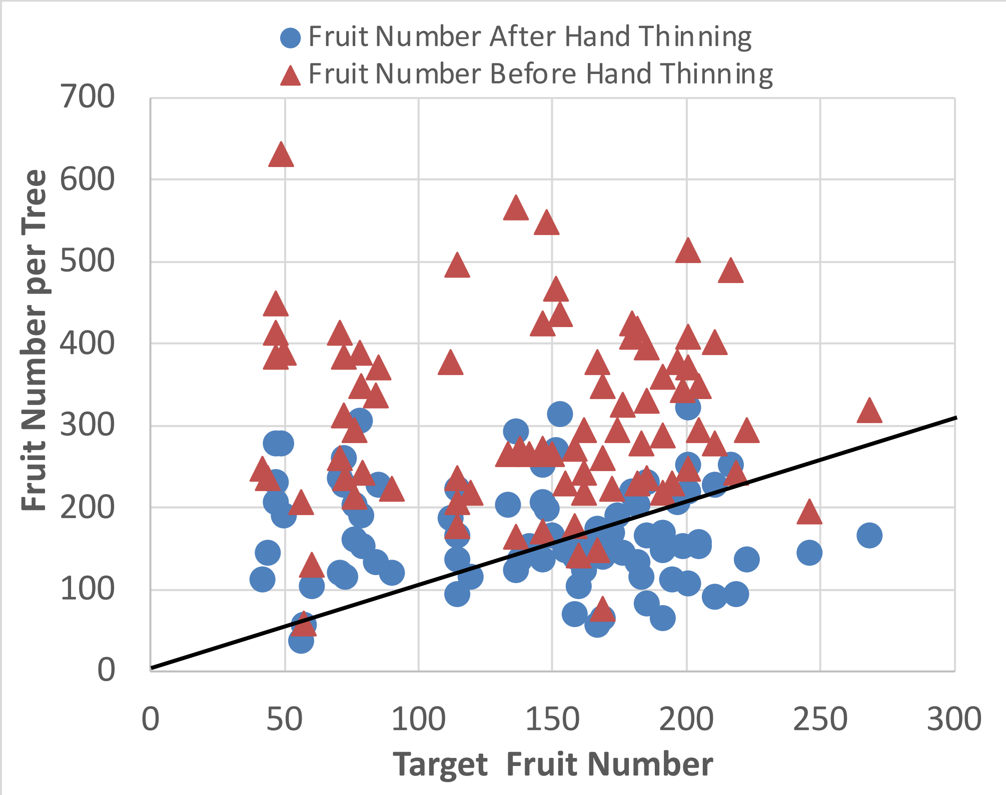

Figure 6. Relationship of the target fruit number per tree and the fruitlets per tree counted with the Orchard Robotics system before and after hand thinning at Hudson Valley, NY.

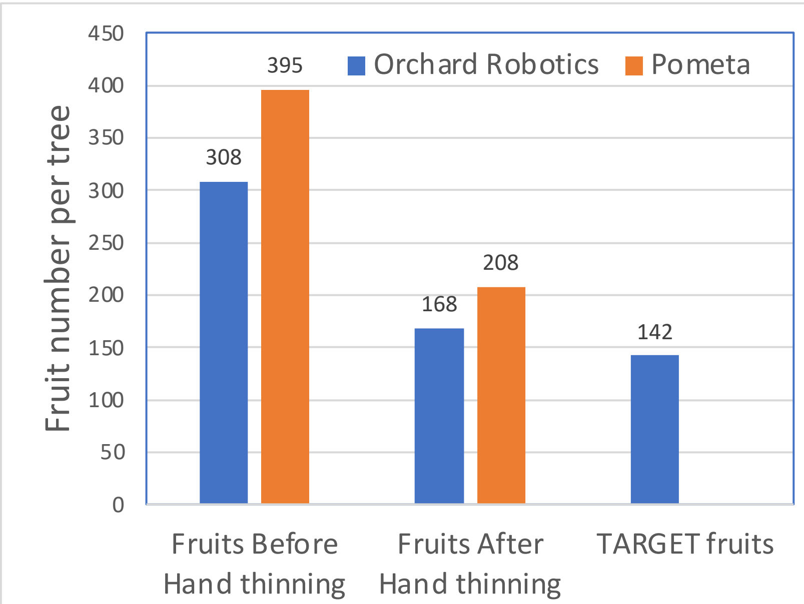

Figure 7. Comparison of the scan results before and after hand thinning using the Orchard Robotics camera system and the Pometa cell phone camera system at Hudson Valley, NY.

DISCUSSION

The results of the camera scans of dormant trees prior to pruning showed there was considerable variation in trunk diameter and bud number per tree. This resulted in a variable optimum (target) fruit number per tree. This variability in tree size and bud number before pruning arises from several sources. An important cause of this variation in NY State is fire blight which in some years results in infections which cause tree death of trees on M.9 requiring re-planting of trees (Gonzalez et al., 2023b). However, there is also variation along the tree row from variation in tree size at the time of planting the nursery trees. In addition, there is variation in tree size due to variability in soil properties along the tree row. This variability in tree size and optimum (target) fruit number is the primary reason why precision crop load management of each individual tree is so important. If the average bud number per tree for the whole row (524) was used and then pruning was done to reduce bud number on each tree to the target number of 304 (a removal via pruning of 220 buds) some trees would have been over pruned while others would have been under pruned. We have previously shown in a 17-year study that a high number of floral buds results in a high number of final fruits despite later chemical thinning (Lordan et al, 2019; 2020). Thus, pruning to a bud number close to the target number is essential for managing crop load to the optimum fruit number (Francescatto, et al, 2020). We have previously proposed for 'Gala' to leave a bud number equal to 150% of the target fruit number (Francescatto, et al, 2020).

The results of the precision hand thinning study whether at Geneva or at the commercial orchard in the Hudson Valley showed that considerable variation in fruit number per tree exists along a row even after pruning and chemical thinning. The variability in trunk circumference between trees in the row resulted in important differences in the optimum crop load (target) of each tree in the row. When each tree was hand thinned to the optimum number the final fruit number was closer to the target number than before hand thinning; however, there was still variability indicating that our hand thinning was not perfect even when we gave each worker a specific number of fruitlets to remove. Nevertheless, the final fruit number was close to the target number and would be a significant improvement over hand thinning all trees in the row similarly.

We have long suggested that precision crop load management should be done on each tree in the orchard and not based only a few representative trees (Robinson et al., 2013, 2021, 2023). It is likely that some orchards in the world have less variability than the two orchards we used in this study but such variability around the world has never been evaluated. In our experience we see significant variability in all the orchards we have visited.

We are working with several companies which use ground driven cameras, cell phones or drones and computer vision to count fruit numbers per tree on a whole orchard basis (Jiang et al., 2023; Robinson et al., 2023; Wallis et al., 2023). Some of the companies do not generate data for each tree but produce data for a section of row. The two companies we compared in this study do give individual tree data. We believe that to precisely manage crop load, estimates of the number of floral buds or flowers or fruitlets of each tree plus geo-referencing of each tree is required so that information on each tree can be communicated to human workers to adjust bud number or fruit number.

All of the computer vision systems we have worked with whether with ground driven cameras or drones have some errors in fruitlet or bud counts because they cannot detect all fruitlets due to occlusion. Thus, they all require a correction factor in their algorithms that is obtained by manual counting of some representative trees or row sections.

CONCLUSIONS

Precision crop load management is currently hampered by imprecise and tedious time consuming manual counting of fruit number per tree. We are developing machines which use computer vision to automate counting of floral buds, flowers and fruitlets to guide precision pruning and precision chemical and hand thinning. These advances should result in greater adoption of precision crop load management of apples than has been currently achieved using manual counting methods.

ACKNOWLEDGEMENTS

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