# **2024 Technology Research Review**



Industry members observe a 3-row, variable rate sprayer in action (company: Munckhof) near Ephrata on April 26, 2023. Photo Credit: Ines Hanrahan

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# Project Title: Automated Apple Harvester

Report Type: Continuing Project Report

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Cooperators: CNH, Yamaha, Kubota

Project Duration: 3-year (already completed first two years)

**Total Project Request for Year 1 Funding:** \$180,000 (completed) **Total Project Request for Year 2 Funding:** \$140,000 (in progress) **Total Project Request for Year 3 Funding:** \$165,000

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

Budget 1 Primary PI: Marc Grossman Organization Name: Advanced Farm Technologies Contract Administrator: Peter Ferguson Telephone: 313-480-6964 Contract administrator email address: peter@advanced.farm

2022	2023	2024
Half of Salary for additional	Compensation for two	Portion of Mechanical
mechanical engineer that	assembly technicians for	Engineer Salary - \$70,000
will work on initial	building additional machines	
harvester development -	- \$70,000	
\$50,000		
Cost to have 1 full-time	Engineering material costs -	Portion of Software
employee in WA during	\$55,000	Engineer Salary - \$70,000
harvest season - <b>\$30,000</b>		
Half of Salary for additional	Travel between WA and CA	Orchard Field Data
emulator developer -	- \$15,000	Collection - <b>\$25,000</b>
\$50,000		
Harvester Materials – Cost		
of 4 robots for prototype -		
\$50,000		
Total: \$180,000	Total: <b>\$140,000</b>	Total: <b>\$165,000</b>

#### Objectives

2023 has come with new opportunities and new challenges for advanced.farm. In October, we announced new funding from CNH. We were very happy to add CNH as a partner and hope that their interest brings credibility to our work.

As stated in the 2021 proposal for advanced.farm, our initial objective was "to develop an automated apple harvester to give apple growers a sustainable solution to deal with labor shortages and rising labor costs. While we are very aware of the painful failures that have occurred in past attempts to develop an automated apple harvesting system, we believe that we have unique competitive advantages to help us meet this objective." This objective remains unchanged, and we have worked tirelessly for the past two years to carry out this vision. **In 2023, our robots picked 270,675 apples, which was over 3 times as many as our 2022 total.** 

Our 2023 development goals submitted to the commission last year are summarized below in the italicized enumerated list. Text in the sub bullets lists our results.

- 1. Change the conveyor belts and bin filler to bring the damage rate down to less than 15%.
  - a. In 2022, one of our most noticeable problems was that we damaged a majority of the apples that we picked. Various tests showed that our gripper did not cause damage to the apples, rather the damage came from our conveyance and bin filler. We achieved the above damage metric on some varieties, but still have improvements we will need to make on varieties such as Honeycrisp. On Envy apples in October, we caused surface damage on less than 10% of apples. We also had good results on Gala apples. Unfortunately, we still damaged about half of Honeycrisp and Pink Lady apples.

The conveyance design changes included decreasing drops during the conveyance and making changes to the flaps and speed of the bin filler. One very noticeable change was that the initial drop onto the conveyance from the suction cup is on to a mechanical conveyor, rather than a drop ramp.

- 2. Adjust harvester size to accommodate nine-foot rows. The majority of formally trained vertical orchards are grown in nine-foot rows. This year we couldn't accommodate anything narrower than nine feet six inches.
  - a. We made our harvester narrower, and we really benefitted from being able to work on a formally trained orchard that was planted with rows 9 feet wide. We can now accommodate orchards with row-widths from 9 feet to 11 feet.

- 3. Build a user friendly operating interface. To operate the harvester this year, you needed to use a laptop and understand basic software code. Our strawberry harvesters have joysticks and simple controls. For this upcoming season, we want to be able to train local operators to use the machines instead of using our engineering team.
  - a. We did make the machine more operable. We had 4 field operators based in California that we sent to Washington for the season to operate the machines. As we work towards a future in which farmworkers employed by the ranches operate our machines, we will continue to look for ways to make for an easy operator experience.
- 4. Increase average apples per hour to 1000.
  - a. Last year, our machine averaged 420 apples per hour. This year, we increased our average to 788, nearly doubling our average from 2022. While we fell short of 1000, we still feel that we accomplished the goal. We averaged 1000 apples per hour for the entire time period from September 7<sup>th</sup> to October 18<sup>th</sup>. Our overall average is brought down by the first couple of weeks of the season when we were still working to integrate changes to our system and also due to a couple of orchards that were not well pruned for robotics. We had periods of 10 minutes when we had pick rates of as high as 2500 apples per hour. These peaks make us very optimistic and hopeful.
- 5. Build three new machines. To maximize our run-time, we will build two production harvesters and one R&D machine.
  - a. We ended up changing course on this shortly after writing last year's proposal. We decided to only build two machines. Until our performance metrics are in line with the needed metrics for commercialization, it does not make sense to spend capital on additional units. The two machines were similar to last years' units but had undergone many changes. I list some of the changes below.
    - i. Changes to make the unit more water resistant. We learned during our first year of harvest, that regardless of weather, we needed to make our system more water-proof to avoid damage to our system from sprinklers.
    - ii. Conveyance and bin filler changes as discussed previously.
    - iii. No more exposed wires. Last year, we had exposed wires on the robotic arms that could get caught on branches. This years' suction cup design was simpler and all wires were internal. This also helped the vision system to have a better view because the gripper was not taking up so much space and blocking the cameras.

- Many software changes were made during the offseason and during the season itself. These greatly contributed to our increased picking speed.
- 6. Work with our growing partners to optimize their orchards for robots. This year we had little pruning done in preparation for the season. For next year, we will work with our partners in the winter to optimize an area for our trial.
  - a. We came out in December and January to visit the orchards we planned to harvest during the 2023 season. We worked with the growers to plan what would be needed. Our instructions were that we needed fruit and branches to not extend more than 12-18 inches from the wire. The results were mixed. Some growers were able to adapt their orchards to meet our requirements, while others struggled to sufficiently open up the canopy. We performed best at orchards that had existing pruning and training conducive to robotics.



Snowy Winter Pruning Visit

- 7. Trial new systems such as an automated stem trimmer and drive system updates that allow us to handle steeper slopes.
  - a. We started prototyping some stem trimming systems this year. The solutions were mechanical, but still manually operated. Our initial tests yielded good results and didn't cause damage to the apples. Next year, we intend to have a semi-automatic version of our stem-trimmer. Likely, the stem-trimming will be automated, while a person will manually orient the apples. In 2025, we intend to have fully developed stem trimming technology. We continued to avoid orchards that had significant slopes.

Because our last day of picking was November 8<sup>th</sup>, our goal-setting for next season is still underway. However, our main objectives will be about increasing pick speed, increasing thoroughness (% of apples we pick vs. the apples left behind on the trees), decreasing the number of apples we damage, and decreasing the number of apples that end up on the ground. We are exploring many possibilities for accomplishing these objectives.

#### **Significant Findings**

- Every ranch is different. Even amongst ranches that have similar set-ups, there will always be differences.
- A major problem that needs to be solved is decreasing the amount of fruit that gets knocked off the trees onto the ground.
- Our system can achieve extremely high picking speeds. This creates a lot of optimism.

#### Methods

Our development is guided by our list of product requirements that we have put together based on input from growers. As we learn more about the problem, we update product requirements. I list some of the requirements below:

- The harvester operates at a pick rate so it reaches positive unit economics identified as >2500 apples per hour. We are proud to have accomplished this rate in 2023.
- 2. Sufficiently high thoroughness to significantly reduce headcount (referring to the percentage of fruit we pick vs. the amount of fruit we leave behind). The exact percentage will vary based on the training and pruning of the orchard. On a highly trained orchard, we want to pick >80% of the available fruit, leaving only 15-20% for humans. Since most orchards are not fully trained with branches tied onto the wires, our actual thoroughness will generally be lower, but will still need to be around 50%.
- 3. The harvester does not damage the fruit from pick to the bin (<5% of apples are culled due to the harvester)
- 4. The harvester minimizes apples falling from the tree. (For every 20 apples the robots pick, they cause no more than 1 apple to fall to the ground)
- 5. One farmworker can operate multiple machines at the same time.
- 6. Harvester maintenance has minimal disruption during the season.
- 7. Harvester is capable of automated stem trimming.

Our list includes more specific requirements as well, for example, the sizes of apples that we need to be able to pick, the uptime we need to achieve (we intend for the machines to be used multiple shifts per day), and several others.

At the end of the 2022 season, we put together several goals for the 2023 harvest season. In subbullets I describe our results.

- 1. 1000 apples per hour average pick rate
  - a. Result already noted.
- 2. <15% apple damage caused by the harvesters
  - a. Result already noted.
- 3. Operate 80 days during the season
  - a. We operated for 62 days. We generally did not operate on weekends. Still, we doubled our picking hours compared to last year.
- 4. 5 hours of picking / day
  - a. We achieved 5 hours of picking per day. This is hard to do. Even though we were often in the orchard for more than 12 hours in a day. There is a lot of time spent working on the machine when it is not actively picking.
- 5. 30% thoroughness
  - a. We struggled with this. We never achieved more than 20% thoroughness. This will be a big focus going into next season. We have already identified a new camera that we are planning to use to address this.

As we continued to develop, we adjusted some of these goals and defined that we wanted to have specific weeks in which we achieved the goals but recognized that due to the ongoing nature of R&D and regular iterations, we likely wouldn't accomplish all of the goals every single day.

In June, we spent 4 days picking stone fruit in Fresno, CA. We met a local grower who is growing peaches, plums, and nectarines on vertically-trellised trees. We identified it as a good opportunity to test our machines during the off-season. Our stone fruit testing allowed us to test our updated autodrive, picking motions, and conveyance system in an actual tree-fruit orchard.

We have many other testing and development tools that we use during the off-season. We have a digital emulator that we use to deploy our code in a virtual environment that mirrors an apple orchard. We also have a test-trellis that has magnetic plastic apples in our machine shop.



Mock Apple Tree with Robot



Digital Emulator Used for Testing

#### Results

We began picking apples on July 31 in Mattawa where we picked Wild-Fire Gala apples and Premier Honeycrisp apples. Our last day of harvest was November 8 in Wapato where we picked Pink Lady apples. Overall, we picked 8 different varieties at 8 different ranches. Our performance generally increased throughout the season but was at times limited by ranch conditions and weather. I list our season's schedule below. Our best performances are underlined.

Dates	Variety	Apples	Avg Apples	Notes
	Region	Picked	/ Hour	
7/31 - 8/17	Wildfire Gala	16,221	365	Apples per hour was lower due to
	Premier Honeycrisp			early season tech issues and ranch
	Mattawa			was bushier relative to other
				orchards we went to.
8/19-8/25	Gala	<u>30,464</u>	<u>858</u>	Significant jump in performance
	<u>Pasco</u>			due to software improvements and
				ranch conditions
8/28 - 9/6	Honeycrisp	5,159	297	Ranch conditions were bushy. Our
	George			machine got caught on branches.
<u>9/7 - 9/21</u>	<u>Honeycrisp</u>	<u>54,095</u>	<u>818</u>	Ranch had ideal pruning and
	<u>Cowiche</u>			training.
9/25 - 10/05	<u>Kanzi</u>	103,089	<u>1,118</u>	Software changes resulted in
	<u>Ephrata</u>			performance jump.
10/09 - 10/18	Envy	26,236	<u>1,045</u>	We continued to improve
	<u>Pasco</u>			hardware/software, but struggled
				with some ranch conditions.
10/16 - 10/18	Fuji	3,299	569	Ranch conditions were bushy. Our
	Zillah			machine got caught on branches.
10/24 - 11/08	Pink Lady	31,950	657	Cold weather had unanticipated
	Wapato			affects to our system that dropped
				our performance

Throughout the season, our performance improved due to software changes. Some of those changes are listed below.

- Decreased the amount of time that it took to drop the apple onto the conveyors and return to picking from 3.5 seconds to 0.9 seconds.
- New machine learning model to decide the order of which apples to pick first (sometimes one apple is impeding access to another apple. In the case of clusters, picking in an optimized order can decrease the number of apples that fall off the tree.)
- We learned how to detect the wire. At the beginning of the season, our system would sometimes try to pick apples that were actually on the other side of the wire. Our suction cups would often get snagged on the wire.
- We gradually started picking fruit that was more occluded.
- We improved our auto-drive system to stay more precisely centered in the rows.

Ranch conditions greatly affected our performance.

- The most ideal conditions are those that are consistent. When all the fruit and branches are within 9-18 inches of the wires, we will have the most success.
- Ideally, the branches will be tied onto the wires.
- Due to the size of our machines, we usually had trouble if branches came out further than 18 inches from the wire. Branches would get caught on the machine and cause errors.
- Because our machine has robots on both sides, we struggled at ranches that had inconsistent row-widths. One ranch was reported to have 10-foot rows, but some of the rows were actually more than 11.5 feet wide. This caused us issues in being able to reach the fruit on both sides of the row.
- The cold weather affected our system considerably during the last 2 weeks of the season. The freezing temperatures affected our camera lens and several parts of our system and caused a decline in performance.
- At times, we struggled with variability in apple size. On early season Galas, we had to use a smaller suction cup. We were surprised by the large size of Envy apples, and had to make changes to our conveyance system to accommodate.

Overall, our robots picked 270,675 apples during the 2023 apple season. Our 2022 total was 79,347. We still have a long way to go, but we are happy with our progress. We have shown that we can pick apples very fast, but we still need to improve in picking a higher % of the apples (thoroughness). We also need to damage fewer apples and avoid knocking apples onto the ground. We intend to return to Washington in 2024 with a system that has improved on these problems.

By keeping our material costs low, we are still confident that we will be able to build a machine that helps solve growers' problems with a shrinking labor supply and increasing labor costs.

### **Funding Request**

Year	2024
Portion of Mechanical Engineer Salary	\$70,000
Portion of Software Engineer Salary	\$70,000
Orchard Field Data Collection**	\$25,000
Total Funding Requested for 2024	\$165,000

The orchard field data collection is a new item on my budget request. I have discussed this with Ines Hanrahan. We desire to hire someone, perhaps a grad student or someone else that is knowledgeable about the industry, to work with us to gather data throughout the season at every ranch we go to. Having deep data regarding our performance and ranch conditions would help guide our development. While we try to gather this data right now, having someone who is completely tasked with this job would help.

### Conclusion

We are passionate about working with the Washington farming community and truly desire to add value by building robots that can alleviate their labor issues. Our work with members of the WTFRC over the last year has proven invaluable. We have appreciated the funding and hope that this fruitful partnership can continue.

# **Project Title:** Soil and Plant Diagnostic Technology for Smart Nutrient Management

Report Type: Continuing Project Report

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**Cooperators**: Elijah Lin (WSU Intern), Elda Bezuayene (WSU Student), Steve Mantle (Innov8Ag), Gilbert Plath (Washington Fruit & Produce), WSU AgAID, SoilTest Lab, Advancing Eco Agriculture.

Project Duration: 1-Year

**Total Project Request for Year 1 Funding:** \$17,812 **Total Project Request for Year 2 Funding:** \$18,094

#### **Other funding sources**

**Amount awarded:** AI Institute: Agricultural AI for Transforming Workforce and Decision Support (AgAID). NSF USDA. \$20,000,000. Kalyanaraman, et.al. (B. Sallato Extension Co-lead) **Agency Name:** NSF USDA

**Notes:** We will leverage extension and outreach activities that fit both project goals, as well resources associated to internships to support summer activities.

#### Budget 1 Primary PI: Bernardita Sallato Organization Name: Washington State University Contract Administrator: Hollie Tuttle Contract administrator email address: prosser.grants@wsu.edu

Item	2021	2022
Salaries		
Benefits		
Wages <sup>1</sup>	6400	6656
Benefits	640	666
Equipment		
Supplies <sup>2</sup>	10272	10272
Travel	500	500
Miscellaneous		
Plot Fees		
Total	\$17812	\$18094

**Footnotes:** <sup>1</sup> Wages: for sampling @ 16 USD/hour x 400 hours total + 10% benefits.

<sup>2</sup>Supplies: laboratory analyses of 384 samples @ \$35.50/sample soil and @ \$18 tissue samples x 2 sites, 4 areas, 3 reps and 8 dates.

#### **OBJECTIVES**

Our specific focus within the 'smart orchard project' has been to assess mapping technology for plant stress, vigor and fruit quality, soil mapping and testing methods, and the correlation between indictors. The project has been conducted in 'Grandview smart orchard' (Washington Fruit & Produce) and in the WSU WA 38 Roza Farm.

In addition, in 2022 we also incorporated plant nutrient analysis: Petiole sap testing (TribusProbe and VerdeSmart), Sap leaf analysis (Advancing Eco Agriculture) and standard leaf tissue testing (Soiltest Farm Consultants, Inc).

- 1. Assess soil variability mapping tools and soil testing methods that best reflect orchard conditions for effective management.
- 2. Evaluate plant nutrient test methods that can better predict nutrient status for effective management.
- 3. Develop outreach and extension activities; field days and durable products for continue learning, in English and Spanish.

#### SIGNIFICANT FINDINGS

- Four sites selected utilizing aerial image continue to have significant differences on productive indicators: yield and bitter pit incidence, being higher in S4.
- BP incidence was 36% lower in 2023 with a max incidence of 19%, strongly related to crop load/vigor.
- Consistent with 2021 and 2022, SoilOptix had a strong correlation with Ca, Mg and B. Providing an appropriate tool to map relative differences across the orchard.

- SoilOptix Mg mapping correlated with UAS derived blue data only.
- Strong positive correlations were found between leaf N% and UAS NDRE derived data and between Ca% and NDVI. While strong negative correlations were found between Fe% and RDVI and SAVI.
- SoilOptix can predict relative differences of K, Ca and Mg in leaves. Thus, aiding to identify sampling areas for greater representation.
- When correlating nutrient levels and productive parameters, fruit count correlated strongly and positively only with leaf N%. While leaf Ca correlated strongly but negatively with K, which reflects the antagonism existent between these two cations.
- Sap analysis of Mg, NH4 and Mo in older leaves correlated strongly with crop load, Ca correlated with fruit size and Cu with BP.
- Sap analysis of N and P in younger leaves correlates strongly with fruit size, while NH4 and S correlated strongly with bitter pit incidence.

### **METHODS**

This project will continue in Grandview Smart Orchard (Washington Fruit and Produce) commercial orchard and at WSU AgAID Demo Farm at the Roza (WA 38) Research block. In Washington Grandview orchard, we continue monitoring natural variability of the orchard, considering four distinct areas that have consistently shown differences in growth (vigor), fruit yield and fruit defects (bitter pit and cracking). In the WSU WA 38 site we focused on heat stress mitigation technology, demonstration of irrigation technology and aerial imaging.

# **1.** Assess soil variability mapping tools and soil testing methods that best reflect orchard condition for effective management.

Several mapping tools were contrasted and characterized in 2023, in relation to plant growth and fruit quality variability, and correlated to the standard soil testing methods recommended for Western soils (Gavlak et al. (2005)). In 2023, we contrasted the relationship between mapping tools, adding to the analysis, several salient data products obtained with a small unmanned aerial system (UAS) mounted with five-band multi-spectral imaging sensors (RedEdge3, Micasense Inc., Seattle, WA) and thermal infrared sensor (Flir DUO Pro R, Flir systems, Wilsonville, OR). These images were analyzed and we calculated several vegetation indices; Green Normalized Difference Vegetation Index (GNDVI), Modified Non-Linear Index (MNLI), Normalized Difference Red Edge (NDRE), Normalized Difference Vegetation Index (GN, Red (R), Near Ifra Red (NIR), Simple Ratio (SR), Photochemical Reflectance Index (PRI), Structure Insensitive Pigment Index (SIPI), Plant Senescence Reflectance Index (PSRI), Ratio Vegetation Index (RVI), Enhanced Vegetation Index (EVI) and Chlorophyll Index (CI).

In addition, continue monitor and ground truth of plant and soil physical and chemical indicators were collected in situ throughout the growing season. In 2023 we included two additional sampling depth (8, 12 and 24 inches) to better understand soil nutrient dynamics through the soil profile. Following the same protocol used in our previous studies, on each site, three composite samples were collected in a bucket, mixed well, placed in a labelled plastic bag and sent to SoilTest Farm Consultants, Inc. in Moses Lake, WA. The laboratory is certified by the Soil Science Society of America and the North American Proficiency Testing Program's (NAPT) <u>Plant Performance Assessment Program</u>, Soil and Plant Program, and Soil Performance Assessment Program. Soil testing methods included standard soil test (soil methods recommended for western US by Gavlak et al. (2005)), and soil health indicators; texture, pH, NO3, POX, Microbial Respiration CO2, PMN 7-day anaerobic Nitrogen.

# 2. Evaluate plant nutrient test methods that can better predict nutrient status for effective management.

In this project cycle we proposed to focus our efforts on plant nutrient / health indicators available. Thus, on each sampling site, three trees per site (n = 12) were selected and monitored for nutrient levels throughout the season, utilizing two methods; standard tissue test by Gavlak et al. (2005) and sap analysis offered as in-kind by Advancing Eco Agriculture (AEA).

Results from both methods were contrasted between each other and in relation to the plant productive variables (tree growth, fruit growth and quality, etc). In addition, nutrient levels were also contrasted with the vegetation indices derived from the UAS mapping detailed above.

# 3. Develop outreach and extension activities; field days and durable products for continue learning, in English and Spanish.

In WSU WA 38, in 2023 we have focused on demonstrating irrigation automation for three different training systems, each being monitored and managed independently. We have incorporated 6 soil moisture and soil water potential sensors and three capacitance-type probes. These sensors are connected to a data logger node (RF-M1, WiseConn Engineering, CA) to acquire data at 15-min intervals. These data wirelessly feed into an automated irrigation controller (DropControl, WiseConn Engineering, CA). We are monitoring localized in-canopy and above-canopy weather parameters to correlate with fruit quality. Additionally, two Crop Physiology Sensing System (CPSS) nodes developed by the CPAAS Precision Ag Lab were installed to monitor fruit surface temperature, critical to monitor and manage apple sunburn/heat stress. This orchard is used as a demonstration site for automation technology.

### RESULTS

Building on our previous project, identifying productive and fruit quality differences across the four selected sites was key to assess mapping technology. In 2021, there were no differences on fruit size among sites, while shoot growth (and indication of vigor) was 54% higher in S4 (30.3 cm), compared to S1 (19.7 cm) with lowest growth. Bitter pit incidence ranged between 1% up to 74% across the orchard with no differences among sites due to high variability. In 2022, total fruit per tree varied tremendously, between 2 and 135 fruit per tree, 4.4 and 2.2 times higher in S3 compared with S4 and S1, respectively. Consequently, fruit size at harvest was 11% smaller in S3 (67 mm) compared to all other sites. Bitter pit at harvest ranged between 2% and 52%, being 30 times higher in S4 compared to S3, correlating negatively with crop load. In 2023, total yield per tree varied between 56.8 to 172.4 lbs., being 2-times higher in S2 compared with S3 (p = 0.014). Despite this difference, fruit count per tree was not different across sites varying between 159 and 302 ± 39.8. Bitter pit incidence was again highest in S4 (p < 0.028) when compared to S2 and S3 (Figure 1), however the ranges were much lower than in 2022 (between 2 – 19%). These results highlight the relationship between bitter pit and crop load, and in this orchard, site differences explain 66% of bitter pit variability.

# **1.** Assess soil variability mapping tools and soil testing methods that best reflect orchard condition for effective management.

#### Soil variability

Consistent with 2022, in 2023 SoilOptix® there were positive and strong correlations with Ca, Mg and B levels on each site. The rest of the parameters had no correlation, weak or inconsistent (data not shown). When contrasting SoilOptix mapping tool and UAS derived vegetation maps, the blue (B)



Figure 1. Percent bitter pit in 2022 (left) and 2023 (right) between sites at the Grandview smart orchard. Bars indicate mean values and error bars indicate the standard error. Different letters indicate significant differences between sites (Tukey test, p < 0.05).

derived data had the strongest correlations (r > 7.0) with SoilOptix, but for a few indicators, including pH (r = 0.68), O.M (r = 0.77), Mg (0.77) and Zn (r = 0.70), however the probability was low (p < 0.10) (Figure 2). Given that SoilOptix Ca, B and Mg where the only elements that correlated strongly with actual nutrient levels (reported in 2022), and that there were no strong correlations between SoilOptix Ca or B with UAS derived maps, the only tool that could be used interchangeable would be UAS blue derived map and SoilOptix Mg.



Figure 2. 2022 correlation (r) between UAS Blue data derived data and SoilOptix pH, organic matter, magnesium, and zinc.

In 2023 we correlated SoilOptix with UAS derived vegetation indices, this time, utilizing all data points (total of 5447 in 16-acre block). The correlations were significant (p < 0.001) but weak (Table 1). Thus, SoilOptix data and UAS derived data provide different sets of information and cannot be used interchangeably.

Variables*	В	Ca	Mg	рН	Sand
SAVI	0.003	-0.109	0.013	-0.126	0.080
В	-0.199	0.328	0.142	0.314	-0.296
GNDVI	0.054	-0.169	-0.013	-0.174	0.136
NDRE	-0.012	-0.087	0.044	-0.099	0.054
NDVI	0.047	-0.163	-0.019	-0.173	0.133

Table 1. Correlation (r) matrix between SoilOptix indicators and vegetation indices derived from UAS mapping.

\*Soil -Adjusted Vegetation Index (SAVI), Blue (B), Green Normalized Difference Vegetation Index (GNDVI), Normalized Difference Red Edge (NDRE), Normalized Difference Vegetation Index (NDVI).

# Tree nutrient variability

The two mapping tools (UAS and SoilOptix) were also contrasted with leaf standard analysis to identify predictability utilizing mapping systems. The UAS vegetation derived indices vary across the season, thus the analysis needs to be conducted by date of sampling. On Jun 28th, strong positive correlations were found between leaf N% and NDRE (r = 0.75), Ca% and NDVI (r = 0.64), while strong negative correlations were found between Fe% and RDVI (r = -0.81) and SAVI (r = -0.82) (data not shown). Additional vegetation indices will be reported in 2024 report.

Similarly, SoilOptix correlations with leaf standard analysis varied across sampling dates. There were no correlations between leaf tissue nutrients and SoilOptix on three out of five dates (data not shown). On June  $2^{nd}$ , SoilOptix and leaf Ca (r = 0.95) and S (r = 0.69) had a strong positive correlation, while Zn (r = 0.82) and Fe (r = -0.65) correlated negatively (opposite) among methods. On June 16<sup>th</sup>, which coincides with the recommended timing for standard leaf tissue testing on 'Honeycrisp', SoilOptix and leaf tissue analysis correlated positively and strongly in K (r = 0.64), Ca (r = 0.85) and Mg (r = 0.65). While S, Zn and B were negatively correlated between methods (r = -0.75, r = -0.59 and r = -0.89, respectively). In conclusion, SoilOptix mapping predicted relative differences of K, Ca and Mg, levels, and could be used to guide sampling zones and variable rate nutrient application.

In addition to the relationship for the corresponding nutrient, SoilOptix CEC, pH, OM, Sand and PA Water correlated strongly (r > 0.66) with leaf P, K, Ca, Mg, Zn, Mn leaf concentrations on June 16<sup>th</sup>, with Ca and Zn on June 2<sup>nd</sup>, and with P and Zn on Sept 1<sup>st</sup> (data not shown). These correlations, attributed to several related factors, such as sand, silt, clay, leak, loam, PA water and CEC will be consistent across sites because they are estimated using models. Thus, the correlation among them ranges between r = 1 and 0.98. Consequently, a strong correlation with one of these indicators will naturally lead to a strong correlation with all others, being positive or negative.

# 2. Evaluate plant nutrient test methods that can better predict nutrient status for effective management.

Nutrient levels in 2023 were within adequate range for all macro elements (N, P, K, Ca, Mg, S), and below adequate range for Zn, which has been reported previously for WA tree fruit (Table 2). Only Zn and Mn were lower in S1 (p < 0.05) (data not shown) compared with S4, note that increased Mn levels is associated to excessive water in the soil.

Nutrient	Apple*	Min	Max	Mean	Std. deviation
Nitrogen (N)	1.7 - 2.5	2.33	3.13	2.66	0.18
Phosphorous (P)	0.15 - 0.3	0.12	0.37	0.22	0.05
Potassium (K)	1.2 - 1.9	0.48	2.44	1.35	0.38
Calcium (Ca)	1.5 - 2.0	0.58	3.10	1.41	0.65
Magnesium (Mg)	0.25 - 0.35	0.23	0.59	0.35	0.07
Sulfur (S)	0.01 - 0-10	0.09	0.36	0.20	0.05
Zinc (Zn)	35 - 50*	7.0	24.0	14.8	3.7
Iron (Fe)	-	140.0	581.0	350.2	108.5
Manganese (Mn)	25 - 150	18.0	73.0	38.1	13.2
Copper (Cu)	5 - 12	2.0	23.0	8.4	4.3
Boron (B)	20 - 60	12.0	62.0	43.0	12.2

Table 2. Leaf nutrient concentration for June 30<sup>th</sup> sampling date.

\*Critical range suggested for apple orchards. (Sallato et al, 2019).

When correlating nutrient levels and productive parameters, fruit count correlated strongly and positively only with leaf N% (r = 0.86), and bitter incidence (Figure 3). Higher BP incidence increases exponentially with fruit count below 50. Note that in 2022, there was a negative relation between P concentration and BP incidence (r = -0.63), with a clear reduction in BP incidence with leaf P levels 0.2%. In 2023, mean P values were above 0.2% in all sites which could explain the reduction in BP levels and lack of correlation.



Figure 3. Correlation between fruit count and leaf N concentration (left) and Bitter pit incidence (right).

Leaf Ca levels also correlated strongly but negatively with leaf K (r= -0.57) and positively with Mg (r= 0.63), Mn (r= 0.69), Zn (r = 0.51). The negative relation between Ca and K reflects the extensively reported antagonism between these two cations. Leaf Mg levels also correlated with Mn levels (r = 0.77).

#### Standard leaf tissue versus sap analysis

Standard tissue testing and sap analysis of old leaf correlated strongly on Ca (r=0.85), and with less strength with P (r = 0.54) (Figure 4). All other elements had no correlations, or the correlations were weak (r < 0.5). Interestingly, standard leaf and sap Ca levels correlated strongly with sap Cl levels (r = 0.83 and r = 0.95, respectively), which might relate to the foliar CaCl sprays commonly used in the orchard.



Figure 4. Correlation between leaf tissue analysis and sap analysis for Ca (left) and P (right). The R<sup>2</sup> value corresponds to the coefficient of determination, and the r value corresponds to the correlation coefficient.

Interestingly, Mg, NH4 and Mo levels in older leaves sap correlated strongly with crop load (r > 0.70), Ca with fruit size (r = 0.80) and Cu with BP (r = 0.73) (data not shown). Sap N and P levels in the young leaves correlated strongly with fruit size (r > 0.85), while NH4 and S correlated strongly with bitter pit incidence (r > 0.81) (Figure 4). In relation to the site differences, sap S and Mn levels were higher in S4 (p < 0.006), like the tissue standard test. No other elements were statistically different across the sites, consistent with leaf standard test.

# 3. Develop outreach and extension activities; field days and durable products for continue learning, in English and Spanish.

We continue sharing findings throughout several WSU extension and outreach efforts. In 2023 we share initial findings at the WFTRC Apple review (January 25<sup>th</sup>, 2023), Apple Day, Chelan Tree Fruit Day, and Okanogan meeting. We provided a summary report on soil mapping technology published in our WSU Tree fruit newsletter "Fruit Matters" (Jan 2023). We conducted a "spring Drone Day" in May demonstrating mapping technology inviting different providers, a summary of the field day was published by Good Fruit Grower and in Fruit Matters. On June 21, 2023, we hosted the Western Ag Leadership tour, comprised ~60 Deans and extension professionals from Universities in the Western

US in the WA 38 site, showcasing heat and irrigation technology of the smart orchard project. In July, we coordinated a field day in Spanish at the WA38 Roza farm to update participants on heat stress mitigation technology, irrigation and the smart orchard initiative. In collaboration with our collaborators (Innov8Ag and WSU AgAID), we conducted two field days (August 2<sup>nd</sup> and September 16<sup>th</sup>) where the PI's and their interns' shared findings. The August field day was attended by over 200 people and close to 30 growers attended the September Smart Orchard + AgAID field day.



Figure. Correlation between sap mineral analysis of young leaves during August and fruit diameter (top) and bitter pit (BP) incidence (bottom).

#### Modifications to our original proposal

Given that the Grandview orchard has been removed. We propose to continue evaluating soil and tissue mapping tools in a new smart orchard site upon approval. The new site is a 3<sup>rd</sup> leaf WA 38 orchard, located near Mattawa. We predict that conditions will be more homogeneous (compared with the Grandview site), however we plan to impose different heat / irrigation strategies that will provide variability and the opportunity to assess these technologies in a different growing condition.

# **Project Title:** Insights into regulated deficit irrigation on apple growth and color development

Report Type: Continuing Project Report – Year 1

Primary PI: Dr. Andrew Bierer Organization: USDA-ARS, Appalachian Fruit Research Station Telephone: 1-304-725-3451 ext(326) Email: andrew.bierer@usda.gov Address: 2217 Wiltshire Rd Address 2: City/State/Zip: Kearneysville, WV 25430

Co-PI 2: Dr. Bernardita Sallato Organization: WSU, Irrigated Agriculture Research and Extension Center Telephone: 1-509-439-8542 Email: b.sallato@wsu.edu Address: 24106 N Bunn Rd Address 2: City/State/Zip: Prosser, WA 99350

CO-PI 3: Dr. Lee Kalcsits
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Telephone: 1-509-663-8181 ext(229)
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Address 2:
City/State/Zip: Wenatchee, WA 98801

**Cooperators:** Erick Smith (Taggares Fruit) <u>esmith@taggaresfruit.com</u>; Aran Urlacher (Zirkle Fruit) <u>aranu@zirklefruit.com</u>

Project Duration: 3-Year

Total Project Request for Year 1 Funding:	\$ 89,586.00
<b>Total Project Request for Year 2 Funding:</b>	\$ 40,557.00
<b>Total Project Request for Year 3 Funding:</b>	\$ 42,380.00

Other related/associated funding sources: Awarded Funding Duration: 2023-2025 Amount: ~\$XX,XXX (total in-kind support not yet known) Agency Name: Phytec Notes: Additional equipment/operating costs for services rendered by Phytec above the sub-award amount made from primary PI to Phytec will be supported by the Phytec organization.

WTFRC Collaborative Costs: None.

#### Budget 1

Primary PI: Dr. Andrew Bierer

**Organization Name:** United States Department of Agriculture, Agricultural Research Service (USDA-ARS)

Contract Administrator: Brandon Riley

**Telephone:** 301-504-3451

Contract administrator email address: brandon.riley@usda.gov

Item	2023	2024	2025
Salaries	\$7,609.00		
Benefits	\$3,196.00		
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	\$40,000.00		
Travel	\$2,500.00	\$2,500.00	\$2,500.00
Plot Fees			
Miscellaneous	\$5,000.00	\$5,500.00	\$6,000.00
Total	\$58,305.00	\$8,000.00	\$8,500.00

**Footnotes: PI Bierer:** Salary at GS:1-step 2 + local adjustment for 4 months, fringe benefit @ 42%. Supplies as \$6,000 for irrigation modifications, \$34,000 for sensory equipment of which \$28,000 slated for sub-award to Phytec. Annual travel expense of \$2,500 to facilitate 2 site visits per year by PI Bierer. Miscellaneous costs of \$2,000 annually for site maintenance/incidentals and \$3,000, \$3,500, and \$4,000 allocated to support outreach through an annual field day event at research sites.

Budget 2: Washington State University Co PI 2: Dr. Bernardita Sallato Co PI 3: Dr. Lee Kalcsits Organization Name: Washington State University (WSU) Contract Administrator: Samantha Bridger Telephone: N/A Contract administrator email address: bridger@wsu.edu

Item	2023	2024	2025
Salaries	\$14,039.00	\$14,600.00	\$15,184.00
Benefits	\$7,336.00	\$7,630.00	\$7,935.00
Wages	\$6,720.00	\$6,989.00	\$7,269.00
Benefits	\$686.00	\$713.00	\$742.00
RCA Room Rental			
Shipping			
Supplies			
Travel	\$2,500.00	\$2,625.00	\$2,750.00
Plot Fees			
Miscellaneous			
Total	\$31,281.00	\$32,557.00	\$33,880.00

**Footnotes: Co PI Sallato:** Salary of 0.2 FTE technician in 2023, 2024, 2025 + fringe benefit @ 57.8%. Wages supporting 8, 40-hour work weeks annually @ \$21.00/hr + fringe benefit @ 10%. Travel budget supporting bi-weekly site visits during the growing season. **Co PI Kalcsits:** Salary of 0.17 FTE technician in 2023, 2024, 2025 + fringe benefit @ 46.5%. Travel budget supporting site set-up, periodic site visit, and annual harvest/post-harvest events.

## **OBJECTIVES**

- 1. Establish 2 replicated RDI research trial locations in WA in collaboration with grower and commercial cooperators for Fuji and Honeycrisp cultivars, respectively.
- 2. Utilize a data-driven approach to autonomous RDI implementation through plant sensory and autonomous irrigation equipment. Provide guidance for RDI implementation when utilizing sensory equipment.
- 3. Determine imposed RDI treatment effects on fruit growth and color development as well as resulting fruit quality parameters (e.g., shape/size, firmness, cuticle thickness, soluble solids, acidity), to assess the efficacy of a data-driven approach to RDI for optimization of fruit quality.
- 4. Estimate economic viability of data-driven RDI implementation for improved fruit quality and color development. Contrast RDI economics with other color improvement strategies.

# SIGNIFICANT FINDINGS

- We established two RDI trials. 1) A Fuji commercial orchard near Mattawa, and 2) A Honeycrisp commercial orchard near Pasco, in collaboration with grower and commercial cooperators.
- Imposition of water deficit levels pursuant to project objectives could not be completed. Therefore, the 2024 cropping season will now be the first year of treatment imposition.
- Initial assessment of plant growth and development was equivalent among experimental units, which provides confidence regarding the experimental design for 2024.

### **METHODS**

1. Establish 2 replicated RDI research trial locations in WA in collaboration with grower and commercial cooperators for Fuji and Honeycrisp cultivars, respectively.

Two factors, water deficit and matric potential sensory depth, will be studied factorially at each location with 4 replicates. There will be 3 levels of water deficit, targeted soil matric potentials will reflect location soil water characteristic curve e.g., -30, -40, -50 kPa, and a control maintained at field capacity. There will be 2 levels of soil matric potential sensory depth, 30.5 and 61 cm, thus each trial will consist of 28 experimental units (EU's). Each EU consists of 5 or more consecutive trees within a row. To reduce border effects, EU's were separated into a minimum of 2 trees or 1 row. Autonomous irrigation activity and orchard sensorization shall provide a data-driven approach to RDI implementation (Figure 1). All infrastructure modifications and sensor equipment installation was completed in year 1. Collaboration with commercial agriculture technology companies is proposed to demonstrate the data-driven RDI use case with commercially available equipment.

a. Alterations to typical irrigation infrastructure will be made to accommodate the replicated RDI research. Existing irrigation infrastructure shall be modified pursuant to installation of hardware enabling automated irrigation control. Individual drip lines will be automated and traced by collaborating regional commercial agricultural technology providers at each location.

b. Four soil matric potential sensors (tensiometers or similar) will be installed 30.5 cm from the base of trees perpendicular to the row direction in each EU. Two sensors will be installed at depths of

30.5 and 61 cm, respectively, to permit study of sensory depth importance on autonomous RDI implementation.

c. Four dendrometers, 2 fruit and 2 trunk, will be installed in each EU. Trunk dendrometers shall be installed 30.5 cm above the graft union; fruit dendrometers will be installed following fruit set. Fruit dendrometers shall be moved every 3 weeks commensurate with field assessment of representative fruit size.

d. One sap flow sensor will be installed 61 cm above the graft union per EU enabling direct monitoring of tree water uptake under imposed RDI conditions.



2. Utilize a data-driven approach to autonomous RDI implementation through plant sensory and autonomous irrigation equipment. Provide guidance for RDI implementation when utilizing sensory equipment.

An RDI implementation shall begin following fruit set and thinning activities. At inception, RDI extremity will be based solely on soil matric potential thresholds corresponding to the soil water characteristic curve (SWCC) of soils at trial locations. The SWCC will be generated using the pressure plate extraction method. Subsequently, RDI extremity shall be modified with additional considerations of weather, field observation, and the array of plant and environmental sensory data.

a. Autonomous RDI implementation shall be achieved initially through pairing soil matric potential sensory data with automated irrigation infrastructure with commercial collaborators (Figure 1). Computer algorithms will be developed to trigger irrigation events as matric potential approaches or exceeds defined threshold levels. Tuning of the algorithm's irrigation frequency, timing, and quantity is anticipated in Year 2 to optimize convergence on matric potential targets.

b. Thereafter, physiological and environmental sensors shall guide the imposed matric potential targets in a feedback loop. In effect, observation of anticipated tree physiological response will indicate suitability of targeted conditions; divergence shall inform modification of RDI targets. Three extremities of RDI implementation remain desirable to inform on the severity of RDI implementation.

3. Determine imposed RDI treatment effects on fruit growth and color development as well as resulting fruit quality parameters (e.g., shape/size, firmness, cuticle thickness, soluble solids, acidity), to assess the efficacy of a data-driven approach to RDI for optimization of fruit quality.

The RDI viability, excluding economics as focused below, of the autonomous approach to RDI implementation will be assessed using descriptive and inferential statistics.

a. Mean and standard deviation will be presented for fruit quality parameters at each site to gauge uniformity of response to the imposed RDI treatments.

b. For fruit quality parameters, linear mixed effect models shall be developed by year and dependent variable. Fixed effects will include RDI extremity, matric potential sensing depth and their interaction. Replicate and location will be considered among random effects specified using the maximal approach. Significant effects shall be identified using the F-test from type 3 ANOVA,

multiple comparison corrected post-hoc testing will follow. Where applicable, orthogonal contrast testing will be used to address additional specific questions of interest posed by PIs, collaborators, and by growers.

c. Fruit growth and color development will be monitored seasonally using commercial fruit dendrometers and handheld color meters, respectively. Timeseries data will be compared with commercial development target guidelines where applicable. Pattern recognition in timeseries data will be performed through series decomposition; forecasting of timeseries data e.g., fruit color and size development, will be performed using machine learning algorithms.

4. Estimate economic viability of data-driven RDI implementation for improved fruit quality and color development. Contrast RDI economics with other color improvement strategies.

The benefit-cost analysis (BCA) will utilize observed and available data to compare economic benefits with economic costs of RDI implementation. A BCA will be conducted for the autonomous RDI approach in this proposal, and for several competing fruit quality improvement practices: reflective cover(s), partial defoliation, summer pruning. The BCA will be conducted using the framework presented in Figure 3, adapted from BCA approaches found in the literature which will guide the approach.

#### Timeline



# RESULTS

1. Establish 2 replicated RDI research trial locations in WA in collaboration with grower and commercial cooperators for Fuji and Honeycrisp cultivars, respectively.

• In 2023, the experimental design was modified to simplify implementation and analysis, with a reduction in the amount of equipment needed. This meant fewer water deficit levels from 4 to 3 plus a control; the remaining factor of soil moisture depth will remain at 2 levels. As a result, the number of experimental units was reduced from 32 to 28.

• Interested collaborators possessing existing Phytec contracts, i.e., Zirkle Fruit and Taggares Fruit, aided selection of research blocks at respective operations. Zirkle Fruit in Mattawa, WA, selected a mature Honeycrisp block planted in 2006; this orchard was specified as a V-trellis with 13' x 1.5' spacing (2200 trees/acre) on M.26 rootstock in Silty loam soil (USDA web soil survey). The Snake River Ranch of Taggares Fruit selected a mature Aztec Fuji block planted in 2015; this orchard was specified using tall-spindle architecture with 10' x 4' spacing (1100 trees/acre) on M.9-T337 rootstock in Loamy fine sand (USDA web soil survey).

• Project plot maps were generated for respective locations and sent to all collaborators on March 14<sup>th</sup>, 2023. At the Zirkle fruit operation, orchard block shape permitted the use of 4 statistical blocks arranged in four planting rows, each containing the 7 randomly assigned treatments. At the Taggares ranch, the shape of the orchard block and landscape heterogeneity resulted in the consideration of 7 planting rows, each containing 4 treatments; in this case randomization of treatment assignment was performed across the 7 planting rows. Plot maps are included below for consideration (Figures 2 and 3).



Figure 2. Arrangement of experimental units at the Taggares Fruit research site. Treatments 1 to 7 respectively correspond as: 1 – minor water deficit at 1' profile depth; 2 – minor water deficit at 2' profile depth; 3 – moderate water deficit at 1' profile depth; 4 – moderate water deficit at 2' profile depth; 5 – severe water deficit at 1' profile depth; 6 – severe water deficit at 2' profile depth; 7 – experimental control.

• Soil samples were taken in May 2023 to determine basic soil properties (Table 1). Soil texture analysis was performed and the results were utilized to derive the soil water retention curve (SWRC) using the Rosetta 3 model (<u>https://dsiweb.cse.msu.edu/rosetta/</u>). Rosetta model outputs were applied to the Van Genuchten model<sup>1</sup> for generation of SWRCs at each research location. Soil texture and Rosetta model results are summarized in Table 2. The derived SWRC for the soils at each site are summarized in Figure 3. Prior to completion of SWRC derivation utilizing specialized HYPROP quipment, the SWRCs depicted in Figure 4 will be utilized to initially guide levels of deficit extremity i.e., treatments.

<sup>1</sup>Van Genuchten SWRC Equation:  $\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha |\varphi|)^n]^{1-1/n}}$ 

 $\Theta$  = Volumetric soil water content, volume volume<sup>-1</sup>

 $\varphi$  = Soil matric potential, pressure<sup>-1</sup>

 $\theta_s$  = Saturated soil water content, volume volume<sup>-1</sup>

 $\theta_r$  = Residual soil water content, volume volume<sup>-1</sup>

 $\alpha$  = Inverse of soil air entry suction, volume<sup>-1</sup>

n = Dimensionless measure of soil pore-size distribution



Figure 3. Arrangement of experimental units at the Zirkle Fruit research site. Treatments 1 to 7 respectively correspond as: 1 – minor water deficit at 1' profile depth; 2 – minor water deficit at 2' profile depth; 3 – moderate water deficit at 1' profile depth; 4 – moderate water deficit at 2' profile depth; 5 – severe water deficit at 1' profile depth; 6 – severe water deficit at 2' profile depth; 7 – experimental control.

	pH	Organic Matter	Olsen P	Total K	Total Ca	Total Mg
		dg kg <sup>-1</sup>	mg kg <sup>-1</sup>		g kg <sup>-1</sup>	
Taggares	7.07	0.97	11.0	127.3	5.5	1.9
Zirkle	8.00	3.10	41.0	622.0	15.9	4.0

Table 1. Basic soil properties collected from research locations in May 2023.

Table 2. Soil texture ana	ysis and derived	Rosetta 3 model out	puts for each rese	arch location.
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	Sand	Silt	Clay	K <sub>sat</sub>	Θ <sub>r</sub>	Θs	α	n
	dg kg <sup>-1</sup>	dg kg <sup>-1</sup>	dg kg <sup>-1</sup>	cm day <sup>-1</sup>	cm <sup>3</sup> cm <sup>-3</sup>	cm <sup>3</sup> cm <sup>-3</sup>	cm <sup>-1</sup>	-
Taggares	70	4	27	8.5	0.11	0.42	0.01	1.37
Zirkle	42	50	8	40.0	0.06	0.41	0.01	1.54

• Irrigation alterations necessary to allow a proper randomized complete block design were made to commercial blocks from late March to early May 2023. Briefly, new 2" poly-line was routed from water mains overhead and across the front of planting rows under consideration. Vertical drops to multi-port distribution manifolds permitted installation of individual electric valving to direct water to each EU through multiple dripline runs. Crude environmental enclosures were installed in May and

June to protect valving from direct spray/sunlight (Figure 5). At the Taggares location, in-season reliance on under-tree sprinklers required installation of "Y" valves directly after electronic valving for experimental control over both drip and under-tree micro-sprinklers.



Figure 4. Derived soil water retention curves using the Van Genuchten model and Rosetta 3 model estimates. Results of soil texture analysis (Sand, Silt, Clay) were the sole Rosetta model inputs.



Figure 5. Electronic valving modifications made at cooperator research locations.

• Communication and logistical delays with the agricultural technology commercial collaborator, Phytec, prohibited installation of (i) soil moisture sensors; (ii) valve control equipment during the 2023 cropping season. Relevantly, USDA was unable to complete sub-award to Phytec stemming from slow administration. As a result, imposition of water deficit levels pursuant to project objectives could not be completed. Therefore, the 2024 cropping season will now be the first year of treatment imposition.

• Conversely, fruit and trunk dendrometers were made available by Phytec and installed at each location in late June 2023. Each EU contains 2 fruit and 2 trunk dendrometers which were placed according to representative tree vigor and average fruit size. Aspects of fruit growth were monitored as a baseline in the 2023 cropping season (Figure 5).

• Absence of a commercial collaborator for sap flow equipment predicated the need for a noncommercial alternative to be constructed. Washington Tree Fruit Research Commission had funded a project "*Development of economical wifi-connected open-source sap flux probes*" which was suitable. To permit deployment of 1 sensor per EU, the required 56 sensors and 28 dataloggers began in April 2023, installation of sap flow equipment occurred in late October and early November 2023 (Figure 6). Firmware concerns will be addressed over winter 2023 prior to initiating data collection.

• Tasks to be completed before imposition of treatments can begin in 2024 include: (i) installation of soil moisture sensors and electronic valve control system; (ii) alteration of sap flow firmware to permit the large scale of deployment and data acquisition; (iii) establishment of web database to coalesce data streams from Phytec and open-source sap flow devices.

• In summary, logistical delays prevented imposition of treatments during the 2023 cropping system, however, significant progress was made after the notice of fund award. Irrigation modifications are complete and await install of commercial valve control equipment. Fruit and trunk dendrometry sensors have been installed and captured baseline dynamics during the 2023 season. Non-commercial sap flow equipment was manufactured and installed. The project timeline has been shifted, accordingly, which may justify submission of a no cost extension to satisfy the intended project duration of 3 cropping seasons.



Figure 6. Growth aspects as monitored by Phytec equipment during the 2023 season.



Figure 7. Construction and installation of open-source sap flow sensors. Physical heat-pulse probes (top-left); datalogger (bottom-left); installed sap flow sensor (middle); environmental enclosure of sap flow system (right).

# **Project Title:** Integrated sensing and real-time control for intelligent fruit picking

Report Type: Continuing Project Report

Primary PI:Joseph DavidsonOrganization:Oregon State UniversityTelephone:541-737-9193Email:joseph.davidson@oregonstate.eduAddress:204 Rogers HallAddress 2:2000 SW Monroe AveCity/State/Zip:Corvallis, OR 97331

Primary PI:	Cindy Grimm
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Cooperators: Munckhof Fruit Tech Innovators, ABB Robotics, Thompson Hill Orchards

**Project Duration:** 3-Year

**Total Project Request for Year 1 Funding:** \$83,701 **Total Project Request for Year 2 Funding:** \$81,836 **Total Project Request for Year 3 Funding:** \$84,463

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

## Budget 1 Primary PI: Joseph Davidson Organization Name: Oregon State University/Agricultural Research Foundation Contract Administrator: Charlene Wilkinson Telephone: (541) 737-3228

Contract administrator email address: charlene.wilkinson@oregonstate.edu

	(Type year of project	(Type year start date of	(Type year start date of
Item	start date here)	year 2 here if relevant)	year 3 here if relevant)
Salaries	\$28,177.00	\$29,022.00	\$29,893.00
Benefits	\$8,674.00	\$9,360.00	\$10,080.00
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	\$3,000.00	\$1,524.00	\$1,500.00
Travel	\$800.00	\$3,500.00	\$800.00
Plot Fees			
Miscellaneous			
Total	\$40,651.00	\$43,406.00	\$42,273.00

#### Footnotes:

<sup>1</sup>Salaries includes a Graduate Assistant on a 9-month, 0.40 FTE appointment in years 1-3 (no tuition). Salaries also include 0.25 months per year for Joe Davidson and Cindy Grimm.

<sup>2</sup>Supplies include consumables such as fittings, raw stock, and off-the-shelf sensors.

<sup>3</sup>Travel budget is requested to support mileage and lodging for data collection and field experiments.

	(Type year of project	(Type year start date of	(Type year start date of
Item	start date here)	year 2 here if relevant)	year 3 here if relevant)
Salaries	\$35,550.00	\$35,430.00	\$36,690.00
Benefits			
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	\$3,000.00	\$1,500.00	\$1,000.00
Travel	\$3,500.00	\$500.00	\$3,500.00
Plot Fees	\$1,000.00	\$1,000.00	\$1,000.00
Miscellaneous			
Total	\$43,050.00	\$38,430.00	\$42,190.00

#### Footnotes:

Salary costs WUR are based on the so called topsector tariff (lower rate than market b2b tariff). Topsector tariff is for example also applied in The Next Fruit 4.0 project. It is a well-balanced calculation of a team consisting of research assistants, junior researchers and senior researchers. Per year the researchers on this project will be able to work about 270 hours (=34 days).

Harvesting is the most labor-intensive activity in fresh-market tree fruit production. The H2A program is becoming increasingly important for filling temporary, seasonal agricultural jobs, despite the costs and logistical complexities incurred by growers using the program. While the industry is highly motivated to automate its labor-intensive operations, there are still no commercial harvesters available for the fresh tree fruit market despite nearly four decades of research. Much of the prior work has focused exclusively on vision as the primary sensing modality, disregarding what happens after initial contact and ignoring the sense of touch that humans use to manipulate fruit during a pick. This has resulted in machines that can effectively see fruit on the tree, but not robustly pick and store them at the rates required for commercial adoption.

Our team's primary goal is to increase fruit detachment rates, reduce fruit spur separations, and minimize fruit damage via a novel, cost-effective end-effector embodied with a human-like sense of touch. To accomplish our goal, we have defined the following three research objectives:

- 1. Develop a prototype picking end-effector with integrated vision, force, and tactile sensors
- 2. Design i) algorithms for fusing multiple sensor streams during the pick; and ii) novel, closed-loop tactile picking controllers that incorporate this multi-sensory feedback
- 3. Evaluate the end-effector in preliminary lab/field trials in both Washington and the Netherlands to study the effects of cultivar, orchard system, and management practices on technology performance

To kick off the project, the project team organized mutual visits between Wageningen University & Research (WUR) and Oregon State University (OSU) for in-depth discussions, information exchange, and studies of regional apple cultivation systems. Two scientists from WUR visited OSU labs in Corvallis in April 2023. During the same visit, the WUR scientists also toured the Washington State University research station in Prosser, visited orchards in the Yakima Valley, and met with WTFRC board members. In return, an engineer from OSU traveled to Wageningen, Netherlands in May 2023 to visit the WUR labs and experimental orchard at Randwijk, where we identified locations for field experiments.

#### Significant Findings

This Continuing Report summarizes research results from the performance period of January-November 2023. The most significant findings from the past year include the following:

- When using the multi-suction cup array (OSU gripper), suction + finger deployment are required for successful picking.
- The single large suction cup (WUR gripper) results in sufficient grip force for picking.
- The Pull&Twist controller is an effective method to harvest apples with the WUR gripper; pulling only does not work in most cases.
- The V-trellis training system results in a very stiff apple suspension, sometimes causing the force-based picking controller to overshoot the target force and result in 'shaky' oscillating behavior.

#### **Objective 1: Develop prototype end-effector (OSU lead, WUR participant)**

Our first objective is fabricating a prototype apple harvesting end-effector with multi-modal in-hand sensing. This effort leverages and expands upon two preliminary designs developed at OSU and WUR, both of which incorporate suction. In this project we are investigating two parallel paths, "suction only" and "suction + soft fingers." Our goal is to identify the respective advantages and disadvantages of both approaches. For example, a potential advantage of "suction only" is less interference from collisions

between fingers and vegetation. A potential advantage of "suction + soft fingers" is a more secure grip that enables high acceleration pick motions; also, the fingers provide a platform to capture additional sensor streams about contact conditions, grip quality, etc.

**OSU end-effector**: We developed a novel dual-mode gripper (Fig. 1a) consisting of an initial suction cup-based actuation followed by a telescoping three-finger deployment that secures the apple. We were inspired by how octopuses catch their prey by gently placing their suckers on their target, and then embracing it with their tentacles. In a similar way, we use three multi-bellow suction cups placed on the palm of the gripper. These suction cups facilitate the initial engagement of the gripper with the apple (Fig. 1b) as they adapt to different shapes and sizes; they also account for localization noise that is often present in robotic manipulation and grasping. Each suction cup has an air pressure sensor providing feedback on the amount of vacuum, which can be used to determine whether the suction cup is engaged with the apple. This allows us to implement feedback control to achieve a better suction grasp by nudging the manipulator wrist until the three suction cups engage. The second actuation mode (Fig. 1c-e) takes place after the initial suction grasp, where three fingers are deployed from underneath the palm with a cam-following mechanism. With this simple approach the design can (i) achieve a circular path around the circumference of the apple, and (ii) perform a clamp that finally secures the apple for the following picking strategy. There are also in-hand vision sensors located between the suction cups, which are further described in Objective 2.



Figure 1. CAD drawing of the dual-mode gripper: a) Gripper with suction cups and fingers retracted. b) Gripper with initial suction stage holding the apple. c) - e) Sequential deployment of fingers for the securing grasp stage.

To evaluate the design, we first performed lab-based studies (using a physical apple proxy) to measure the grasp performance of the gripper. We checked the pose of the gripper w.r.t. the apple that provides the best engagement of the suction cups without any further control action. We found that when the gripper is oriented in such a way that it has two suction cups on the bottom of the fruit and one on top, it facilitates the engagement of the suction cups with the surface of the apple. Furthermore, we found that the most beneficial pitch of the gripper w.r.t. the apple occurs between 75 and 90 degrees (0 degrees aligned with apple calyx), which is where the apple surface is more even. Additionally, we tested how much offset from the apple center the gripper can withstand and still engage at least two suction-cups. In general, the gripper can withstand +/- 15mm of localization error w.r.t. the apple center and engage at least two suction cups over 80% of the time.

**WUR end-effector**: We developed an end-effector prototype with a single suction cup for the experiments in the Dutch orchard (see Fig. 2). The suction cup used in this gripper is very similar to the one used in an ongoing robotic apple picking project between WUR and two Dutch companies, RIWO Engineering and Munckhof Fruit Tech Innovators. The prototype end-effector was mounted on
the same type of robotic arm used at OSU (Universal Robots UR5e). We completed laboratory experiments at WUR to evaluate code and motion controllers for picking (see Fig. 2 (top right)). Our aim is to use identical experimental setups at WUR and OSU so that we can compare results. During the laboratory apple picking experiments at WUR a copy of the apple proxy and wireless IMU modules developed by OSU were used. The initial design of the prototype aimed to use the integrated force/torque (FT) sensor of the UR5e to collect force torque signals. During the first field trials it became clear that the somewhat rigid hoses connected to the prototype end-effector introduced significant sensor noise Therefore, we decided to integrate a decoupled force torque sensor in the prototype to improve FT readings and enable control of the robot.

The final tested prototype (Fig. 2 (bottom)) consists of the following components: a soft silicone rubber suction cup with tubes bypassing the FT sensor; a sensor to measure force and torque (Robotiq FT300); a pressure sensor to measure the vacuum levels in the tube (Festo SPTE); a combined color and depth camera (Intel RealSense D405) on top of the end-effector. The suction cup is connected to a vacuum pump with a buffer tank, and electric valves are used to switch suction on and off. The end effector has the following general operating principle: the camera on the gripper detects and localizes the apple, when the gripper reaches the apple the valves are actuated to turn the vacuum on. If positioned correctly, the apple gets firmly attached to the suction cup; the soft material of the suction cup prevents bruising during the picking process. While attached the apple can be picked from the tree, for example by a pull and twist motion of the robotic arm. After detachment the apple is released from the gripper by switching the vacuum off.



Figure 2. (Top left) CAD drawing of the end-effector developed for the Dutch field trials. (Top right) Laboratory experiments at WUR using the OSU apple proxy, wireless inertial measurement units, and initial prototype end effector design. (Bottom) Suction cup-based end-effector used in the Dutch field trials.

# **Objective 2: Design sensor fusion and control algorithms (OSU lead, WUR participant)**

#### Task 1 – Precision alignment using visual plus depth

The core algorithm for visual fruit localization using the OSU gripper's in-hand sensors is a Kalman filter running on a YOLO-mask image (in-plane control) plus a Kalman filter on the depth data from the time of flight sensor. We updated the deep learning algorithm from YOLO to YOLO 8, improving the output of the mask stage. We performed in-lab robustness to occlusion testing by building a rig (see Fig. 3) that enabled a custom amount of occlusion (using plastic leaves placed in a 3D printed frame). The results of these tests (with the new YOLO mask image) are that the algorithm is robust up to 80% occlusion. We also performed field trials (backyard and Prosser); the results of these have not been formally analyzed yet, but the primary observation is that the time of flight sensor can generate spurious data when outside. Plans for the next year are to 1) change the control to directly move the arm, rather than using MoveIt's path planning (the majority of the time spent on approach is in this routine), and 2) to analyze the time of flight data to robustly handle outliers.



Figure 3. Experimental setup used for occlusion testing with the OSU griper.

# Task 2 – Measuring grip/grasp quality and stem orientation

We did not work on Task 2 during this performance period. We will focus on this task next year, leveraging the field data that we collected this fall.

#### Task 3 – Intelligent pick directions

For our data collection, we implemented two naive geometric controllers and a more intelligent forceresponsive controller. The simpler of the two geometric controllers is a linear pull controller which pulls back along the central axis of the palm at a fixed speed until the apple is separated. The other geometric controller is a pull-twist controller which does the same thing as the linear pull, but simultaneously rotates about the same axis at a fixed angular speed. Unlike these two, the forceresponsive controller applies a series of heuristics to achieve and maintain consistent tension in the stem while disturbing the apple. The goal of this controller is twofold. First, we hope to better understand the tree's response to fruit displacement by examining the relationship between the path taken by the robotic gripper and the force data from the FT sensor in the wrist. Second, we hope to minimize the force needed to separate the fruit by changing the direction of the force until the abscission layer (which is weak in shear) fails, rather than increasing the force magnitude.

In addition to exploring the plant dynamics via this controller, we also gathered insight by directly sensorizing the tree. Each fruiting limb was sensorized with three wireless modules: one near the trunk, one near the free end, and one intermediate module. The modules are powered with a rechargeable battery and communicate with a central device using Bluetooth Low Energy (BLE). The modules can transmit their individual acceleration, angular velocity, and orientation over time. Our intention is to use this data to analyze the branch dynamics that lead to dropped fruit, in order to minimize the robot causing dropped fruit during physical interaction with the tree.

# **Objective 3: Integrated field trials (WUR lead, OSU participant)**

The main objective during the first harvest season of the project (Fall 2023) was to collect data in the real world. We conducted data collection at both Randwijk, NL and Prosser, WA. At each site we collected data twice, making improvements to hardware and software between sets of trials. The experimental data will be used to further develop sensor fusion and control algorithms and to refine the design of the two prototype end-effectors.

**Randwijk experimental orchard**: For data collection at Randwijk all equipment was mounted on a trolley (see Fig. 4). The goal of this year's orchard experiments was to collect data on different types of orchard systems/cultivars so that we can study the relationship between cultivation systems and successful robotic picking using the different picking controllers.

We collected data on apple trees of the Gala variety, including trees grown in a traditional spindle system and a planar fruiting wall (2D) system on a vertical trellis. Data was collected for a total of 62 apples (see Table 1 for details). Automatic fruit localization using computer vision was not included during this part of data collection; for each apple the robot arm with the end-effector was manually placed in front of the apple. Data collection started by switching vacuum on, attaching the apple to the suction cup, followed by letting the motion controller (either heuristic or a pull and twist motion) try to detach the apple from the tree. We recorded the following data during each iteration:

- 3D locations of the wireless IMU modules (near the trunk, at the fruit being picked, at the end of the branch)
- Branch thickness at branch probe points using digital caliper
- 3D location of the abscission layer of the apple
- Size and weight of the apple, length of the peduncle
- Harvest success or failure
- Damage and number of dropped apples
- IMU data on branch vibrations
- Time series of the force/torque data from both the Robotiq FT300 and integrated UR5e FT sensor
- In-line vacuum measurements
- Video footage from the camera on the gripper and an external GoPro camera observing the scene from a tripod

Date	Gala spindle	Gala 2d	Total
14 September 2023	17		17
27 September 2023	9	36	45
Total	26	36	62

Table 1. Number	of apples ha	rvested during data	collection at Randwijk.
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The main findings/lessons learned from the Randwijk field tests were:

- Using the integrated force/torque sensor of the UR5e robotic arm causes a lot of sensor noise as the data is influenced by the vacuum tube and cables.
- The fruiting wall tree training system results in a very stiff apple suspension, making the heuristic controller likely to overshoot the target force and result in 'shaky' oscillating behavior.

- The heuristic controller still has a tendency to sometimes push the apple when the target force is set to 0. Additional investigation of this behavior is required.
- The single large suction cup results in sufficient grip force for picking
- The Pull&Twist controller is an effective method to harvest apples; pulling only does not work in most cases.



Figure 4. Data collection setup during field trials (September 2023) in Randwijk, NL.

**Yakima Valley Orchards (Prosser, WA)**: In Prosser we collected data on Envy apples grown in a 2D trellis system (see Fig. 5). Using manual measurements, we collected the poses, dimensions, and abscission layer locations for each fruit. We also measured the diameters of the branches on which the fruits were growing. We then conducted picking attempts on the measured fruits, using our custom gripper and the three controllers described in Objective 2 / Task 3. During each attempt, we recorded timeseries data from the tree sensorization modules and the robot, recording the same quantities as in the Randwijk trials. Additionally, we collected data from the tree sensorization modules during six manual picks on two limbs. This will allow us to



Figure 5. Data collection at Prosser, WA (October 2023).

compare robotic and manual fruit picking with respect to their effect on the tree. Table 2 summarizes the scope of data collection at Prosser. As analysis is ongoing, significant results were not available at the time of submitting this report but will be shared during the upcoming research review.

Table 2.	Number	of picking	attempts	during	data	collection	at	Prosser.	Not	all	attempts	resulted	in
successfu	ıl picks. Al	l data was (	collected of	on a V-ti	rellis	system (En	ivy	cultivar)	•				

Dete		Total		
Date	Force-based	Pull-twist	Linear pull	Total
17-18 October 2023	19	16	6	41
1 November 2023			29	29
Total	19	16	35	70

# **Project Title: Low-Cost, Reliable Soft Arm for Robotic Tree Fruit Operation Phase II**

Report Type: Continuing Project Report

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**Project Duration: 2-Year** 

**Total Project Request for Year 1 Funding:** \$ 106,029 **Total Project Request for Year 2 Funding:** \$ 110,010

Other related/associated funding sources: None Funding Duration: Amount: Agency Name: Notes: WTFRC Collaborative Costs: None Budget 1 Primary PI: Ming Luo Organization Name: Washington State University Contract Administrator: Anastasia Mondy Telephone: (916) 897-1960 Contract administrator email address: <u>arcgrants@wsu.edu</u> Station Manager/Supervisor: Station manager/supervisor email address:

			(Type year start date of
Item	2023	2024	year 3 here if relevant)
Salaries	\$51,618.00	\$53,683.00	
Benefits	\$9,718.00	\$10,106.00	
Wages	\$23,314.00	\$24,246.00	
Benefits	\$2,379.00	\$2,475.00	
RCA Room Rental			
Shipping			
Supplies	\$8,500.00	\$8,500.00	
Travel	\$10,500.00	\$11,000.00	
Plot Fees			
Miscellaneous			
Total	\$106,029.00	\$110,010.00	\$0.00

Footnotes:

# **Objectives:**

*Objective*#1: Design, fabricate, test, and optimize a growing arm/manipulator for orchard operations (Luo – Lead, Karkee – Co Lead;)

*Overview in the proposal:* To perform various field operations in tree fruit production, our soft growing manipulator will have the following mechanical features: 1) 4 ft radius workspace - the proposed manipulator length (4 ft) is expected to cover the entire tree height (~8ft) when installed on a ground platform that is approximately half of the tree height. 2) Free movement in 3D space with up to 3 lbs payload (which is sufficient to carry most of the end-effectors such as a fruit picker or an electric scissors for pruning) - Our proposed manipulator must overcome gravity to grow, retract, and steer to reach any target within its workspace. 3) Ability to maneuver freely inside most tree canopies under 8 ft height: The diameter of our proposed manipulator and updated design of end-effector adaptor/mount allows the manipulator to pass through narrow spaces between branches.

*Our current achievement:* 

- Length: Can extend up to 4 ft (4ft is enough to achieve apple harvesting with a moving platform according to the current modern orchard's tree architecture and commercial robotic platforms).
- Speed: Manipulator displays 1.08 ft/s growing speed with 8 psi of pressure. We have observed that higher internal pressures and airflow rates result in dramatically faster extension speeds. Currently, the speed is limited by the airflow rate and the free spin speed of the central motor.
- Targeting Speed: The manipulator displays a target response time of 1.56 seconds with less than 0.1 in of steady-state error.
- Payload: 3.1 lbs. payload at 10 psi pressure input. This payload includes the weight of the tip mount, soft-gripper, and fruit. With the tip mount and gripper being under 2 lbs., there is sufficient payload to carry an apple under 1 lbs.
- Workspace: One ZED camera is able to detect around 6\*6-ft range within 3 ft depth. Our robot's optimal workspace has a spherical sector shape with a radius of 4 ft and 60 degrees of actuation in the 2D plane, providing a total workspace volume of 63.7 ft<sup>3</sup>.
- Pressure Reliability: The maximum input pressure of our fabric material's sealing is above 20 psi, and 5-10 psi is our operation pressure since it displays an adequate payload. In addition, we installed a pressure relief valve to reduce the risk of pressure overloading.
- System Reliability: The system can operate for prolonged periods of time, >1 hour, without a significant decrease in control performance due to the design improvements.
- R&D cost: The current prototyping cost (\$) of a single robot manipulator is eight times less than a single commercially available rigid manipulator. The estimated cost is approximately \$4,379, which is broken down into \$574 for materials, \$547 for manufacturing, \$2,474 for electronics, and \$784 for other mechanical components. The most expensive part is the central motor, which costs \$1,117. Due to the urgent timeline, we purchased an expensive and powerful motor to verify our system first. We believe we can find an alternative item under \$100 when system verification is done, and the overall cost will be under \$3000 at the commercial manufacturing stage.

*Objective*#2: Manipulator integration with a low-cost machine vision system and selected end-effector tools (e.g. for picking, year 1) (Karkee – Lead, Luo – Co Lead).

*Overview in the proposal:* To prototype a robotic system for field testing with various operations, we will develop a perception system and integrate it with the soft, growing manipulator. In addition, a commercially available cable driven soft gripper will be integrated (one at a time) with the end-effector mount (Obj # 1) to support apple harvesting use case.

Our current achievement:

- Machine Vision Model: The current model, utilizing yolov7, was trained on apple data collected in previous years at the Allan Brother's apple orchards in Prosser, WA. The measured apple distance has an error range from 0.04-1 in when varying the distance to the trees and 0.16-0.4 in when varying the angle to the trees. The average detection rate when varying the distance is 39.4% when varying the distance to trees and 27.0% when varying the angle to the trees. Newly collected 3D images of apples in the orchards will provide greater diversity in the dataset used to train a new machine vision model to improve proficiency in apple detection and position estimation.
- Machine Vision Utility: The apple detection module is compatible with the soft robotic manipulator's processing system, we are able to transfer positional data of apples through Arduino to later be used to direct the arm towards apples via servo actuation.
- Gripper Efficacy: The soft gripper with a stiff 3D-printed endoskeleton can grasp apples without causing damage to the fruit. This gripper end-effector has achieved a successful pick rate of 87% in a field test during the 2023 harvesting season.
- Gripper Weight: The gripper is lightweight enough (0.67 lbs.) to be mounted to the soft manipulator arm without exceeding the payload limit.
- Gripper Cost: Given the current design that does not require costly sensors, the price of one soft gripper unit stands at \$36.

*Objective#3:* Design and implement a low-level controller to achieve automated operation (Luo – Lead, Whiting – Co-Lead).

*Overview in the proposal:* Once the perception/vision system, end-effector tool (Obj#2) and soft manipulator (Obj#1) have been tested separately for their functionality, they will be integrated together for overall system evaluation in the simulated, laboratory environment as well as in the field environment using automated motion/control techniques discussed below.

Our current achievement:

- The current system is controlled using a split controller that adjusts the steering angles and the arm length simultaneously. The control loops for each of the system parameters were tuned individually before being combined.
- For a given goal point within the system's workspace, the current system has a response time of 1.56 seconds and a steady-state error of 0.1 in from the desired goal point.
- The control of the system can be further improved by the introduction of feed-forward terms determined by the improved mathematical model and by implementing an optimal controller. Both methods are currently being implemented and verified.

# **Overall progress**



Figure 1. Goals vs. current progress.

# **Significant Findings:**

*Objective*#1:

- The maximum operating pressure of the system is dependent on the maximum pressure of the fabric arms. So far, our fabric arms are capable of withstanding 20 psi. Thus, we can reliably operate at 10 psi, which is sufficient for apple harvesting.
- The growing and retracting speeds are affected by the airflow rate in and out of the system.
- The configuration of the steering motors impacts the system's ability to compensate for the effects of gravity on the fabric arm.
- The placement of the central motor outside of the enclosure prevents overheating and electrical connection issues.
- The friction from the end-effector mount has a significant impact on the speed of growing and retraction. The current design of the mount dramatically reduces this friction.
- The robustness and power output of power supplies need to be considered when using stronger central brushless motors and while using higher pressures.

*Objective#2:* 

- Compiling new 3D apple training data will create a more effective apple detection algorithm. Current average detection rates are 27.0% and 39.4% when varying angle and distance to trees respectively.
- Wrote Python code to communicate between the apple position reading code and sending that to the Arduino COM port.
- Embedding a flexible but stiff thermoplastic skeleton into the fingers of the soft gripper dramatically improves the picking rate.
- Found a successful pick rate of 87% for our gripper during picking efficacy experiments conducted in the 2023 harvesting season.
- Design changes drastically reduced the overall weight of the soft gripper end-effector to under 1 lbs., thereby meeting the payload requirements.
- Including a metal bolt as the soft gripper's pulley significantly improves the integrity and reliability of the soft gripper.

Objective#3:

- Tuning the control loops of each of the system's parameters resulted in faster response times and lower steady-state errors.
- The control of the system can be further improved by introducing feedforward terms and developing an optimal controller.

# Methods:

# *Objective*#1:

To address the design limitations of our previous work, the soft growing manipulator arm platform was redesigned from the ground up. Specifically, several aspects were improved to mitigate the effects of gravity and enhance the speed and control performance. These enhancements include a redesigned steering system, stronger fabric arm material and sealing, and a more potent central motor positioned externally to the pressurized enclosure. A diagram of the updated design is displayed in Figure 2. The fundamental design of the



Figure 2. The updated design of the soft growing manipulator arm platform.

soft growing manipulator still retains its four main components: the fabric arm, pressurized enclosure, steering system, and end-effector mount. Besides the addition of the electrical components required for the new central motor and increasing the airflow rate of the system, the electrical system and the

pressure regulation system remain unchanged. Even with all of these changes, the overall cost of the robotic platform has not dramatically changed, at an estimated cost of \$4,379.

<u>Pressurized Enclosure:</u> The pressurized enclosure utilizes a stock square aluminum extrusion and aluminum plates to reduce weight, machining time, and cost. The two plates with rubber gaskets clamp on the open ends of the extrusion using threaded rods to create an airtight seal. A threaded sanitary seal adapter is attached to the front of the enclosure to provide a place for the steering system to attach to the rest of the assembly. The central motor was moved to the exterior of the pressurized enclosure is the central pulley. To improve the safety and reliability of the enclosure, a pressure relief valve was added to the pass-through end plate, and the threaded rods were replaced with stronger, wider, and finer threaded rods. In order for the central motor to still have access to the central pulley, a pass-through hole was added for the pulley's rotary shaft. This pass-through hole uses a mechanical seal to retain air pressure while allowing the shaft to freely rotate.

<u>Fabric Arm</u>: The arm has a diameter of 3.2 in and a length of 2.3 ft. The arm connects to the front of the system using hose clamps, and the central pully cable connects to the end of the fabric arm. The white thermoplastic polyurethane heat-sealable coating is significantly thicker and denser. This thicker coating results in stronger and more reliable heat-seal without drastically impacting the weight or compliant nature of the fabric arm.

<u>Steering System:</u> The steering system now connects to the front of the pressurized enclosure using a clamping mechanism sourced from a sanitary seal, shown in Figure 3. The clamp allows the steering system to be adjusted as needed or removed entirely. The steering system is composed of three motors and pulleys mounted onto a steel plate, which use cables connected to the fabric arm via the steering collar to steer the arm. The orientation of the steering motors has been rotated 90 degrees counter-clockwise so that one motor's pulley is oriented completely vertically. This change allows the system to counteract the aforementioned effects of gravity on the fabric arm. Another change is the introduction of a TPU buffer that covers the region of the fabric arm in between the steel plate

and the steering collar. The buffer holds extra fabric from the fabric arm in a consistent shape. The extra fabric allows the steering region to extend when the steering motors release their cables. This change forces the steering cables to remain in tension during the steering process, thereby increasing the consistency of using buckling as a steering mechanism.

End-effector Mount: The end effector mount was also redesigned to reduce impedance during extension and retraction, as shown in Figure 4. The major changes include making the inner shell's diameter smaller and the outer shell's wider. The roller magnets are able to interact due to the inner shell magnets being connected to the shell via free-moving rails that side in and out radially. The outer shell is split into three sections held together via rubber bands. This design allows the outer shell to vary in diameter as the fabric arm slightly stretches while pressurized. This design significantly reduces the impedance by limiting the pinching one the fabric arm done by the mount without drastically increasing the weight. The entire mount is still lightweight at only 0.608 lbs.



Figure 3. Picture of the updated steering system design



Figure 4. The end-effector mount with all major components labeled.

*Objective#2:* 

Camera Selection: For our vision system, we utilize two RGBD cameras, one global camera, and one local camera on the end-effector of our soft robotic manipulator. The global camera is an Intel Realsense 435i camera, and the local camera is an Intel Realsense 405 camera. The average width of the space between apple trees is approximately 7.54 ft across the aisle. Therefore, the Realsense 435i's range of 1-10 ft is sufficient for this application. The Realsense 405 camera is a small and lightweight depth perception camera, which helps reduce the weight of the end-effector. The Realsense 405 camera has an ideal range of 1.64 ft for accurate readings, which is appropriate for the end-effector camera as it will be used for fine-tuning the position of the end-effector towards its target through actuation.

Apple Detection Algorithm: The current apple detection system is a trained yolov7 machine vision model. The yolov7 model has been trained on collected pictures from the orchards at the Allan Brothers apple orchards in Prosser, WA. 3D pictures were taken in fair weather conditions (mostly sunny), and frames of the RGB information were taken and labeled before being used as a training and testing dataset. In addition to the training of the machine vision system, we have implemented an additional code to run in conjunction with the yolov7's detect module. The additional code uses the real-time RGBD information from the camera and the results of the trained yolov7 algorithm to determine the 3D position of detected apples before sending this information to our console.

Design and Fabrication of soft robotic gripper: To overcome the shortcomings of the previous prototypes, our soft gripper end-effector went through multiple redesigns to improve harvesting efficiency. The current design uses fingers made from silicone rubber with a flexible embedded skeleton to increase the force produced at the tip of the fingers. This internal skeleton was 3D printed using thermoplastic polyurethane, a flexible material that would increase the rigidity and provide significant force at the tip of the fingers. Cables running from the fingertips to a pulley connected to a servo motor cause the fingers to collapse inwards, allowing them to fully wrap around the apple when triggered. Previous pulley designs were fragile and too complex to repair in an orchard environment. To address this issue, the pulley design was simplified to reduce repair time and increase lifetime. To detect apples, the gripper has a limit switch located in the center of the palm. Once the center switch is triggered, the servo motor rotates the pulley, creating tension in the cables and a moment at the tip of the fingers, bending them Figure 5: Soft robotic inwards and fully wrapping around the apple. The bottom limit switch is used for testing purposes to release the tension in the cables when pressed. The



gripper

gripper weighs approximately 0.67 lbs., thereby meeting the payload requirements.

#### *Objective*#3:

Mathematical Model: With the redesign of the physical structure of the robotic platform, a new mathematical model of the system was created. The updated model provides a far more accurate depiction of the physical system, which makes the control and movement planning of the robotic platform simpler and faster to compute and execute.

Controller: Using the updated mathematical model, a simple controller that controls the steering angles and the arm length concurrently was created. The parameters in this controller were individually tuned to achieve ideal performance for the respective parameter. Then, all of the tuned parameters were combined into a single controller. This controller shows promising response times and limited error, but it can be further refined through the implementation of an optimal controller and feed forward terms.

#### **Results and Discussion:**

#### *Objective*#1:

Manipulator Arm Payload Testing: The maximum payload of the arm was determined by incrementally adding 0.22 lbs. weights to the tip of the fabric arm while at a given pressure and length. The amount of weight, including the weight of the end-effector mount, that caused the arm to either buckle or sag significantly was considered the maximum payload for the given pressure. This process was repeated for pressures ranging from 1 to 10 psi in 1 psi increments. The entire process was repeated three times to account for possible sources of error. The test was conducted at a 2.6 ft arm length, as this length is representative of the typical operational arm length. This test found a maximum payload of 3.1 lbs. while at 10 psi. This payload capacity is more than sufficient for apple picking, as the end-effector mount and soft gripper combined weigh less than 2 lbs., allowing for apples up to 1 lbs. to be picked. Also, this process shows a linear relationship between the internal pressure and payload. This relationship means that with stronger fabric arms and better pressure systems, the payload capabilities can be further improved. Increasing the payload capabilities will increase the robustness of the system and allow for greater use in other orchard operations that require higher payloads.

<u>Growing and Retracting Speed Testing:</u> The growing and retraction speeds were determined by using motion-tracking cameras and reflective markers to record the positional data of the tip of the fabric arm while it moved. For growing speed, the arm was allowed to freely grow while the system was held at 8 psi. For retraction speed, the central motor pulled on the fabric arm as fast as it could while the system was set to 3 psi. From these processes, the growing and retracting speeds were found to be 1.08 ft/s and 0.82 ft/s respectively. These speeds can be further increased by using a more powerful central motor, as higher pressures can be used during growing, and faster speeds can be used during retraction. While more powerful motors may increase the cost, the central motor drastically impacts the performance of the system. Therefore, the benefits of a more powerful motor outweigh the costs.

<u>Fabric Arm Pressure Testing</u>: The heat sealing of the fabric arms with the new material was verified by testing three small fabric arms. These fabric arms were around 1.3 ft in length. The fabric arms were attached to a pressure testing setup where the internal pressure applied to the arms was slowly increased from 0 to 20 psi. All the arms tested survived the pressure testing up to 20 psi without any significant damage to the heat-welds. Pressures beyond 20 psi were not tested as the pressure testing setup was designed for a max operating pressure of 20 psi. This process demonstrated that the fabric arms can reliably operate at higher pressures without failing. Thus, while at our operating pressure range of 3 to 10 psi, the fabric arms are significantly more reliable, last longer, and are more durable.

#### Objective#2:

<u>Machine Vision Experimental Results:</u> The local (Realsense D405) and global (Realsense D435) cameras were used in the evaluation of the machine vision system's apple detection and distance estimation capabilities. The local camera had both distance and angle varied. The local camera was mounted to a linear rail and was moved toward and away from the trees. The distances measured from the tree were from 2 to 0 ft in increments of 0.33 ft. The angle of the camera with respect to the tree line was varied from -60 to +60 degrees in increments of 30 degrees. The local camera was initially placed 2 ft from the tree line. The global camera had only the angle with respect to the trees varied, as the distance between the tree line and the global camera will not vary drastically. The angle of the camera was positioned so it was 3.3 ft from the tree line.

The efficacy of the apple detection system was evaluated by comparing how many apples were detected versus the number of apples in the picture while varying the distance and angle to the tree line. From this process, varying the angle to the tree line decreases the likelihood of detecting all apples in the camera's view. Also, there are distances from the tree line that cause the vision system to struggle to detect all of the apples. However, these results do indicate ideal angles and distances that are feasible to implement with the soft manipulator platform.



Figure 6. Percentage of apples detected per (a) distance to tree line and (b) angle to tree line.

The distance was evaluated by taking the root of the sum of the squares for each position coordinate. The positions read by our console were the experimental positions, and the real positions of the apples were also measured by hand. The difference between the experimental distance and the real distance is the resulting error. When comparing the difference made by changing the distance or the angle relative to the tree line, the angular difference results in a smaller error margin across the board. There were two recordings where the yolov7 algorithm could not determine the locations of apples on the tree. These instances are recorded as non-values and treated as 0 apples detected.



Figure 7. Average distance error per (a) distance to tree line and (b) angle to tree line.

in the angle and distance relative to the tree between the experimental data gathered and the original data set used for training. For reference, the pictures used to train the model were relatively uniform in their distances from the tree line.

<u>Next Steps:</u> The current system has issues with detecting apples in certain positions or lighting, likely due to the lack of variation in the training set.

To improve the detection system, another set of 3D images were captured of the apples in Allan Brother's orchards this year, including cloudy

The positional information of the apples in each frame was recorded when varying the distance and angle to the tree line. The recorded positions included the 3D (X, Y, and Z) position of each apple relative to the camera. The camera's X, Y, and Z positions are read in from the camera's view as left is negative and right is positive (X-direction), up is negative and down is positive (Y-direction), and further in front of the camera is positive, and behind the camera is negative (Z-direction).

On average, the error in determining the apple positions is relatively uniform except at 1 ft and at rotations from -60 to 0 degrees relative to the trees. However, the average percentage of detected apples to undetected apples is still low at around 30%. The average day in Prosser, WA during October is cloudy with lighting conditions often changing throughout the day as the sun is occluded by the clouds. Additionally, there may be some discretion



Figure 8. Rate of successful picks for each of the gripper types.

weather, rainy/dewy weather, sunny weather, and in the morning, noon, and afternoon. This variation in data will make training more representative of the actual orchard, which will make the model more robust. Over 12,500 images were collected from the apple orchards and will be labeled to train a new model.



Figure 9. Gripper approaching, encompassing, and picking apple.

<u>Gripper Harvest Testing</u>: During the 2023 harvesting season, the gripper was tested to determine its performance in a practical setting. The testing was performed at the Allan Brother's orchard with the Envy apple variety. Certain aspects of the gripper were examined, including the reliability of the gripper, maneuverability within the tree canopy, and the rate of successful picks performed. Using thin fingers, the gripper was able to successfully wrap around apples with minimal interference from

obstacles such as neighboring apples, branches, and leaves. Three different types of printing patterns were tested for the embedded TPU skeleton, and full prototypes were fabricated from each. Around 40 apples were picked using each of the finger types, totaling 120 apples. The top performing gripper yielded a successful harvesting rate of 87%. Future work will include the addition of a twisting motion to replicate the motion of a human wrist, possibly further increasing the harvesting rate.



Figure 10. 3D positional data compared to the path specified by the mathematical model.

#### Objective#3:

Workspace Testing: The workspace of the system was verified by using the improved mathematical model to draw three different circle paths that within the proposed are workspace. Each path used the same arm length but had a different angle at the base of the arm. The 3D positional data of the tip of the endeffector mount was collected using a motion capture camera system. From this test, the paths



Figure 11. Plots of the response times for the manipulator arm's control parameters. All parameters converge to the desired point within 1.56 seconds with an error less than 0.1 in.

that the arm made using solely the mathematical model were relatively close to the desired paths and resembled a spherical sector shape.

<u>Response Time Testing</u>: To test the response time of the system and the controller, a simple point test was conducted. In which an arbitrary point within the system's workspace was chosen as the goal location, and the manipulator arm moved from its default configuration to the goal point. From this test, the response time was 1.56 seconds while only having a distance error of 0.1 in. As mentioned before, these metrics can be further improved by adding feed forward terms to the controller and developing an optimal controller for the system.

#### Project Title: The Next Fruit 4.0

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3,156k€ for 4 years
Dutch ministry of Ministry of Agriculture, Nature and Food
Total project size is 3,156k€ for 4 years, the other half (1,578k€)
nd companies (in cash/in kind) and the Washington Tree Fruit
t that is financed by WTFRC is stated below.

Item	2021	2022	2023
Salaries	\$54,000	\$54,000	\$54,000
Benefits			
Wages			
Benefits			
Equipment	\$5,000	\$5,000	\$5,000
Supplies			
Travel			
Miscellaneous			
Plot Fees			
Total	\$59,000	\$59,000	\$59,000

#### **Objectives overall project**

Making fruit cultivation more efficient, intelligent, sustainable, and future-proof requires us to be able to monitor, manage, and make decisions at the level of individual trees. **Smart Technology** will enable getting the most out of an orchard through the targeted, efficient use of crop protection agents, plant hormones and fertilizers, while saving on labour and minimizing food waste. This all contributes to the creation of a sustainable fruit cultivation system.

The project has therefore three key objectives in relation to technology development:

- 1. Improving the sustainability of cultivation and the supply chain by:
  - a) developing ways of applying crop protection agents, plant hormones or fertilisers to individual trees (or parts of trees) based on new ways of detecting stress, pests, and diseases (using sensors and new algorithms) and
  - b) by combining data to develop new decision support models using AI. This will, for example, give decision support in storage duration and conditions to prevent loss and waste of the fruit, or help to determine the optimal dose of crop protection agents, growth regulators and fertilisers.
- 2. Maximising yields by optimising cultivation and storage through the optimisation of individual tree growth.

3. Minimising costs by developing multifunctional robots to replace human labour and ensure the efficient use of inputs.

The need to achieve these objectives has led to the project being organised in four case studies. A brief description of the four case studies is provided below, including an explanation of how they mutually reinforce each other.

#### *Case study 1: Further development of precision sprayer*

The former project Fruit 4.0 demonstrated that precision spraying at the level of individual trees is possible. In The Next Fruit 4.0 we want to further develop and broaden the application of precision spraying by controlling it down to individual nozzles and by using sensors to detect pests and diseases and apply sprays in response. Being able to control sprays at the level of individual nozzles also optimises the use of regulators for growth and fruit setting, resulting in a more uniform orchard. Hot spots of insect infestation can also be controlled without spraying the whole orchard.

#### Case study 2: Advanced crop management and yield registration

This case study is based on the use of sensors to collect data and translate it into decision support models visualised as clear dashboards. This will involve making the sensor platform from the Fruit 4.0 project applicable to more than just apples. The wide range of data and information gathered will also be distilled into clear insights around cultivation management. With help from experts and the use of modern AI algorithms, decision models will be created that can contribute to optimising and improving the sustainability of fruit cultivation.

#### Case study 3: Cool data

Apples and pears are often stored for a long time, even up to the following harvest. Storing the fruit for any length of time often leads to substantial losses due to a lack of clear, objective information on how long a particular batch can be stored. This case study will focus on maximising the use of data derived from the cultivation phase (climate, crop, and soil) and the focused application of new technology (sensors), leading to decision models that deliver better risk assessments and storage strategies. This will help reduce loss and waste during storage.

#### Case study 4: Multifunctional robot

Finally, The Next Fruit 4.0 will also work on expanding the functionality of existing robots which are already in development (e.g. by adding a gripper for picking pears, or for pruning and removing suckers) and which could perform more efficiently through technological improvements and better orchard design. All of this will help solve the problem of increasingly limited availability of seasonal labour.

The results presented are from the last 12 months. Results are presented per case study.

#### **Case study: Precision sprayer**

#### **Objectives**

A validated prototype precision sprayer for several fruit crops, which is directed at nozzle level on the basis of smart algorithms and decision models and combined with stress, disease and pest detection.

#### Significant Findings

- Laser scanner data can be translated into spray actions
- 2 prototype sprayers were build
- 1 prototype has been tested, finding is that the system was functioning well but a constant driving speed was needed. In the field the results therefor were not satisfying. The other

prototype can handle difference in speed and is now far enough in development for testing in November and December 2023.

# Methods

The third year of the project concentrated on:

- Building an improved sensor platform for a sprayer with LIDAR and GPS and (later in the fourth year of the project with RGB sensors).
- Processing data into usable data for spray decisions at nozzle level
- Build 2 sprayers with laser scanner that can spray at nozzle level and that can adapt dose on tree volume

# **Results and Discussion**

In practice, the most important benefit is that in the future fewer spray products will be needed to achieve the same result and that emissions to the environment will be further limited. The LIDAR scanners that make this possible are placed at the front of the sprayer. They determine the tree volume and gaps while driving. Both spray systems use PWM (Pulse Width Modulation) technology to vary the amount of spray liquid. This is done by changing the length of those pulses. Based of the tree volume an algorithm determines the amount of spraying liquid for each nozzle.

Within this work package, two types of sprayers have being build. The first is from Munckhof, the second from KWH. In the past period, the focus has been on getting both systems working. In collaboration with Munckhof, a first so-called timing measurement has been made, not yet in the field, but on asphalt with art objects and water-sensitive paper. This showed that the system already functions well, but that it is still very sensitive to driving speed. The results of the first measurements taken in the orchard showed that the deposition was lower than the standard sprayer that was used. In order to do further testing, the system needs to be improved.

With the KWH sprayer, work was mainly done to get communication between the different parts of the system going. The Lidar sensors are read by a separate computer. This computer also decides whether and how much to spray. These instructions are then communicated to the sprayer system (from the company BBLEAP). The entire system is now basically working and the first measurements will be taken in the coming weeks.

Below 2 pictures of the sprayers, one in the field during tests and one during installation of the components.





# Case study: Advanced crop management and yield registration

# **Objectives**

- Validated sensors and algorithms to collect physiological and phytopathological characteristics of apple and pear.
- Validated decision models developed on the basis of collected data and expert knowledge; targeted on production optimization.

# Significant Findings

- Blossom detection method did not work sufficient enough, a higher resolution camera is needed in combination with flash lights.
- Detection method to detect fruit tree canker and apple blossom weevil
- Trunk detection to get the GPS locations for individual trees.
- Field trial on blossom and fruit thinning showed for third year in row that precision spraying on trees with a high amount of flowers is the most effective strategy to make the orchard more uniform.
- Experiments were done to develop a thinning decision support system for Conference pear.
- Proof of principle was demonstrated for automated detection of apples and also pear in top layer of storage bins.

# Methods

The third year of the project concentrate on:

- Testing systems for automated detection of pear in top layer of storage bins.
- Building data and decision support models and dash boards for growers for presentation and management at tree level
- Setting up trails on thinning based on sensor input

# Results and Discussion

At harvest, growers and sales organisations like to know what the fruit quality is in the storage bins. For apple the size can easily be determined by making a picture from the top of a bin. For pear it is in development now. For that reason an algorithm was developed for the Conference pear.

#### Image processing photos storage bin



Within the project, WUR is developing image processing in which the size distribution of the pear is initially determined from photos of the storage bin. In subsequent steps, other quality aspects can also be analysed, such as fruit shape, colour and certain damages. For the size measurement specific points in the shape are now detected. This concerns the stem and nose position and the widest point of the fruit to determine the diameter. Several steps are required to validate the data. First, it must be determined how reliable the size measurement for the detected pears is and then it must be determined how well this size distribution corresponds to the entire storage bin or the entire batch.

The image processing model is running on a trial basis at the project partner Bodata. The goal is to bundle the collected information into a quality report. We are currently discussing with the

consortium partners involved how the analyses can be incorporated into daily practice. Preparations are also being made for market introduction.



#### **Develop crop growth model**

Drive through automatic photo portal for picking trains Because there is little time during the harvest to photograph each storage bin by hand, it was thought that it would be practical to drive a picking train under a gate where the photos could be taken automatically. By then linking the photo to this storage bin via an RFID chip, it will be possible to quickly gain insight of a complete batch. A test setup was tested at the experimental orchard Randwijk during the past harvest period. As soon as a storage bin passes the camera, a photo is automatically taken and the RFID chip is scanned. To ensure consistent photo quality, it was decided to shield the portal from daylight and artificially illuminate it with construction lights. To minimize motion blur in the photo, the picking train had to pass in the lowest gear. Integration with RFID stickers turned out to work fine. There are still some points that require attention, such as fruit brilliance and colour correction.

Within this work package, Delphy is working on developing a crop growth model. The aim is to predict the June drop and the final fruit numbers for Conference pear.

Many counts and measurements were again carried out in various tests in 2023. In addition to validating the model, work has been done to collect information about the course of the June drop and the factors that influence it. The results of all tests have now been worked out. It is clear what causes this difference. As is known, there are many factors that influence moulting, such as planting system, planting year, number of flower clusters, soil, crop health, etc.

This year, time was also spent on developing the dashboard for fruit growers together with the project partner Agromanager. An important point of attention here is the easy exchange of data.

#### **Precision thinning**

Last season, WUR and Delphy carried out an extensive thinning test on a task map at the Experimental orchard in Randwijk on Elstar apple. A total of 7 treatments in 4 flowering classes, i.e. 28 combinations, were carried out.

Counting was carried out at three times, namely at the end of June (end of June drop), in July (hand thinning) and in August (just before harvest). Just before harvest, a random fruit size measurement was also carried out in all treatments. The results will be analysed in the near future It is clear that it was a difficult thinning year. As with many growers, it was difficult to spray under ideal conditions. As a result, the thinning result was often disappointing in the trial.

Unfortunately, the Apple Blossom Beetle also caused noise in the data because counted flower clusters did not yield any fruits due to damage. The June drop may also have been less strong than we expected. It is clear that a strong thinning treatment on trees with many flower clusters does not quickly lead to over-thinning.

In Conference pear, ongoing fruit thinning research based on The Next Fruit 4.0 has been expanded with additional treatments to clarify the opportunities for precision thinning and precision fruit setting. Trees with many flower clusters have been thinned more often with Brevis to reduce the manual thinning. Trees with few flower clusters were stimulated to fruit set to increase yield. The number and weight per tree were determined during the harvest in September. These results are also currently being analysed.

# Case study: Cool data

### **Objectives**

The focus for this year was to select and evaluate tools for non-destructive quality assessment of fruit both preharvest and postharvest. Observed differences between batches of fruit should be related to relevant quality characteristics of the fruit. Not only aiming at quality assessment of freshly harvested fruits but also related to storage behavior of the respective batches. *Results and Discussion* 

First the tools to evaluate the fruit have been selected. Non-destructive measurements using new tools are being related to common (destructive) quality assessment methods.

# Common quality assessment

- Firmness, Brix, Weight
- Photographic analysis (color, shape, percentage russeting)

#### Non-destructive assessment

- Near Infrared both a hand held sensor from the project partner Kubota and hyperspectral imaging from our in-house facility
- Microwave based -a hand held sensor from the project partner Vertigo







The project partner Kubota decided to pause the further development of the NIR hand held sensor. Therefor the focus was on Fresco sensor from Vertigo.

During the past harvest period, photographic recordings were made of 20 storage boxes per sample at 19 locations, of a total of 23 samples of Conference pear.

Vertigo was also present at a number of locations to validate the Fresco in practical situations in order to look at the effects of

variation in light, temperature and moisture.

The preliminary results are shown in the figure below. Companies were visited in the most important Conference growing regions (Limburg, Zeeland, the Betuwe, Utrecht, Flevoland, North Holland and the Belgian fruit region). In some cases, the storage boxes were labelled so that they can be reanalysed as soon as they leave storage. Fruits from each batch were collected and stored in parallel at WUR Randwijk. Photo material and data about hardness and sugar content are added to the Agromanager database as much as possible. Agromanager is data platform for fruit growers where all data can be collected and analysed by the grower.



Figure: results of measurement of 23 different samples of pear fruit by hand (standard in blue), with the Fresco sensor (light grey sample of 20 fruits and dark grey with 200 samples)

# **Case Multifunctional robot**

#### **Objectives**

The main objective of the multifunctional robot case is to expand the functionality of existing orchard robots and of orchard robots currently under development in parallel research projects. The focus of the work is on two topics, namely the development of a sensing system and a gripper for picking pears and on a sensing system, robot control and end-effector(s) for robotic pruning of fruit trees and red currant bushes. On the longer term additional tasks such as automatic thinning, removing weeds and precision spraying will be targeted.

#### Significant Findings

- Detection system developed for robotic harvesting pear to detect the position but also the orientation and some other key points of the fruit.
- Prototype gripper that can do the required motion to detach a pear from a tree which is significantly different from that to detach an apple.
- Extensive knowledge and expertise on automatic pruning and fruit harvesting is exchanged with Washington State University and Oregon State University. Close cooperation and knowledge exchange between Dutch and US researchers is of mutual benefit.
- A prototype gripper for pruning is developed and tested on red currant.

#### Methods

The third year of the project concentrated on:

- Designing first prototypes for pruning and picking end effectors.
- Designing an algorithm to detect pears and pose estimation.
- Testing different camera's for making 3D models of dormant red currant plants.

#### **Results and Discussion**

#### Gripper testing pear picking

Within the project the prototype to pick pears was tested in the field. The most important innovation lies in the moving gripper system (photos 2 and 3) with suction cup. Unlike conventional methods that use the robot's arm movement to loosen the fruit from the tree, the new

concept allows the gripper mechanism itself to perform the crucial picking motion. The gripper also has an integrated colour and 3D (RGB-D) camera.

WUR researchers wrote software to integrate the deep-learning peer detection algorithm developed earlier in the project into an operating system for the robot using ROS2 (Robot Operating System 2).

After the first tests on the indoor test setup, a two-day test was carried out with the harvest of Conference pears at Experimental orchard of Randwijk during the harvest period in September 2023. The results are convincing: the robot can detect and harvest pears without damaging the pear. But we're not there yet. The tests in the orchard have provided valuable insights into what works well and what can be improved. The data collected during these picking experiments will be analysed to further refine the robot's capabilities and make necessary improvements.

#### **Pruning red currant bushes**

The past summer months have been used to explore better options for the sensor system. The research team is looking for high-quality sensors that can map plant architecture in 3D. Two way are being followed for this.

On the one hand, (combinations of) various 3D sensors (cameras, LIDARs) and associated classification algorithms are investigated in collaboration with the sensor experts from the company IMEC. On the other hand, the collaboration between WUR (Jochen Hemming) and Oregon State University (Alex You, Joe Davidson and Cindy Grimm) contributed to a study investigating how a branch can be mapped in 3D with a simple 2D camera. The results of this research will be presented at a leading scientific robotics conference in Japan (ICRA 2024) in May next year





Photo 1 Robot setup in orchard



Photo 3

#### Photo 2 Gripper with suction cap



Photo 4 Making 3D model of red currant

# **Executive Summary**

Title: The Next Fruit 4.0

Abstract: The object is to make fruit cultivation more efficient, intelligent, sustainable, and future-proof. This requires us to be able to monitor, manage, and make decisions at the level of individual trees with the help of smart technology. The **first example** is the development of a precision sprayer that can spray at a nozzle level with sensors that detect the volume of the trees. Two prototypes were build and one needs further development and the other is ready for field trials. A later add on are camera's that can detect pests and diseases. Precision spraying for fruit thinning showed that aiming on the trees with a high amount of flowers gave the best results on effects on return bloom. The **second example** is the development of a storage bin. Specially for pear an algorithm was developed to measure the size. Colour measurements will follow. The **third example** is the use of a non-destructive sensor to measure fruit quality like firmness and brix. The sensor Fresco showed reliable outcomes on a set of more than 20 samples. And finally the **fourth example** is the build of end effectors for picking and pruning to make robots multifunctional. The first end effector to pick pears was made and tested with success in the field. This winter red currant plants will be pruned with the pruning end effector.

# **Project Title:** Apple Harvest End Effector and Apple Transport System

Report Type: Final Project Report

Primary PI:Dominic Milano, Soummya Datta (Co PI)Organization:Milano Technical Group Inc.Telephone:(925) 642-3123Email:dominic@milanotechnicalgroup.comAddress:1574 W. 18th StreetAddress 2:City/State/Zip: Merced, CA 95340

**Project Duration:** 2-Year

**Total Project Request for Year 1 Funding:** \$155,000 **Total Project Request for Year 2 Funding:** \$90,000

Other related/associated funding sources: None

WTFRC Collaborative Costs:

Budget 1 Primary PI: Dominic Milano Organization Name: Milano Technical Group Inc. Contract Administrator: Brian Bourquard Telephone: 208-286-5575 Contract administrator email address: bbourquard@milanotechnicalgroup.com Station Manager/Supervisor: Dominic Milano Station manager/supervisor email address: dominic@milanotechnicalgroup.com

Item	2022	2023
Salaries	\$67,000.00	\$40,000.00
Benefits	\$23,100.00	\$15,000.00
Wages		
Benefits		
Equipment	\$55,900.00	\$26,000.00
Shipping		
Supplies		
Travel	\$9,000.00	\$9,000.00
Plot Fees		
Miscellaneous		
Total	\$155,000.00	\$90,000.00

#### **Original Objectives and Findings:**

The primary objectives of the project were to:

- 1. Design and build a robotic apple harvester system that included an Apple Harvesting end-of-arm tool, arm structure, and an Apple Harvest Transportation subsystem.
  - a. System ROI goal for cost to efficiency targeted at 90-120 days.
  - b. Preserve fruit, tree, and bud integrity.
  - c. Transport module to prevent bruising or puncturing (limit fruit damage).
  - d. Harvesting module fits on commercially available platforms (demonstrated on an Amiga machine by Farm\_ng).
  - e. Arm control system architecture will support common location outputs using a known computer vision system.
- 2. Performance of each subsystem is economic feasible:
  - a. The end-effectuator has appropriate speed, picking an apple every 3-4 seconds.
  - b. The system can perform at least 3 million total actuations between maintenance periods.

#### Original Proposed System Overview

The original proposal included a focus on two subsystems:

- 1. The apple transportation system, originally proposed as a wall of conveyor belts designed specifically for apple transport to move the apples from the end effectors to a storage bin.
- 2. The harvest end effector, or end-of-arm, system, which was envisioned as a grasp and twist mechanism to remove the apple from the tree with a telescoping arm.

In our original proposal, we had envisioned a "wall" with conveyors on the inside to transport apples from the robotic picking arms to the storage bin. During our discovery process, discussed in more detail in the findings below, we determined that the points of failure and robustness challenges of this system were potentially over-complicated and that simpler solutions presented themselves. Through the development of the end-effector, we also found that a telescoping arm presented some mobility limitations, particularly given the unstructured nature of the field-wall. We ultimately developed a system built on a five degree-of-freedom (DOF) robotic platform. By moving from the conveyor and telescoping arm system to a 5-DOF platform, we were able to substantially speed up the system without materially increasing the cost.

# Findings

During the two-year effort, we were able to complete approximately 90% of the system while making critical discoveries, and enhancing our fundamental understandings of the system requirements, that we believe will lead to a viable commercial solution. Our solution will be easily adaptable for FLC, small growers, and large growers alike. With the understanding that the price of harvesting utilizing an automated system is heavily dependent upon both human interaction and capital investment, our design efforts were weighted towards these two concerns. To be commercially viable, the operational cost of the machine must be approximately cents per apple; to achieve this, it was critical to push the bounds of both physics and cost. Some of the critical findings of our research were that the passive apple transportation system operates consistently without damaging apples, trees, or buds, and a very inexpensive actuation model was viable. The system would be fully functional operating at full speed while using under 2000W while harvesting a simulated 2.2 apples/second. We have found that these simulated scenarios translate into real world actuation and harvest speeds. The in-field testing of the system, which will be conducted at the end of this season and the beginning of the 2024 season, remains to be completed.

#### General overview of the mechanical design:

- 1. **Five Degree of Freedom Robot Platform**: The 5-DOF robot is a multi-actuator design in which the suitability for outdoor use and fast actuation is paramount. This general 5-DOF robot design is known for its high speed and precision, which makes it ideal for quickly positioning the end-of-arm tool to pick apples.
- 2. **End-Of-Arm Tool** Attached to the 5-DOF robot is a end-of-arm tool that has rapid actuation while maintaining gentle interaction with the apple to be harvested. The end-of-arm tool is specifically designed to mimic the action of a human hand gently gripping an apple while manipulating it.
- 3. **Sensors and Cameras**: The system is equipped with sensors and cameras that help in identifying apples. In our system, the cameras suggest to an operator the apples to pick, and the operator verifies the apple and provides positive feedback to the machine to pick the apple. In future models any vision system may be adapted to the mechanical system to indicate which fruit to harvest.
- 4. **Transfer system**: After the apple is picked, the apple slides into a transfer tube on the backend of the gripping mechanism. This tube is a soft, flexible chute that safely guides the apple down to the base chassis system. The design of the tube minimizes the potential for bruising or damage during transport.
- 5. **Apple collection System**: The base of the harvester contains a bin holding system where the apples are collected after being transported through the tube. This system is designed with cushioning to absorb any impact and prevent damage to the fruit during transport off the field.
- 6. **Mobility and Navigation**: The entire system is enabled to be mounted on a mobile platform equipped with wheels or tracks that can navigate through orchard rows. The platform can use a localization system to enable optimized route finding if wanted by user.

7. **Power and Control Systems**: The harvester is powered by a combination of batteries and electric motors. The control system, with specialized software, coordinates the movements of the robot arms, the end-of-arm tool, and navigation of the chassis.

The system is developed to be "mobile base" or chassis agnostic, with the ability to mount onto any ground-based robotic or other platform, which provides flexibility to the user.

To validate the fundamental understandings, the team is planning to conduct field trials in late 2023 and/or the 2024 pre-season.

Design considerations and discoveries for the end of arm tool and arm include material for: handling of the fruit, manufacturability, cost, and reliability. The requirements above meet the condition that the end effector actuation achieves a total harvest time per apple per arm of 3-4 seconds. The end effector and arm includes a 5 degrees of freedom (DOF) actuation, and a telescoping tube that is attached to a two-axis gimbal mechanism at its base. Once the apple is selected, and the gimbal mechanism orients the arm, the telescoping tube will extend the end effector to the apple. At this point the end effector will grasp and twist to remove the apple. A full-time budget for the system is developed during our study. Initial calculations show the two processes, closing of the end effector and twisting, are estimated to take 300 - 400 ms per apple.

#### Field Demonstrations:

*Objective:* To evaluate the efficacy of the apple harvesting robotic system with a focus on the integrity of the harvested apples, the presence of any fruit or tree damage, and the time the picking motion takes.

*Test Environment:* The test will be conducted outdoors in Washington state late in the harvesting season or in the 2024 pre-season on test plots in the orchard.

Test Material: A minimum of 25 apples for each motion profile will be used for testing.

#### **Results and Discussion:**

We developed three R&D workstreams: the gripper mechanism (end of arm), the robotic arm, and the cost and feasibility of the unit.

The gripper mechanism was developed to facilitate the reliable grabbing of apples with the appropriate force within a 3-dimensional, unstructured field-wall environment. The grippers went through multiple iterations to identify the appropriate materials, shape, and approach dynamics to prevent fruit or tree damage. Early versions of the gripper mechanism used a telescoping arm to place the gripper mechanism near the fruit, mounted on a 2-DOF gimbal mechanism. Further discovery on the dynamics of apple picking from our simulated environment indicated that the use of a 5-DOF system with an integrated end-of-arm tool was both faster from apple-to-apple movement and created a greater verity of paths that can be taken for these apples. This 5 DOF and gripper combination created a much more flexible and operationally robust system.

The cost and feasibility of developing a lightweight, robust, and mobility-base agnostic robotic apple harvesting system hinge on balancing advanced technology with practical design considerations to ensure robustness, low bill-of-materials cost, and adaptability. The agnosticism of the mobile base is a particularly strategic feature, allowing the robotic system to be mounted on various platforms—be it wheeled carts for smaller orchards or larger vehicles for extensive agricultural operations, and ranging from fully autonomous to operator driven—making it versatile across different scales and methods of farming. This feature is possible because of the modularity of both the arm and software system in conjunction to the vision system. This universality not only widens the potential market for such systems but also means that upgrades or replacements of the mobile base can be done independently of the harvesting mechanism, potentially reducing lifecycle and maintenance costs.

Currently our system uses lightweight, low-cost materials and deploys "off-the-shelf" components where appropriate to control total materials and manufacturing costs. The system, as intended for testing, is mounted to a farm\_ng Amiga mobile base. While we are currently testing quantity one arms on one robot the system is engineered to have up to 6 on each side of the harvesting platform. Through our discovery process, we found that we can service a 9-foot tree with four arms instead of the originally estimated eight. While we will not be testing with all four on each side, scalability is already built into the software. Once we confirm the in-field efficacy of the mechanical design, we will test one complete side at scale.

Our arm design, after over 20 iterations, has been shown to operate without load for over 1.2M actuations without failure. The Gripper design has been tested to operate an order of magnitude less reliably at 10's of thousand. The main challenges with the current gripper design, beyond robustness, include safely handling the fruit without damage and unintentional interaction with the surrounding fruit. Simulations demonstrate that the likely interactions are within the acceptable tolerances, which we expect to verify via field testing.

#### Looking Forward.

Automated or semi-automated robotic apple harvesting technology represents a significant advancement in agricultural practices, with benefits for farmers and downstream processors if implemented in conjunction with data collection.

The potential for systemic advancement in orchard harvesting operations through automation is substantial – but the technical challenges are non-trivial. While currently we use an operator-in-the-loop system, the leap to full autonomy requires substantial investments in machine learning, perception systems, real-time decision making, navigation and safety. The physics of delicate, soft-touch robotic arm systems are well known and are widely used in manufacturing and packaging operations globally; however, the environments in which they operate are often highly structured and amenable to pre-determined solutions. Unstructured environments, such as the orchard wall, require substantially more sophistication, including physical systems that interact with the fruit in multiple dimensions, including time, and from multiple angles. Further work is required with growers, processors, and cold storage facilities to understand if the implementation of robotic solutions decreases fruit quality or quantity.

#### **Executive Summary**

### Title: Apple Harvest End Effector and Apple Transport System

# Keywords: Automation, Apples, Harvesting, Low-Cost, Reliability

Abstract: Milano Technical Group was provided funding to research and develop a robotic apple harvesting system, including an end effector and apple transport system, to reduce in-field harvest operations and labor costs. After a substantial discovery process and many iterations, we determined that a potential multi-objective solution system consists of a five-degree of freedom system with a padded gripping mechanism and actuating arm, which allows for freedom of fast movement in multiple dimensions. The system is mobile base agnostic and will be tested using an Amiga from farm\_ng. Where feasible, the system was built with off-the-shelf and low-cost parts to minimize build and maintenance costs. We estimate that each arm can retrieve an apple every 3 to 4 seconds and actuate between 1 and 2 million times between major maintenance periods.

# Project Title: Modeling Orchard Effects on Meteorological Measurements

**Report Type:** Final Project Report

Primary PI: CO-PI: Lee Kalcsits Organization: WSU Telephone: 509-293-8764 Email: lee.kalcsits@wsu.edu Address: 1100 N Western Ave City/State/Zip: Wenatchee, WA 98801

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Cooperator(s): Meter Group

**Project Duration:** 3 Year

**Total Project Request for Year 1 Funding:** \$60,025 **Total Project Request for Year 2 Funding:** \$62,916 **Total Project Request for Year 3 Funding:** \$65,113

Other related/associated funding sources:

WTFRC Collaborative Costs: Budget 1 PIs: Lee Kalcsits, Lav Khot Organization: Washington State University Contract Administrator: Anastasia Mondy Telephone: 916-897-1960 Contract administrator email address: <u>Anastasia.mondy@wsu.edu</u>

Item	2020	2021	2022		
Salaries	\$13,245.75	\$40,693	\$42,321		
Benefits	\$4,517.25	\$14,223	\$14,792		
Equipment	\$36,150	\$0	\$0		
Travel	\$6,000	\$8,000	\$8,000		
Total	\$60,025	\$62,916	\$65,113		

<sup>1</sup> Salaries include 2 months of postdoc time at AgWeatherNet in year 1 and 4 months in years 2-3, 1.5 months of research associate time in the Kalcsits lab (years 1-3), 1 month of field meteorologist time at AgWeatherNet (years 1-3), and 1.75 months of systems analyst/programmer time (years 1-3).

<sup>2</sup> Benefit rates are budgeted for 35%.

<sup>3</sup> Equipment includes 8 weather sensors, 8 soil moisture sensors, and 2 instrument towers.

<sup>4</sup> Travel budgeted for travel to field sites, meetings with collaborators and presentation of results at industry winter meetings in Washington State.

# Objectives

- 1. Measure the effects of irrigated orchard canopies on meteorological measurements relative to standard unobstructed, unirrigated meteorological sites.
- 2. Construct statistical models that estimate the magnitude of orchard effects on air temperature, relative humidity, and wind speed as a function of weather conditions and irrigation.
- 3. Develop and implement algorithms in AgWeatherNet to dynamically correct for orchard effects and support orchard-specific delivery of weather data, forecasts, and decision-support tools.

# Key findings:

The effects of orchard canopies and management practices on the orchard microclimate were studied at different time scales.

- 1. All the apple orchards had similar mean seasonal weather. Significant orchard effects were observed between the open-field and in-orchard weather at all sites, supporting the need to quantify orchard effects for tree-fruit crop decision support.
- 2. The orchard air temperature was 1.9 to 4.4 °C cooler and relative humidity was 9.2 to 27.5 % higher due to evident effects of cooling and moisture increase caused by plant transpiration. Canopy solar radiation was reduced by 267.8 to 483.2 W m<sup>-2</sup> and wind speed reduced by 2.2 to 3.7 m s<sup>-1</sup> due to the interception by the upper canopy, resulting in shadows. V-trellis orchards have lower weather offsets (AT<sub>o</sub>, RH<sub>o</sub>, and SR<sub>o</sub>) than solaxe and bi-axis training systems, indicating substantial effects of orchard canopies on in-canopy weather conditions. The yearly means of the daily maximum offsets show high diurnal variations due to differences in weather patterns, plant physiological processes, and management practices at different time scales.
- 3. Monthly weather offsets between in-canopy and out of orchard weather (AT<sub>o</sub>, RH<sub>o</sub>, and SR<sub>o</sub>) increase from April to August as the plant develops toward fruit maturity and decreases as the plant approaches dormancy. The patterns were consistent during years 1 and 2. WS<sub>o</sub> was more influenced by the open-field conditions and did not show variations among plant growth stages.
- 4. AT<sub>o</sub> and RH<sub>o</sub> were highest during the summer season due to active plant physiological processes. High humidity inside the orchard can increase pest infestation and disease spread. The SR<sub>o</sub> peaks around noon for the solaxe training system (site 1a, b), while V-trellis (site 2,3,6) have two peaks at 9 hr and 16 hr.
- 5. Training systems and orchard pruning can modify the orchard microclimates.
- 6. Overhead sprinklers reduced air temperatures by 2°C and relative humidity by 15% in the orchard. The effects can linger during the evening and night hours. Therefore, growers should consider the lingering cooling and moisture effects when employing overhead cooling sprinklers to manage heat stress, as it can possibly impact fruit quality and disease pressure.
- 7. Open field weather data based in-orchard AT, RH and WS prediction models have been developed successfully. Amongst the multiple linear, nearest neighbor, and random forest regression models, latter two had lowest root-mean-squared-error (RMSE) of prediction. The RMSE for AT, RH, and WS prediction by the nearest neighbor and random forest regression models was <0.7 °C, <3%, and < 0.25 ms<sup>-1</sup>, respectively.

**Objective 1.** Measure the effects of irrigated orchard canopies on meteorological measurements relative to standard unobstructed, unirrigated meteorological sites.



**Fig. 1**. Example of open-field, and in-orchard weather station installations at (a) site 1b (architecture: solaxe) and (b) site 5 (architecture: V-trellis).

#### Effects of canopy attributes

Canopy attributes, namely training system and canopy height, will likely influence the orchard effects. The differences in hourly  $AT_o$ ,  $RH_o$ ,  $SR_o$ , and  $WS_o$  due to the type of canopy architecture (solaxe, V-trellis, bi-axis) during the summer season were studied using two-way ANOVA at a 5% significance level (Table 1). All the statistical analysis was performed in Python 3.11.4.

#### Effects of overhead evaporative cooling and irrigation

Among the six commercial apple orchards, sites 1, 2, and 6 were used to evaluate the effects of overhead evaporative cooling and irrigation, as both management practices were operative at the three orchards during the data collection season. The mean and SD of hourly  $AT_o$ ,  $RH_o$ ,  $SR_o$ , and  $WS_o$  were calculated for three groups: dry days, overhead cooling days, and irrigation days during the summer seasons.

#### **Results and Discussion**

#### **Open-field seasonal weather patterns**

Overall, the open-field seasonal weather patterns were similar for all the sites and are characterized by warm-dry summers and cool-wet winters. During the study period, mean AT showed an increasing trend from spring (3.8 to 6.9 °C) to summer (15.3 to 21.4 °C) and then decreased during fall (7.0 to 8.7 °C) and (-2.97 to -1.26 °C) winter across all sites. The mean RH was lowest during summer (49.4 to 64.8 %) and highest during winter (83.3 to 88.2 %). Similar to AT, the mean SR (considering both daytime and nighttime) was highest during the summer (216.2 to 237.2 W m<sup>-2</sup>).

The paired t-test results confirmed significant differences between the open-field and in-orchard AT at all sites during the spring, summer, and fall seasons, underscoring substantial orchard effects (p < 0.05). During winter, when the trees are in dormancy, the AT differences were insignificant at sites 4 and 5. The mean seasonal RH, SR, and WS were also significantly different between open-field and in-orchard at all sites for all four seasons.

#### **Daily orchard effects**

In general, the daily maximum offsets in all the weather variables for either annual cycle were similar. There were low inter-annual fluctuations and consistent variability during this project (Table 2). Note that long-term comparison would be needed to capture abnormal annual variations.

The daily maximum  $AT_o$  indicated a cooler orchard microclimate with mean values of 1.9 to 4.4 °C across different sites. These cooling effects could largely be due to canopy transpiration and evaporative cooling (Landsberg et al., 1973). Other factors such as canopy size, inter-row vegetation, and pruning may have contributed to  $AT_o$  variation at different sites. The solaxe (site 1a, b) has the highest offset compared to high-density V-trellis and bi-axis training systems. This indicates that canopy volume could have prominent effects on the in-orchard AT. For instance, the short and tall yet voluminous canopy in the solaxe training system (site 1a, b) had mean  $AT_o$  of 4.4 °C, 3.2 °C, while the same for V-trellis (site 2) was 1.9 °C. The diurnal variability of  $AT_o$  was highest at site 5 (78.2 %) and lowest at site 6 (46.4 %), where the distance between in-orchard and open field stations was the lowest. Higher AT fluctuations were observed during daytime compared to nighttime and could be attributed to variations in SR. The CV ranges were notably higher during December (95.8 to 108.6 %) and January (74.2 to 120.9 %) across all sites when the daily AT was low. This suggests that the cold hardiness models currently using open-field data (Aniśko et al., 1994) may result in higher uncertainty due to large  $AT_o$  variations.

Orchard microclimates resulted in higher RH compared to open-field conditions. The yearly mean of the daily maximum RH<sub>o</sub> varied from -9.2 to -27.5 % across all the sites. The highest effects were observed in site 1 (solaxe training system), where the AT<sub>o</sub> was also the highest. The lowest RH<sub>o</sub> was observed at site 5 (V-trellis training system), and the resulting CV was also the highest (122.6 %). The lowest daily fluctuation of the RH<sub>o</sub> was observed at site 3 (60.3 %), where the RH was relatively lower compared to other sites. Similar to AT<sub>o</sub>, most of the daily variability occurred during December and January (Table S3).

Lower SR was observed under the canopy. The SR<sub>o</sub> varied from 267.8 to 483.2 W m<sup>-2</sup> across different sites (Table 1). Site 1a had the highest SR<sub>o</sub>, indicating the effects of tall voluminous canopies. The other orchard sites showed similar SR<sub>o</sub>. The CV varied from 51.9 to 66.5 % and did not follow a similar pattern across the sites. For instance, the CV was higher during July and August for site 6, while the same was higher for Site 1 during the December and January months. This indicates differences in the uncertainty across sites and seasons.

The WS<sub>o</sub> varied from 2.2 to 3.2 m s<sup>-1</sup> across the six sites. WS<sub>o</sub> was highest at site 5 and lowest for site 6 and was proportional to the open-field wind speed variation. Orchard canopies act as wind barriers, which may result in trapping of the air mass and reduced mixing of moisture inside the orchard block. Canopy size, planting density, and pruning practices can affect the WS<sub>o</sub>. Contrary to other variables, the CV in WS<sub>o</sub> was higher during nighttime than daytime conditions. All the daily maximum offsets show high variability (CV > 40 %), which can be attributed to nuanced processes across diverse temporal scales, including the phases of canopy development, maturity, senescence, and dormancy.

Variables*	Statistical parameter	sites												
		1a		1b		2		3		4		5		6
		Y1**	Y2	Y1	Y2	Y2								
AT <sub>o</sub> (°C)	Mean	4.4	4.2	3.1	3.2	1.9	1.9	3.1	3.0	2.4	2.9	2.2	2.3	2.2
	SD	2.5	2.5	1.8	1.7	1.3	1.4	1.8	1.7	1.6	2.0	1.7	1.7	1.0
	CV (%)	57.6	57.8	59.2	52.7	67.2	71.5	58.7	56.1	67.2	68.0	78.2	73.0	46.4
RH <sub>o</sub> (%)	Mean	-27.5	-23.3	-14.6	-13.5	-10.7	-10.1	-17.4	-19.2	-13.1	-13.0	-9.2	-10.9	-10.6
	SD	17.2	16.1	11.7	10.3	8.3	7.9	11.6	11.6	10.7	12.6	11.2	10.9	7.4
	CV (%)	62.3	69.0	79.7	76.3	77.2	78.3	66.8	60.3	81.6	96.4	122.6	100.5	69.6
SR <sub>o</sub> (W/m <sup>2</sup> )	Mean	483.2	461.2	338	413.9	298.9	327.7	364.3	332.0	381.6	439.9	331.3	267.8	300.7
	SD	262.1	241.4	206	221.1	198.6	200.0	199.3	181.4	231.7	228.3	211.6	143.0	158.3
	CV (%)	54.2	52.3	61.0	53.4	66.5	61.0	54.7	54.6	60.7	51.9	63.9	53.4	52.6
WS <sub>o</sub> (m/s)	Mean	3.2	3.4	2.8	3.1	3.0	2.8	2.6	2.4	3.0	3.2	3.7	3.7	2.2
	SD	1.6	1.7	1.5	1.5	1.4	1.3	1.3	1.2	1.1	1.1	1.7	1.6	1.0
	CV (%)	50.2	50	51.9	46.8	47.9	46.3	49.2	50.6	37.0	35.0	45.8	43.7	44.4

Table 1. Daily offsets for key weather variables in different orchard training systems for both years (Y1 and Y2).

\* AT<sub>0</sub>: Air Temperature Offset; RH<sub>0</sub>: Relative Humidity Offset; SR<sub>0</sub>: Solar Radiation Offset; WS<sub>0</sub>: Wind Speed Offset; \*\*Y: year
#### Monthly orchard effects

Fig. 2 show the line graphs of the monthly offsets during year-1 and -2, respectively. Offsets of allweather variables varied monthly depending on the weather conditions and canopy growth stages. All the orchards had similar monthly SR<sub>o</sub>, AT<sub>o</sub>, RH<sub>o</sub>, and WS<sub>o</sub> patterns through year-1 and -2, even though the magnitude varied between the sites.

Mean monthly AT<sub>o</sub> and RH<sub>o</sub> showed an increasing trend starting in April, with the peak in July (year 1) or August (year 2) when the mean AT was highest. The peak offsets had shifted from year-1 to -2, differing by one month. This can be likely attributed to large-scale atmospheric circulation and weather variation between the two years. Such variations can impact the timing of seasons, temperature ranges, plant productivity, and other climate-related factors in different years, potentially resulting in variations in the orchard effects (Jonas et al., 2015). During the peak months for respective years, the orchard microclimate was 4.1 to 1.1 °C and 3.7 to 1.0 °C cooler across different sites. The tall voluminous canopy in the solaxe training system has the highest effects (3.7 °C). Higher humidity was observed inside the orchard as the canopy developed in May. The peak RH<sub>o</sub> varied from -34.0 to -6.3 % and -27.9 to -6.8 % across different sites during year-1 and -2, respectively. The cooler AT<sub>o</sub> and higher RH<sub>o</sub> inside the orchard can be attributed to plant transpiration and evaporation from soil surfaces (Landsberg et al., 1973).

The SR<sub>0</sub> peaked in June and July during year-1 and -2, respectively. This could be due to weather station shadowing by the canopies and the highest magnitude of SR received during these months (Landsberg et al., 1973). During year-1 and -2, the voluminous canopy in the solaxe training system at site 1a had a peak SR<sub>0</sub> of 247.2 W m<sup>-2</sup> and 231.1 W m<sup>-2</sup>, which was the highest among all the sites. The peak SR<sub>0</sub> for the remaining sites ranged from 51.9 to 107.1 W m<sup>-2</sup>, which was relatively lower than site 1a. This indicates that the canopy size may play an essential role in the SR<sub>0</sub>, as voluminous canopies have more shadows on the sensor than smaller canopies. SR<sub>0</sub> depends on canopy architecture, a function of factors such as cultivar, rootstock, and pruning (Proctor, 1978). The SR offsets can be avoided by placing the sensor above the typical canopy height.

Contrary to other variables, the  $WS_o$  showed monthly fluctuations, indicating that the effects were influenced by the canopy and the magnitude and directions of the wind recorded by the open-field stations (Kalma & Stanhill, 1972). Wind speeds were lower inside the orchard due to aerodynamic resistance caused by the canopies (Belcher et al., 2012).  $WS_o$  was highest at site 5, with the highest open-field wind speed, indicating a positive relationship between WS and  $WS_o$ . Among the remaining sites, the voluminous canopy with solaxe training systems at site 1a has the highest  $WS_o$ . This suggests that the voluminous canopy can cause more obstructions than typically well-hedged V-trellis and biaxis. Also, though the general trends and seasonality of orchard effects could be established from monthly scale analysis, it would not capture the finer orchard effect variations resulting from varying open-field weather conditions during the day.

#### Seasonal hourly orchard effects

The mean hourly offset patterns were similar for all the sites, and the magnitude varied across seasons during year -1 and -2 (Fig. 3). The AT<sub>o</sub> was highest during the summer season. The values ranged from -1.1 to 1.5 °C, -0.5 to 3.8 °C, -1.2 to 2.4 °C, and -0.9 to 1.1 °C across sites during spring, summer, fall, and winter, respectively. The cold air trapped inside the orchard at night during spring would be critical for cold protection as it would increase the risk of frost damage (Cittadini et al., 2006; Peters & Bauman, 1978). Around noon, the warm air (1.2 to 0.1 °C) gets trapped due to canopy resistance and reduced air mixing inside the orchard. This phenomenon was pronounced during winter due to the absence of cooling transpiration.

All the sites have higher humidity inside the orchard compared to the open-field during the summer season and were highest at site 1a orchard with voluminous canopies. However,  $RH_0$  shows negative

and positive values in the other seasons, indicating higher and lower humidity inside the orchard. The seasonal hourly mean  $RH_0$  varies from -9.4 to 7.7 %, -28.0 to -0.8 %, -13.8 to 4.4 %, and -5.8 to 8.5 % during the respective seasons. Orchards have drier microclimates during winter and spring when the plants are in dormancy or post-dormancy stages.

The peak hourly mean  $SR_o$  was highest during summer and lowest during winter. On comparing year-1 and -2, the peak shifted during the winter season (Fig 3). The timing of shadows cast on the weather station varied across sites depending on training systems and canopy size. For instance,  $SR_o$  peaks around noon for the solaxe training system (site 1a, b), while V-trellis (sites 2,3,6) have two peaks at 9 hr and 16 hr. Two peaks indicate different shadowing of the weather station by the two sides of the canopy in the V-trellis system. Similarly, Tooke et al. (2011) reported that tree structures (height, volume) influenced the intercepted SR at urban rooftops.

As discussed, reduced wind speed inside the orchard affects the AT and RH. The WS<sub>o</sub> shows a similar pattern at all sites except for site 5. Wind effects were lower during winter (0.5 to  $1.5 \text{ m s}^{-1}$ ) when wind speed was lower. The seasonal hourly averages vary from 0.7 to 2.1 m s<sup>-1</sup>, 0.5 to 3.1 m s<sup>-1</sup>, 0.5 to 2.1 m s<sup>-1</sup>, and 0.4 to 1.5 m s<sup>-1</sup>, respectively. Due to canopies and atmosphere interactions, such near-surface turbulent wind conditions can affect tree response behavior and growth (Schindler et al., 2012).

#### **Effects of canopy attributes**

Results of the two-way ANOVA indicated significant impacts of canopy height and training system on hourly AT<sub>o</sub> and RH<sub>o</sub> during the summer season at a 5 % significance level (Table 4). Alteration of tree height or choosing a training system during a new orchard plantation can substantially impact microclimate and the associated biophysical processes (Wilcox & Davies, 1981). Similar findings were reported in urban environments where voluminous and high-density trees have a higher cooling effect than less-density trees (Chen et al., 2021). However, the two factors do not significantly impact mean hourly SR<sub>o</sub> and WS<sub>o</sub> as the study considered only three training systems and seven heights. Canopy branches, leaves, and twigs influence the magnitude of SR<sub>o</sub> in tropical forest microclimates due to differences in radiation absorption and transmission by the leaf (Aakala et al., 2016).

Factors	p-value			
	AT <sub>o</sub>	RHo	SRo	WS <sub>o</sub>
Height	0.11	0.02*	0.09	0.06
Training system	0.01*	0.00*	0.06	0.09
Height x Training system	0.00*	0.00*	0.18	0.18

**Table 2.** Statistical evaluation of the effects of height and training systems on mean hourly offsets during summer using two-way ANOVA.



**Fig. 2** Mean monthly offsets between open and in-orchard (a) solar radiation (SR<sub>o</sub>), (b) air temperature (AT<sub>o</sub>), (c) relative humidity (RH<sub>o</sub>), and (d) wind speed (WS<sub>o</sub>) for orchards for year-1. The different color lines represent different sites.

#### Effects of irrigation and overhead sprinklers

In general, irrigation days have similar hourly  $AT_o$  and  $RH_o$  with the dry days except for site 1a, b (Fig. 4 and 5). The AT and RH effects at site 1b can be attributed to the combined influence of undertree sprinklers and drip irrigation. Unlike drip irrigation, which directly adds water to the soil, undertree sprinklers increase moisture in the lower (3m AGL) orchard microclimate, reducing AT. Overhead sprinklers have pronounced effects with maximum AT reduction by 4.1 °C, 4.4 °C, 4.7 °C, 5.2 °C, and maximum RH increase of 9.2 %, 4.8 %, 3.6 %, 3.8 % compared to dry days at sites 1a, 1b, 2 and 6 respectively. The effects linger in the orchard microclimate during evening and night hours. These effects will vary depending on the amount of water applied and the canopy characteristics. For instance, the  $AT_o$  and RH<sub>o</sub> for the voluminous canopy at site 1a was 2 °C and 15% higher than at site 1b.

Contrary to AT<sub>o</sub> and RH<sub>o</sub>, irrigation and overhead sprinklers do not affect SRo and WSo more than dry days (Figs. 6 and 7). This indicates that both the management practices do not impact SR and WS. Orchard microclimates are complex and understanding the effects of different weather variables provides comprehensive insights and aids in understanding different processes in the orchard environment.



**Fig. 3.** Mean hourly seasonal offsets between open- and in-orchard (a) air temperature  $(AT_o)$ , (b) relative humidity  $(RH_o)$ , (c) solar radiation  $(SR_o)$ , and (d) wind speed  $(WS_o)$  for apple orchards for year-1. The different color lines represent different sites. The shaded gray areas represent night hours.



**Fig. 4.** Site-specific mean hourly  $AT_o$  (line) and 0.5 SD (shaded) between paired open- and in-orchard stations for dry, irrigation, and overhead sprinkler days at (a) site 1a, (b) site 1b, (c) site 2, and (d) site 6.



**Fig. 5.** Site-specific mean hourly  $RH_o$  (line) and 0.5 SD (shaded) between paired open- and in-orchard stations for dry, irrigation, and overhead sprinkler days at (a) site 1a, (b) site 1b, (c) site 2, and (d) site 6.





**Fig. 6.** Site-specific mean hourly solar radiation  $(SR_0)$  (line) and 0.5 SD (shaded) between paired openand in-orchard stations for dry, irrigation, and overhead sprinkler days at (a) site 1a, (b) site 1b, (c) site 2, and (d) site 6.



**Fig. 7.** Site-specific mean hourly wind speed (WS<sub>o</sub>) (line) and 0.5 SD (shaded) between paired openand in-orchard stations for dry, irrigation, and overhead sprinkler days at (a) site 1a, (b) site 1b, (c) site 2, and (d) site 6.

Objectives 2 and 3. Modeling the orchard effects and AWN integration.

Modeling was done for each of the weather parameter (AT, RH, WS) separately using methodology flowchart depicted in the figure below. For example, Multiple linear regression (MLR) and two

machine learning models namely K Nearest Neighbor regression (KNN) and Random Forest (RF) were developed to predict air temperature. Likewise, three separate models were developed respectively for WS and RH prediction. It total, 9 models were developed.



**Fig. 8.** Flowchart of in-orchard temperature weather prediction using open-field weather, calendar parameters, orchard canopy parameters and geographical attributes. The same approach was used to model in-orchard relative humidity and wind speed.

#### **Results and Discussion**

Due to space constraints, we are unable to include all the plots and model performance data in this report. As an example, the model validation results for in-orchard air temperature are presented here (Fig. 9a). Pertinent model validation performance, i.e., root-mean-squared-error (RMSE) for in-orchard AT, RH, and WS prediction by all three models are also reported in Figs. 9b,c, and d, respectively. Overall, KNN and RF models have have shown good performance to predict these key variables with RMSE <0.7 °C, <3%, and < 0.25 ms<sup>-1</sup> in all four seasons considered for modeling. These results are being written as peer-reviewed publication and the offset/modeling efforts will be transitioned into AgWeatherNet portal to dynamically correct the open-field data for orchard effects.



**Fig. 9. a)** Model performance metrices on the test dataset for in-orchard air temperature prediction, and root-mean-squared-error (RMSE) of predicting in-orchard **b**) AT, **c**) RH, and **d**) WS using Multiple Linear Regression (MLR), K-Nearest Neighbor Regression (KNN) and Random Forest Regression (RF) modeling approach.

#### **Executive summary**

Project title: Modeling Orchard Effects on Meteorological Measurements

Keywords: Weather, orchard temperatures, decision-support, heat, cold

Executive summary: Weather-based decision-support tools for in-orchard management are derived from open-field weather station data with an assumption that there is minimal to no difference between open-field and in-orchard weather. This project results invalidate above assumption. Architecture type, growth stage, and various management practices do cause different weather conditions inside the orchard, that may lead to bias and uncertainty in the weather-based models. This project quantified orchard and management effects on air temperature, relative humidity, solar radiation, and wind speeds at different time scales using two seasons of data from six commercial apple orchards. A paired t-test revealed significant differences (p < 0.05) between the seasonal means of the open-field and in-orchard weather, indicating substantial orchard effects. Typically, orchards have 1.9 to 4.4 °C cooler air temperature and 9.2 to 27.5% higher relative humidity due to the evident impacts of tree transpiration. Also, in-orchard microclimates stations recorded lower solar radiation  $(267.8 \text{ to } 483.2 \text{ W m}^{-2})$  and wind speed  $(2.2 \text{ to } 3.7 \text{ m s}^{-1})$ . Monthly averages data revealed the dependence of orchard effects on the phenological stages of apple canopies. Wind resistance and air mixing caused drier microclimate during winter (RH offset: 8.7 %) and spring (RH offset: 7.7 %). Orchard training systems and height do significantly (p < 0.05) affect the hourly air temperature and relative humidity offsets during summer. Overhead sprinklers enhanced the reduction in air temperature (4.6 °C) and increase in relative humidity (16.2 %) inside the orchard, and the effects tend to linger during evening and night hours. Project has also successfully developed regression model(s) to predict in-orchard air temperature, relative humidity, and wind speed with respective RMSE <0.7 °C, <3%, and < 0.25 ms<sup>-1</sup>.

# Project Title: Decision Support Tool for Precision Orchard Management

Report Type: Final Project Report

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Cooperators: Dave Allan (Allan Brothers Fruit Co.)

Project Duration: 3 Year

**Total Project Request for Year 1 Funding:** \$73,569 **Total Project Request for Year 2 Funding:** \$77,335 **Total Project Request for Year 3 Funding:** \$71,596

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

# Budget 1 Primary PI: Joseph Davidson Organization Name: Oregon State University/Agricultural Research Foundation Contract Administrator: Charlene Wilkinson Telephone: (541) 737-3228

Contract administrator email address: charlene.wilkinson@oregonstate.edu

Item	2020	2021	2022
Salaries	\$31,331.00	\$32,271.00	\$26,622.00
Benefits	\$8,311.00	\$9,206.00	\$8,162.00
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	\$2,986.00	\$4,000.00	\$4,000.00
Travel	\$3,000.00	\$3,000.00	\$3,000.00
Plot Fees			
Miscellaneous			
Total	\$45,628.00	\$48,477.00	\$41,784.00

<sup>1</sup>Salaries include a Graduate Research Assistant on a 12-month, 0.49 FTE appointment in years 1 and 2, and a 9month, 0.49 FTE appointment in year 3. Salaries also include 0.25 months per year for Joe Davidson and Cindy Grimm.

<sup>2</sup>Leaf samples are included in the supply budget.

<sup>3</sup>Travel budget is requested to support mileage and lodging for data collection and field experiments.

# Budget 2 Co PI 2: Manoj Karkee Organization Name: Washington State University Contract Administrator: Katy Roberts Telephone: 509-335-4564 Contract administrator email address: katy.roberts@wsu.edu

Item	2020	2021	2022
Salaries	\$17,840.00	\$18,554.00	\$19,296.00
Benefits	\$5,101.00	\$5,304.00	\$5,516.00
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	\$4,000.00	\$4,000.00	\$4,000.00
Travel	\$1,000.00	\$1,000.00	\$1,000.00
Plot Fees			
Miscellaneous			
Total	\$27,941.00	\$28,858.00	\$29,812.00

<sup>1</sup>Travel budget is requested to cover the mileage for field experiments.

**Introduction:** The standard practice of broad-acre orchard management does not result in targeted actions that are optimal for individual trees – this reduces the impact of management decisions and wastes resources while falling short on achieving the yield and quality potential of individual blocks. **Our team's overall goal was to improve fruit quality and yields by managing individual trees through a combination of automated sensing, learning algorithms, decision support tools, and precision application with variable rate technology**. While for this project we focused on matching nitrogen (N) fertilizer to N demand, our long-term vision is to extend this framework for farming at the tree level to other orchard management decisions (e.g. plant growth regulators, root pruning, tree pruning, chemical thinning). The conceptual framework that we developed for precision N application is shown in Fig. 1 and included the following sequence of activities:

- 1. Build a site map of individual trees (performed once at the beginning of the project)
- 2. Use non-contact sensing to estimate tree nutrition (performed annually)
- 3. Recommend tree-specific fertilization plans using decision support tools incorporating machine learning
- 4. Apply variable rate N using real-time vehicle localization and precision technology
- 5. Use historical data to improve the performance of the decision support tool



Figure 1. Project framework. A detailed tree map was developed for the site at the beginning of the project. Raw sensor data on various orchard parameters was used as input to a learning algorithm that provides precision fertilization plans. Onsite vehicle localization was used to execute precision application of nitrogen. Historical data on destructive leaf N measurements, horticultural measurements, harvest yields, etc. was used to tune the learning algorithm.

To implement the framework shown in Fig. 1, we created the following 3 specific research objectives:

- 1. Develop a ground vehicle-mounted sensor system that *i*) maps the geographic location of individual trees within an orchard block; and *ii*) measures plant parameters (e.g. shoot vigor, trunk cross-sectional area, and fall leaf color) to estimate the N status of individual trees
- 2. Develop a decision support tool that recommends N application levels per tree and tracks the tree's long-term response
- 3. Develop and demonstrate a proof-of-concept precision spray system that localizes the vehicle with the orchard map, identifies the neighboring trees, and then selectively applies the desired level of N within the root zone

This final report summarizes research results over the performance period of January 2020 – November 2023. *The most significant findings from the project include the following*:

- Trees in the test plot used for the long-term study were more likely to have excess leaf N than be N-deficient.
- Consumer grade RGB-D sensors and state-of-the-art deep learning models can be used for automatic measurement of trunk cross sectional area.
- Normalized canopy area is highly correlated (negatively) to the target N application rate for the upcoming season. The use of normalized canopy area as a measure of canopy vigor and an indicator of the N need of individual trees is promising.
- The yellowness index of a tree at different weeks and the pattern in which they are changing can be a potential indicator of the N status in the tree. Also, weeks 3-4 can be a good time to differentiate between high N and low N trees as the trees with low N start to change color.
- Trunk width can be used to precisely localize a robot within an orchard without the need for GPS.

# **Objective 1: Orchard mapping & nitrogen sensing**

# Task 1 – Tree trunk detection (OSU lead, WSU participant)

We created a method that uses an RGB-Depth camera (Intel RealSense D435) to automatically calculate trunk width, which is needed for robot localization and is also an indicator of tree nutrition. The first step to estimate trunk width is to pass the RGB image through an image segmentation model (Deep Neural Network) that determines where the trunk is in the image. The depth image can then be used to determine the distance between the trunk and the camera, which is used to calculate the width of the tree.

**Instance segmentation**: The segmentation model we adopted was YOLOv8. To train it, 1090 images from the Jazz test block (Yakima Valley Orchards, Prosser, WA) were labeled with post and tree classes. Images from multiple seasons were included to increase model robustness (e.g. dormant season, bloom, and shortly before harvest). The segmentation model performs best when it is used in the test block with the camera positioned similarly as in the training images. Thorough tests were not conducted for other camera positions or in other orchards, but preliminary findings show that its performance notably diminishes. However, training a new segmentation model for images taken from an alternate perspective, or from a different orchard, is relatively simple and very easy to swap out in the width estimation pipeline. Figure 2(left) shows an example of the segmentation. Processing time was 14.6ms per image on our test computer.



Figure 2. (Left) A typical segmentation of an image with a post and trunk. (Right) the width calculation method. The pink lines are the left and right sides of the object, the blue lines are the centerlines, the red lines are the initial width predictions, and the green lines are the corrected widths. The width is shown at three locations for illustration purposes.

Width estimation: Once a trunk or post has been found in the image, we use the aligned depth image to calculate its width. First, the distance to the trunk is found by taking the median depth to the trunk. Next, we calculate an initial estimate of width in pixels by finding the distance between the right and left most pixels of the trunk for each row of the image. However, this estimate is only accurate if the trunk is perfectly vertical, so the width must be adjusted based on the angle of the trunk in the image. To do this, the center line of the trunk is approximated as the point between the rightmost and leftmost point, and then the local angle of the trunk is found by calculating the angle between every 15<sup>th</sup> pixel along the centerline (Figure 2(right)). We then multiply the width by the sine of the local angle to correct it and use the  $40^{\text{th}}$  percentile width as the width estimate. Finally, there is a final correction based on the proximity of the trunk with the edge of the image. We observed that widths for trunks near the edge of an image are overestimated, due to distortions in the camera, so we developed a regression model to correct for this effect. The performance of the final system vs. ground truth human measurements is shown in Figure 3. Mean absolute error was 2.56mm with a standard deviation of 2.39mm. Average processing time to calculate the width was 37.2ms.

#### <u>Task 2 – Orchard mapping (OSU lead, WSU</u> <u>participant)</u>

At the beginning of the project, we created an accurate map of the orchard test block. To create the map, we installed both an RTK GPS (elevated to the top of the canopy on a boom) and an RGB-D camera (mounted on the side) on a utility vehicle and collected data while driving through each row of the site. The data was then postprocessed to create an initial map using our image segmentation pipeline and the GPS recordings. Some corrections had to be made manually, primarily due to either poor image segmentations or errors when matching trunks between successive images from the video stream. Figure 4 shows the final corrected map of the orchard test block. The 200 treatment trees that we used for long term studies are shown within the map.

#### <u>Task 3 – Nitrogen measurements and non-contact</u> sensing (WSU lead, OSU participant)

We collected leaf samples for the 200 test trees each of the 4 years of the project. Figure 5 shows the results of the mineral analysis. In general, the treatment trees had excess leaf nitrogen as opposed to too little, and the nitrogen status appeared to remain relatively consistent year to year.



Figure 3. The predicted vs. ground truth measurements for 224 trees using our width measurement system.



Figure 4. Corrected map of orchard test block.



Figure 5. Leaf nitrogen percentage of test trees for 2020-2023. The location of the dot for each treatment tree corresponds to its actual position in the orchard and the size and color correspond to the leaf nitrogen content.

#### Normalized Canopy Area Estimation

Methods: The dataset for this study was collected during the end of the growing season (late July to early August) in 2021, 2022, and 2023 using a commercial Zed2i sensor mounted on a ground vehicle (Fig. 6). The camera was positioned approximately 7.5 ft above ground and 5.0 ft from the tree trunk so that the entire canopy was visible in individual frames. The vehicle was driven straight in between the tree rows, maintaining an approximately constant distance between the camera and the trees.

After extracting the colored point cloud of the desired frames with the test tree, all points with missing depth information (which could be caused by occlusion or other sensor



Figure 6. Data collection setup that includes a utility vehicle with Zed2i camera (Stereolabs, France) for image acquisition. The camera and its axes are zoomed in on the right.

limitations) were removed followed by color, depth, and height thresholding to remove points from the ground, background, and sky. The point cloud at this step was still noisy, and therefore a radius-based outlier removal technique was used to remove one or a small group of points that were not within a specific distance from the rest of the points in the point cloud. A radius of 20 mm and a total number of points of 50 were used as thresholds to implement this technique using the open3D library, which meant that if there were 50 or fewer points in a spherical neighborhood of 20 mm radius, those were removed from the point cloud. After the radius-based outlier removal, a camera-axis-aligned bounding box was fitted to the point cloud. The bounding box was set to an overall height of 3.5 m, a width of

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1.2 m, and a depth of 1.6m. This bounding box ensured that the sample tree was positioned inside the box and that the box size remained the same for all the trees used in this study. The close spacing of trees in the high-density orchard makes it difficult to delineate the boundaries of individual trees. By considering the overall width of 1.2m (4ft) (which is the spacing between trees), we can safely assume that the foliage from the neighboring trees does not significantly affect the calculation of the normalized canopy area of the trees. The segmented point cloud was then projected back to a 2D color image using the indices of the points in the point cloud to obtain the segmented foreground tree image.

To assess the performance of the canopy segmentation technique, the original RGB images for 20 individual tree canopies were manually annotated and compared against the results of the automated segmentation system. The outer boundary of the manually annotated tree canopies was outlined with red, and the holes within the outer boundary of the canopies were outlined with blue (Fig. 7a). The area covered by the outside and inside boundaries was then subtracted to get the total mask (and area in the number of pixels) for the target tree canopies. The canopy areas of individual trees segmented by the proposed algorithm were then compared against the area calculated with the manual annotation (Fig. 7b). The performance of the segmentation algorithm was then evaluated using the Precision, Recall, and F1 matrices as defined by equations 1, 2, and 3, respectively.

$$Precision = True Positive \div (True Positive + False Positive)$$
(1) $Recall = True Positive \div (True Positive + False Negative)$ (2) $F_1 = 2 * Precision * Recall \div (Precision + Recall)$ (3)





(a)

(b)

Figure 7. a) Manually annotated canopy boundary of a sample tree; the red line represented the outside boundary, and the blue lines represented the holes within the overall canopy boundary; b) Segmentation results (yellow) on top of the manually annotated (blue) canopy of the sample tree. White-colored regions represented portions present in both. Sections AA-1 and AA-2 represented the manual annotation and automated segmentation masks for section AA.

The segmented image obtained in the previous step was then used to create a binary mask for the target trees. A rectangular bounding box was fitted outside the binary mask of the segmented tree, which gives the maximum area the canopy could cover. The normalized canopy area was then calculated inside the

bounding box using equation 4, which measures how much of the total possible area of the tree is covered by the actual canopy.

## Normalized Canopy Area = Pixels occupied by vegetation $\div$ Total number of pixels (4)

The normalized canopy area was then correlated with the N application rate recommended by 4 experts based on their assessment of tree vigor. The experts were requested to evaluate the trees and recommend a N application rate on a scale of 0-50 lbs per acre (0 - 56 kg/ha) at an increment of 10 lbs per acre. Two of the experts were growers/orchard managers and were directly involved in orchard management for more than 30 and 15 years, respectively. The other two were from academia and were involved in research, education, and outreach on tree fruit physiology, including nutrition management. The experts independently evaluated the trees after harvest in the same season, as per their availability, before the trees started losing leaves to ensure that the canopy growth from the current season was still completely visible. These experts qualitatively assessed the trees in terms of their vigor (e.g., shoot growth, canopy area) and any other apparent factors (e.g., trunk diameter) they would use in their day-to-day decision-making and incorporated their experience to recommend a N application rate. A higher N application rate means the experts found the trees to have lower vigor than desired for target fruit yield and quality and vice versa. A sub-sample of 55 trees from a total of 199 treatment trees was chosen randomly for the experts' evaluation.

**Results & Discussion:** A normalized confusion matrix was created to qualitatively assess the performance of the segmentation method (Fig. 8). In this case, false negatives are foreground pixels classified as background, and false positives are background pixels classified as foreground. True positives and true negatives are correctly classified foreground and background pixels. The algorithm achieved a precision of 0.79, recall of 0.77, and an F1 score of 0.78 and was able to segment the foreground tree properly. These results suggest that parts from the ground, background rows, and neighboring trees were properly removed from the analysis with minimal errors.

A generally linear relationship existed between the normalized canopy area and the experts' N recommendation (Fig. 9). A correlation coefficient of - 0.86, -0.84, -0.96, and -0.78 was obtained between the



Figure 8. Normalized confusion matrix comparing the automated canopy segmentation with the manually segmented ground truth canopies.

normalized canopy area and the N application recommendations provided by Experts 1, 2, 3, and 4, respectively. The high negative correlation coefficients among the experts showed that the normalized canopy area is highly correlated (negatively) with the target nitrogen application rate for the upcoming season. The results also indicate that the use of normalized canopy area as a measure of canopy vigor and an indicator of the nitrogen need of individual trees is promising.





Figure 9: Relationship between normalized canopy area and N application level recommended by (Top left) Expert 1, (Top right) Expert 2, (Bottom left) Expert 3, and (Bottom right) Expert 4. The red line shows the regression plot for the expert nitrogen recommendation level and the median normalized canopy area at each recommendation level for each expert.

#### Temporal leaf color assessment

**Methods:** Another parameter of interest is the temporal change in leaf color during the fall. For this study, we collected images of the leaves' color change from green to yellow over 6 weeks starting on October 8, 2021 (the leaves froze before showing any color change in 2022, and more data is being collected in 2023). Figure 10 shows the data collection setup and color during the different weeks of the study for one of the sample trees. The point cloud obtained from the camera was thresholded using color and depth thresholds and downsampled uniformly at a 10:1 ratio. The downsampled point cloud was then clustered using a hierarchical clustering technique on the CIE-L\*a\*b color space. A hierarchical K-means clustering was used to first group the points into 20 clusters. A threshold in both a\* and b\* spaces for the group centers was applied to merge the classes into 3 final clusters: Yellow, Green, and Trunk. The Yellow cluster included the foliage that had turned yellow, the Green cluster included foliage that was still green, and the Trunk cluster included the remaining points from the trunk, branches, some brown leaves, and soil from the background (and the leaves that had turned red on a few trees). The final output from the clustering algorithm included three clusters: Green cluster (c<sub>g</sub>), Yellow cluster (c<sub>y</sub>), and Trunk cluster (c<sub>1</sub>). Figure 11(left) shows the result of the clustering technique for one of the sample trees where yellow, green, and trunk clusters belong to  $c_y$ ,  $c_g$ , and  $c_t$  respectively.

After the grouping of points into 3 clusters/classes, the Yellow  $(c_y)$  and Green  $(c_g)$  classes were used to calculate the yellowness index of each tree, a metric that we defined to indicate what fraction of the foliage is yellow as compared to green. The yellowness of each tree was calculated using equation 5.

$$Yellownes \ Index = (y - g) \div (y + g)$$
(5)

where, y = number of pixels/points in the Yellow Cluster,  $c_y$  and g = number of pixels/points in the Green Cluster,  $c_g$ .



Figure 10: Data collection setup and color change during the six weeks of the study.



Figure 11: (Left) Segmented point cloud and clustered point cloud (i.e. Green, Yellow, and Trunk cluster) of a sample tree. (Right) Yellowness for all trees during different weeks of study.

**Results & Discussion:** The yellowness index of each tree was calculated over the 6 weeks of the study. Figure 11(right) shows a plot of yellowness for all trees during the 6 weeks. The results show a general trend of yellowness increasing with each week (i.e. trees turning more yellow), as expected. The boxplot shows that all trees start out at a yellowness index of ~-1 during the first week (i.e. all trees were completely green). However, at week 3 there is an increase in the yellowness index. At week 4, the change is more prominent where there is a significant increase in yellowness index. By week 6, most of the trees have a high *yellowness* value (i.e. they are almost through the complete color change and have turned yellow). However, there are still some trees with a negative yellowness index (i.e. still on the greener side).

The trees were classified into 5 classes of N status: Very low N (N < 1.7), Low N (1.7 < N < 2), Good N (2 < N < 2.4), High N (2.4 < N < 2.6), and Very high N (N > 2.6). Figure 12 shows the yellowness values by week with a color code assigned to trees from the different N classes. Trees with lower N start the transition earlier in the season. At week 4, this is more clear as the trees with lower N start the transition to yellow. However, most of the higher N trees are still towards the greener side. At week 6, most of the lower N trees are already at yellowness index of +1 (i.e., completely yellow), however, there are still quite a few higher N trees transitioning color. This transition is affected by several factors including environmental stress, nutritional stresses, and aging. The results show correlation between the yellowness index and the N content at different weeks ( $R^2 = 0.14 - 0.18$ ) and indicate that the yellowness index of a tree at different weeks and the pattern in which they are changing can be a

potential indicator of the N status in the tree. Also, weeks 3-4 can be a good time to differentiate between high N and low N trees as the trees with low N start to change color.



Figure 12: Yellowness during different weeks of the study for trees with different nitrogen levels. Week 1 started on October 8, 2021.

#### **Objective 2: Decision support tool (WSU/OSU joint lead)**

**Methods:** The parameters discussed above were used in the decision support tool to decide the fertilization rate for individual trees. A simple gradient boost regressor was used to fit a model to predict the leaf N concentration using the trunk cross-sectional area and normalized canopy area as input. The predictions were further classified into 5 classes: 5 - Very low N (N < 1.7), 4 - Low N (1.7 < N < 2), 3 - Good N (2 < N < 2.4), 2 - High N (2.4 < N < 2.6), and 1 - Very high N (N > 2.6) based on their predicted leaf N concentrations. The model was trained on 50% of the data from 2022 and tested on the classification of the trees (i.e. tree with class 1 targeted with a rate of 10 lbs/acre, and a tree with class 5 targeted with a rate of 50 lbs/acre by varying the volume of liquid sprayed around the tree).

**Results & Discussion:** The model was able to predict the leaf N concentration with an RMSE of 0.32%. With this level of RMSE, the predicted classes of the target trees are expected to be within one class (one class higher or lower). The current model for decision support is expected to be further improved with the integration of fall leaf color, the yield from previous years, and experts' rating as feedback to the system.

#### **Objective 3: Variable rate N application**

#### Task 1 – Vehicle localization (OSU lead, WSU participant)

**Methods**: To accurately apply N autonomously based on visual tree metrics, it's essential to identify the specific tree being examined, ensuring the data corresponds to the correct tree. This was accomplished by localizing the ground robot (Clearpath Warthog) on a pre-made map of the orchard

using a particle filter system. Particle filters localize by first scattering a large number of potential position estimates (i.e. the particles) across the map. Then, as more data from the environment is captured while the robot traverses, including RGB-D images of trunks and wheel odometry, the algorithm uses probability theory to update predicted positions until only one position estimate remains. For brevity, we do not present the details of the algorithm in this report. Figure 13 shows a graphical depiction of the multiple stages of the algorithm.



Figure 13. Graphical depiction of four stages of the particle filter system. In the map, posts are red dots, treatment trees are large blue dots, other trees are green dots, particles are small blue dots, and the final position estimate is a large purple dot. The left image shows the initial spread of the particles. The next image shows the system once a single tree has been seen. The third is after several trees have been seen. In the right image the particles have converged (purple dot).

**Results & Discussion**: The localization system was tested in real time in the field and shown to perform well. Localizing in an orchard is difficult primarily since everything looks very similar: the trees all look the same, are similarly spaced, and are in straight rows. The addition of the width as a metric for calculating the probability of the particles aids in reducing this ambiguity, but it's still a challenge. On the other hand, once the robot has converged on the correct general location, the error in the localization is largely a product of the accuracy of the camera system, the accuracy of the transform between the camera and the robot, and the accuracy of the map. To this end, most of our analysis focused on whether the algorithm converged correctly and how long it took to converge, for various sized initial spreads of particles.

To evaluate the system's performance, we tested 3 different sizes of spread in the field, conducting approximately 20 trials for each (see Table 1). Each trial started at a unique location on the map. For clarity, the spread height and width indicate the size of the initial spread; for instance, the example in Figure 13 has a width of 4 m and a height of 20 m. The 'distance to converge' metric is how far the robot traveled before the system converged. It's evident from our trials that there was a large variation in convergence time and distance, as indicated by the large standard deviation, but as one would expect, larger initial spreads result in longer convergence times and reduced convergence accuracy. The particle system converged to the correct location 90% of the time even when the initial spread was large.

Table 1. Results for the particle filter trials. The spread width and height give the initial spread area, the correct convergence gives the % of trials that converged correctly. The time to converge is how long it took the system to converge, and distance to converge is how far the robot traveled before the system converged.

Spread width (m)	3	4	12
Spread height (m)	10	20	20
Num. trials	21	21	32
Correct convergence (%)	95.2	90.5	90.6
Avg. time to converge (s)	16.19 +/- 10.47	18.73 +/- 9.69	25.39 +/- 8.66
Avg. distance to converge (m)	3.99 +/- 2.62	5.16 +/- 2.73	7.17 +/- 2.67

#### Task 2 – Precision spraying (WSU/OSU joint lead)

Methods: The N application rate recommended by the decision support system was administered through an automated system capable of self-localization within the orchard. The main platform for the integrated system was a Clearpath Warthog ground robot as shown in Fig. 14. A 25-gallon reservoir was mounted on top of the ground robot to store the liquid solution to be sprayed (the system was tested with water in field trials). The solution was then applied with an 80° flat-fan spray nozzle (TeeJet Technologies, Illinois, USA) and 12V solenoid valve (TeeJet Technologies, Illinois, USA) that was attached to the ground robot at an angle of  $20^{\circ}$  with the robot body, oriented towards the root zone of the trees. The solenoid valve was actuated with a microcontroller. The front-facing 2D LiDAR (Sick LMS 111-10100 (Sick AG, Waldkirch, Germany)) was used to capture a laser scan in front of the robot to control its motion and ensure safe operation. The side facing Realsense D435i (Intel Corp., CA, USA) was used to detect trees while the platform was moving. The LiDAR, Realsense D435i camera and Arduino were connected to a Jetson Nano (NVIDIA Corp., CA, USA) on the Warthog. Both the Jetson Nano and the Warthog computer were connected to a common network via an ethernet switch (TP-Link Tech. Co., China). The entire system can be accessed through the network switch or wireless router connected to the switch. The spray line was pressurized at 40 psi with a pressure regulator and relief lines. Two 12V batteries were connected to power the pump for spraying and actuating the solenoid valve, while the Warthog was powered with rechargeable lithium batteries. The integrated system was self-contained with all power required for running the equipment on-board.



Figure 14: The integrated system: a) from front and b) from back. The front-facing LiDAR and the sidefacing camera are visible in a), while the spraying nozzle has been zoomed in on b). The yellow tank on top contains the spray solution.

**Results and Discussion**: The integrated system accurately sprayed a quantity of liquid, as decided by the decision support system, directly onto the root zone of the trees. The integrated system accomplished the following tasks: i) Autonomous navigation within a row in the orchard, ii) Detection of trees and localization in the orchard, and iii) Precise application of the designated N amount to the tree's root zone. The overall system integration was implemented using Robot Operating System (ROS). These tasks were run on multiple computers connected to the same network through the network switch and communicating with each other in real-time through ROS.

**i) Autonomous Navigation Node:** The autonomous navigation system was able to identify the left and right tree lines based on the incoming laser scans by fitting a least square fit line to the points on the left and right. The center line was the average of the right and left lines (Fig. 15). The heading and position of the robot were identified using the orientation of the center line. Angular velocities were

controlled to maintain a constant distance of 0.1m to the left of center and oriented parallel to the orchard rows with a constant linear velocity. The system was set to observe 5m in front of the robot.

**ii)** Localization Node: The localization system, as discussed in Task 1 of Objective 3, was used in the integrated system to identify the position of the ground robot with respect to the trees on the map. The localization node identified the tree trunk and estimated its diameter in real time, which was used as an input for the decision support system to decide the amount of liquid to be sprayed on each treatment tree.

**iii) Sprayer Node:** A proportional amount of fertilizer based on the classification result from the decision support system was applied to the test trees. The



Figure 15. An instance of the laser scan (red dots) and the fitted line for left and right rows. The green lines show the fitted line for left and right tree rows, and the blue line shows the center line.

decision support system took as input the real-time diameter estimation from the localization node and normalized area for the corresponding tree from the 2023 data that was calculated in early August (the system was tested in late October). The spray was actuated for a time proportional to the required volume of spray as would be required for a solution with water-soluble 20% N fertilizer diluted at 1 lb of fertilizer per liter of water. The flow from the spray nozzle was calibrated using a measuring cylinder with different volumes. The calibration model allowed for obtaining a precise volume output from the spray nozzle within 5 ml. The nozzle remained off until it reached the test tree and actuated at 5 different distances from the test tree based on the required volume, which was proportional to its N requirement. The spray time was calculated based on the flow from nozzle, the desired concentration of fertilizer in the solution, and the linear velocity of the robot to uniformly apply the solution to the test tree. The spray area of the system was tested using two 4ft wide paper rolls spread 2 ft to the left and 2 ft to the right from the tree trunk (Fig. 16). To make the spray area visible, water-soluble food coloring was added to the water.



(a)

(b)

Figure 16: Paper roll spread out in front of the tree a) before spraying and b) after spraying. The red color on the paper shows the sprayed area.

**Results & Discussion:** The system was able to: correctly center itself in the row, autonomously navigate within the rows, precisely localize within the orchard, and spray the solution at desired locations around the test trees. The sprayer was able to target the spray within an area of 4ft of the target trees on the sides and 1.5 ft on the front of the trees, which was within the root zones for the target trees. The video of the overall system operating in the field can be found by clicking the <u>link</u>.

#### **Executive Summary**

Project title: Decision Support Tool for Precision Orchard Management

Key words: Precision fertilization, variable rate technology, computer vision, deep learning

**Abstract**: The standard practice of broad-acre orchard management does not result in targeted actions that are optimal for individual trees – this reduces the impact of management decisions and wastes resources while falling short on achieving the yield and quality potential of individual blocks. The primary goal of this project was to improve fruit quality and yields by managing the Nitrogen (N) of individual trees through a combination of automated sensing, machine learning, decision support tools, and variable rate application technology. To accomplish our goals, we created three specific research objectives:

- 1. Develop a ground vehicle-mounted sensor system that i) maps the geographic location of individual trees within an orchard block; and ii) measures plant parameters (e.g. shoot vigor, trunk cross-sectional area, and fall leaf color) to estimate the N status of individual trees
- 2. Develop a decision support tool that recommends N application levels per tree and tracks the tree's long-term response
- 3. Develop and demonstrate a proof-of-concept precision spray system that localizes the vehicle with the orchard map, identifies the neighboring trees, and then selectively applies the desired level of N within the root zone

Over the duration of the project we collected leaf samples from 200 treatment trees within the test block (Jazz cultivar; Yakima Valley Orchards, Posser, WA). Mineral analysis showed that most treatment trees had excess leaf N as opposed to too little and that N status remained relatively consistent year to year. To automatically detect trees and estimate trunk cross sectional area, we used a consumer grade RGB-Depth sensor and deep learning. Compared to manual measurements with calipers, the mean absolute error of the trunk width estimation algorithm was 2.56mm. The deep learning algorithm was then used in conjunction with RTK-GPS to create an accurate map of all trees and posts within the test block.

To estimate tree nutrition with non-contact visual sensing, we created new techniques that measured canopy area and temporal changes in leaf color. We found that normalized canopy area is highly correlated (negatively) with the target N application rate for the upcoming season (based on human expert guidance). The use of normalized canopy area as a measure of canopy vigor and an indicator of the N need of individual trees is promising. Also, the yellowness index of a tree at different weeks and the pattern in which they are changing can be a potential indicator of the N status in the tree. We observed that Weeks 3-4 can be a good time to differentiate between high N and low N trees as the trees with low N start to change color.

Our final contribution of the project was an in-field demonstration of autonomous variable rate application with a ground robot. Using a particle filter system that incorporated the orchard map and trunk segmentation algorithm, the robot was able to quickly and accurately localize with respect to individual trees without the need for GPS. A decision support tool incorporating a simple gradient boost regressor was used to determine the fertilization rate for individual trees. The N application rate recommended by the decision support system was applied through an automated liquid spray system. The integrated system accomplished the following tasks: i) Autonomous navigation within a row in the orchard, ii) Detection of trees and localization in the orchard, and iii) Precise application of the designated N amount to the tree's root zone. The sprayer was able to target the spray within an area of 4ft of the target trees on the sides and 1.5 ft on the front of the trees, which was within the root zones for the target trees. Future work will focus on using historical data (e.g. yields) to improve the decision support tool.

# Project Title: WTFRC Technology Roadmap

Report Type: Final Project Report

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**Project Duration:** 1-Year

**Total Project Request for Year 1 Funding:** \$97,200

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

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## Recap original objectives and significant findings

The Washington Tree Fruit Research Commission (WTFRC), founded in 1969, represents tree fruit producers in Washington state, including apple, cherry, pear, and stone fruit growers and packers. Today, the industry is facing numerous challenges - from climate pressures to macroeconomic uncertainties - and recognizes that technology will be key to thriving in an increasingly complex and uncertain future. WTFRC identified the need for a technology roadmap that catalyzes and inspires action within and beyond the industry, with a deep dive emphasizing 2-3 high priority areas.

The purpose of this project was to engage with the commission, and consult deeply with industry stakeholders, to develop a technology roadmap that prioritizes action in the next two years. All objectives for the project have been achieved.

The roadmap developed considers the broader trends impacting the industry, and the barriers to adoption of technology that the industry currently faces. The roadmap specifically includes 3 high priority areas for near-term focus, that will have an impact on industry over near, mid, and long-term: irrigation (near-term), crop load management (mid-term), harvest labor (long-term). For each priority area, the current state of technology is discussed, including example companies. Specific strategies are also presented and prioritized within each area, with example activities that are designed to attract a broad range of collaborators.

#### **Results and Discussion**

The purpose of this project was to engage with the commission, and consult deeply with industry stakeholders, to develop a near-term (2 year) technology roadmap.

As a result of engagement with over 100 industry stakeholders via focus groups, 1:1 interviews, small group discussions, and an open survey, three areas were selected for the roadmap: irrigation, crop load management, and harvest labor. Strategies, with example activities, are defined for each area and prioritized overall, to create the roadmap.

## **Executive Summary (attached).**



# WTFRC Apples Technology Roadmap 2024-2026

# Key words

Technology Roadmap, Irrigation Technology, Crop Load Management, Harvest Automation

# **Executive Summary**

The Washington Tree Fruit Research Commission (WTFRC), founded in 1969, represents tree fruit producers in Washington state, including apple, cherry, pear, and stone fruit growers and packers. Today, the industry is facing numerous challenges - from climate pressures to increasing costs to macroeconomic uncertainties - and recognizes that technology will be key to thriving in an increasingly complex and uncertain future.

This report, focused on apples, presents a technology roadmap for the next two years of research, development, and extension activities. Through deep engagement with over 100 stakeholders across the industry, and in line with the principles shown below, three high priority areas have been selected across three different timelines to impact: Irrigation (near-term), Crop Load Management (mid-term), and Harvest Labor (long-term). Within each area, the existing technology landscape is described, and strategies and example activities have been identified for focus and action in the next two years, and prioritized across the roadmap (i.e., overall priorities).

Selection Principle	Details
Mission alignment.	Alignment to the WTFRC mission to "inspire strategies and promote collaborative science-based solutions to foster economic security and sustainability for Washington tree fruit growers"
Balance timeframes to impact.	Focus on near-term (2 year) strategies that will move the needle for growers, including groundwork that needs to be laid today to tackle mid- (3-5 year) and long-term (5-10 year) priorities.
Overcome barriers.	Target specific barriers to technology adoption, as identified via desktop research and interviews.
Leverage strengths.	Focus on WTFRC strengths (i.e., don't suggest things WTFRC is not well placed to take on).
Encourage diverse partners and broad thinking.	Specify outcomes and provide example (but not prescriptive) activities to encourage "out of the box" thinking and attract a diverse range of traditional (i.e., researcher) and non-traditional partners.



# Technology Roadmap

Priority Area	Strategy	End Goal	Priority
Irrigation	Create and improve incentives for new and existing irrigation service providers to support advanced irrigation technologies.	Eliminate real and perceived service gaps that can limit growers from investing in advanced irrigation technologies.	2
	Increase the availability of third-party data showing the effectiveness of irrigation technologies.	Increase confidence in the effectiveness of existing and emerging irrigation technologies.	2
	Develop a local evidence base for how irrigation technologies can enable the use of non-traditional irrigation techniques that improve fruit yield and/or quality.	Improve apple yield and quality through innovative irrigation techniques.	1
	Document and share irrigation technology strategies that growers are using to reduce costs.	Motivate adoption of irrigation tech by appealing to cost-saving opportunities, and leveraging social proof.	3
	Build capacity and capabilities for the effective use of irrigation technologies.	Improve the confidence and skills of operators across all levels of orchard operations related to effective use and optimal utilization of irrigation technologies.	2
Crop Load Mgmt	Incentivize research on the precision application of plant growth regulators.	Improve the effectiveness of existing chemical thinning tools to reduce labor and input costs.	2
	Advance the availability and effectiveness of crop load modeling tools, with special emphasis on early season prediction.	Farmers have access to high quality data around crop load management as early in the season as possible.	1
	Incentivize research and development work in pruning technology.	Increase the amount of technologists creating tools to advance pruning efficiency.	1



	Advance awareness of, and evidence for, the value of tech-enabled crop load management tools.	Increase crop load management tool exploration and adoption among growers.	3
Harvest Labor	Lower the costs of developing commercially viable mechanical/autonomous apple harvesting solutions.	Increase the amount of collaborations between technology developers, academic researchers, and commercial R&D providers to reduce duplication of efforts in the development of harvest labor solutions.	1
	Educate vendors and developers to ensure harvest labor solutions are designed to work within the operational and financial constraints of existing systems.	Vendors come to market not just with technology that works, but that is also affordable and easily integrated into apple orchards	2
	Help Washington apple growers get "robot ready."	WA apple growers are able to take advantage of emerging harvest labor solutions with minimal negative commercial impacts / trade-offs.	3
	Update WTFRC's RFP processes to efficiently engage the appropriate experts in vetting new research and commercialization proposals.	Ensure that limited resources for harvest labor solutions are appropriately and efficiently distributed, based on a range of required lenses for evaluating technologies (e.g., technical, industry, commercial, etc.) and development teams.	2