2027 Technology Research Review



Dave Allan explaining his ideas on how to best train apple orchards to be 'automation ready' to engineers from Case New Holland (CNH) and Anne Visser (social scientist from UC Davis)

December 3, 2026

Hybrid Format
Yakima, WA

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

Report Type: Continuing Project Report – No-Cost Extension

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: Bernardita Sallato
Organization: Washington State University
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
Organization: WSU, Tree Fruit Research and Extension Center
Telephone: 1-509-663-8181 ext(229)
Email: lee.kalcsits@wsu.edu
Address: 1100 North Western Ave.
Address 2:
City/State/Zip: Wenatchee, WA 98801

Co-PI 4: Dr. Lav Khot
Organization: Washington State University
Telephone: 509-786-9302
Email: lav.khot@wsu.edu
Address: 24106 N Bunn Rd.
Address 2:
City/State/Zip: Prosser, WA 99350
Cooperators: Aran Urlacher (Zirkle Fruit) aranu@zirklefruit.com.

Project Duration: 3-Year + NCE

Total Project Request for Year 1 Funding: $ 89,586.00
Total Project Request for Year 2 Funding: $ 40,557.00
Total Project Request for Year 3 Funding: $ 42,380.00

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

Category/Object	2023-2025	2026	Total
Salaries and Wages - 00 & 01	-	-	-
Purchased Services - 02	-	-	-
Goods/Services - 03	2,930.77	3,874.23	6,805.00
Travel - 04	-	-	-
Equipment - 06	-	-	-
Benefits - 07	-	-	-
Tuition (QTR) - 07QT	-	-	-
Scholarships and Fellowships - 08	-	-	-
Award Restrictions - 14	-	-	-
Total Direct Costs	**2,930.77**	**3,874.23**	**6,805.00**
F&A - 13	-	-	-
Total Costs	**2,930.77**	**3,874.23**	**6,805.00**

Footnotes: PI Bierer: The table above reflects expenses on USDA's WTFRC accounts during the project. Various USDA accounting delays/errors necessitated use of the PI's base-funds in pursuit of project objectives. Expenses not reflected in the table incurred from 2023 to 2025 total $42,322.65: Supplies = $23,212.19; extramural (ORISE student 0.5FTE) = $10,649.50; Travel = 8,460.96.

Budget 2
Co PI 2: Dr. Bernardita Sallato
Co PI 3: Dr. Lee Kalcsits
Co PI 4: Dr. Lav Khot
Organization Name: Washington State University (WSU)
Contract Administrator: Samantha Bridger
Telephone: N/A
Contract administrator email address: bridger@wsu.edu

Category/Object	2023-2025	2026	Total
Salaries and Wages - 00 & 01	28,686	48,887	77,574
Purchased Services - 02	3,069	2,500	5,569
Goods/Services - 03	4,559	35,334	39,893
Travel - 04	170	4,657	4,827
Equipment - 06	-	-	-
Benefits - 07	15,599	22,256	37,855
Tuition (QTR) - 07QT	-	-	-
Scholarships and Fellowships - 08	-	-	-
Award Restrictions - 14	-	-	-
Total Direct Costs	**52,084**	**113,634**	**165,718**
F&A - 13	-	-	-
Total Costs	**52,084**	**113,634**	**165,718**

Footnotes: Co PI Sallato: Salary and wages + fringe benefit at 55% supporting on site sample collection and plant monitoring during the season. Travel budget supporting bi-weekly site visits during the growing season. **Co PI Kalcsits:** Salary for technician + fringe benefit @ 46.5%. Travel budget supporting fruit sampling. **Co-PI Khot:** Salary for research assistant + benefit @ 35%. Instrumentation for irrigation system automation and sensing technology, and cloud data storage. Travel to field sites for installation, troubleshooting and monitoring technology during the season.

OBJECTIVES

1. Establish a Long-Range Wide Area Network (LoRaWAN) automated system for regulated deficit irrigation (RDI) in a commercial apple orchard in Mattawa, WA.
2. Utilize data-driven closed-loop technology to monitor and automate the RDI, based on the integration of weather-soil-plant sensors through the AWN Smart Farms platform.
3. Evaluate the impact of RDI on plant growth, yield and fruit quality, including a cost benefit estimation.
4. Develop technology "know-how" information and organize demonstrations and trainings to Washington apple growers and farm workers.

SIGNIFICANT FINDINGS

- A LoRaWAN closed-loop irrigation system hardware was deployed in 16 replicated plots (4 treatments × 4 blocks) in a commercial Honeycrisp orchard in Mattawa, WA and operationalized through AWN Smart Farms Platform.
- Soil water retention curves (developed using Hyprop) showed that most of the water available to trees in this silt loam type soil is held between −6 and −33 kPa. These results were only used as a reference and not to set the thresholds.
- The deficit irrigation logic applied separated the treatments: root-zone available water content and water applied decreased from T1 (100% FC or full irrigation) to T4 (25% FC or deficit irrigation).
- Trees in the drier treatments had lower daily trunk shrinkage and lower overnight recovery, showing that tree water status responded to the treatments in about ten days after implementing the treatments.
- Treatments started on August 17, 2026, three weeks before harvest. Hence, fruit weight, red color, and soluble solids did not differ among treatments.

METHODS

1. **Establish a Long-Range Wide Area Network (LoRaWAN) automated system for regulated deficit irrigation (RDI) in a commercial apple orchard in Mattawa, WA.**
   Site and experimental design. The experiment was conducted in a mature Honeycrisp orchard (planted 2006, M.26 rootstock, Figure 1) trained to a V-trellis and managed by Zirkle Fruit in Mattawa, WA. Four irrigation treatments were arranged in a randomized complete block design with four replicates, for a total of 16 experimental units (EU). Each treatment plot contained 35 trees spaced 1.2 m in the row and 4 m between rows (≈4 × 13 ft). Each EU was irrigated by drip through its own valve, with emitters spaced 0.8 m (2.63 ft) and a flow rate of 75 L/h (≈20 gal/h). The soil type is a silt loam (42% sand, 50% silt, 8% clay; 2023 soil analysis) at this block.



Figure 1. Layout of the RDI experiment in a commercial Honeycrisp orchard (Zirkle Fruit, Mattawa, WA). Four irrigation treatments (T1–T4, refill to 100, 75, 50 and 25% of available water content aka Field Capacity) were randomized within each of four blocks, for 16 experimental units. Boxes show the approximate extent of each treatment plot, colored by treatment: 35 trees along one row (≈42 m [138 ft]). Sensors and samples were in the middle row of each plot (dashed line). Pins mark the location of the soil moisture probe (Sentek Drill & Drop, 36 in) and trunk dendrometer (ePlant) installed in each plot. *Illustration created by Claude from Image © 2026 Google.*

Sensors and control. At each EU, a soil moisture probe (Drill & Drop, 36 in, Sentek Inc.) and a trunk dendrometer (ePlant Inc.) were installed to monitor soil water and tree water status. A LoRaWAN gateway was deployed at 700 m (2297 ft) from the experimental block, and all the deployed sensors were configured to record data at 15-minute intervals. The data gets transferred to AWN managed cloud and is visualized on AWN Smart Farms platform (https://weather.wsu.edu/smartfarm, Gorthi et al., 2026). Irrigation commands were sent to solenoid valve controllers (UC511, Milesight Inc.) through the same platform, and the irrigation was applied between 10 am to 6 pm pacific, when the block pump of the orchard was operational.

2. Utilize data-driven closed-loop technology to monitor and automate the RDI, based on the integration of weather-soil-plant sensors through the AWN Smart Farms platform.

Soil characterization. Undisturbed soil samples (one per EU, 16 in total) were collected at 15 cm (6 in) with a sample ring and analyzed by the evaporation method (Hyprop, Meter Group Inc.) to describe soil variability among treatments and replicates. The van Genuchten model was fitted to each curve to estimate water content at field capacity (FC, pF 2.5, ≈ −33 kPa), permanent wilting point (PWP, pF 4.2, ≈ −1,500 kPa) and available water capacity (AWC = FC − PWP). Because Hyprop

tensiometers measure only to about −100 kPa (pF ≈ 3), PWP is extrapolated from the fitted curve. The fitted curves were used to convert each AWC target into the equivalent soil matric potential, to check the variability across locations and verify sensor readings.

Irrigation treatments. Treatments were defined as refill targets of the available water content in the root zone (between 4 and 16 in) based on the soil moisture sensors data. Treatment were set as: T1 = 100% (fully irrigated reference, FC), T2 = 75% of FC, T3 = 50% of FC and T4 = 25% of FC. Targets were fixed to compare full irrigation with increasing levels of deficit, estimated using following algorithm, also illustrated in Figure 2.

Soil water balance algorithm. The algorithm ran each morning at 9:00 am and calculated the irrigation needed in each EU:

1. Soil moisture at 4, 8, 12 and 16 in (4-in layers) was aggregated to hourly medians to reduce sensor noise.
2. Root-zone water storage (S) was calculated as the sum of each layer's volumetric water content × layer thickness. Storage at field capacity (S_{FC}) and permanent wilting point (S_{PWP}) were calculated the same way from the maximum and minimum readings of each sensor and validated with the Hyprop moisture curves.
3. Total available water was estimated as TAW = $S_{FC} - S_{PWP}$. Current AWC (%) = $(S - S_{PWP}) /$ TAW × 100.
4. Target storage for treatment *j*: $S_{target} = S_{PWP} + \alpha_j \times$ TAW, with α = 1.00, 0.75, 0.50 and 0.25 for T1–T4.
5. Irrigation depth required: $I_{req} = \max(0, S_{target} - S)$. Events below 0.1 in were skipped.
6. Irrigation volume: $V_{req} = I_{req} \times A_w \times 0.6234 / 0.95$ (gallons; A*w* = treatment area in ft²; 95% efficiency). Run time = V_{req} / Q, with Q = 75 L/h, limited to 3 h per day; any remaining deficit was applied the next day. The irrigation was limited to three hours to limit the water drainage beyond the root zone.
7. Drainage check: soil moisture at 24 in was used to detect deep percolation and if it changed by more than 5% in one hour, irrigation was not stopped.

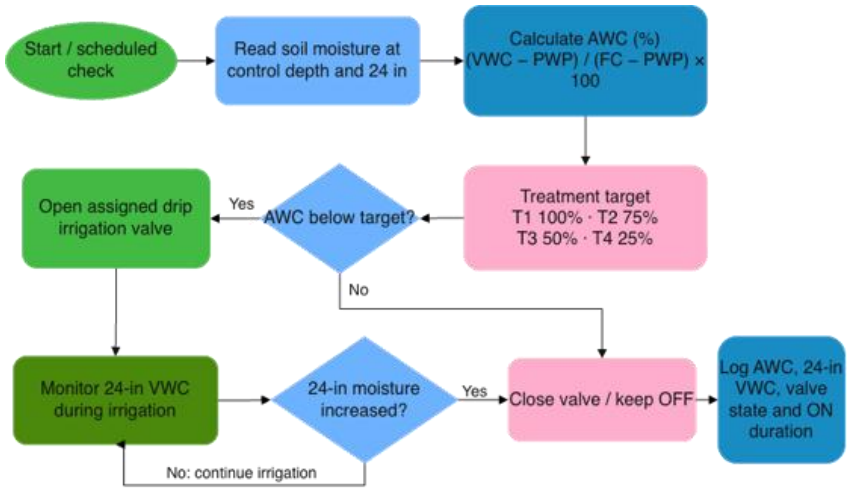


Figure 2. Flowchart of the soil moisture sensor–based regulated deficit irrigation algorithm.

Treatment period. Treatments were imposed from August 17, 2026, when the system became fully operational, and maintained until harvest. Data were analyzed from August 17 to September 17 (about one month).

3. Evaluate the impact of RDI on plant growth, yield and fruit quality, including a cost benefit estimation.

Tree water status. Dendrometer (ePlant) data were aggregated to hourly means, soil moisture to hourly medians, and both were matched by timestamp. Maximum daily shrinkage (MDS) and daily recovery (DR) of trunk diameter were calculated for each EU and day.

Fruit quality. Fruit was sampled from each EU at the first harvest pass, when approximately 10% of the crop was picked (by Co-PI Kalcsits team). Fruit weight (g), red color coverage (%) and soluble solids (°Brix) were measured.

Note: *Given that the treatment implementation was delayed and only runed for 3 weeks before harvest, yield, storage and cost-benefit analysis were not conducted in 2026.*

Statistical analysis. AWC and MDS were compared among treatments by one-way ANOVA with treatment as a fixed effect, followed by Tukey's test. Fruit quality was analyzed by ANOVA and Tukey's test ($\alpha = 0.05$) using EU means ($n = 4$).

4. Develop technology "know-how" information and organize demonstrations and trainings to Washington apple growers and farm workers.

The team leveraged ongoing extension programs on irrigation technology and heat mitigation, the Smart Orchard project and WSU Tree Fruit webinars on Irrigation Technology to share project progress with growers and farm workers. Additional efforts are planned for 2027 if a second NCE is approved; including participation in the Irrigation Fruit School, Spanish Tree Fruit Days and an Irrigation training (in Spanish).

RESULTS AND DISCUSSION

Objectives 1 and 2.

The closed-loop LoRaWAN irrigation system is fully operational in all 16 EUs. In spring 2026, valves were repaired and reinstalled, and the new sensing and control hardware was installed. Soil moisture probes were on back order, and once installed in early-summer of 2026, changes to the grower's main irrigation system were needed during cherry harvest. The treatments became fully operational on August 17, 2026.

The algorithm separated the treatments by soil water (Figures 3 and 5). Median root-zone AWC was about 72% in T1, 55% in T2, 36% in T3 and 27% in T4, and all four treatments differed. T1 and T2 were refilled every 2–4 days, while T4 stayed below 40% most of the period. Some T1 values exceeded 100% AWC due to long irrigation application as the water was not available over certain days.

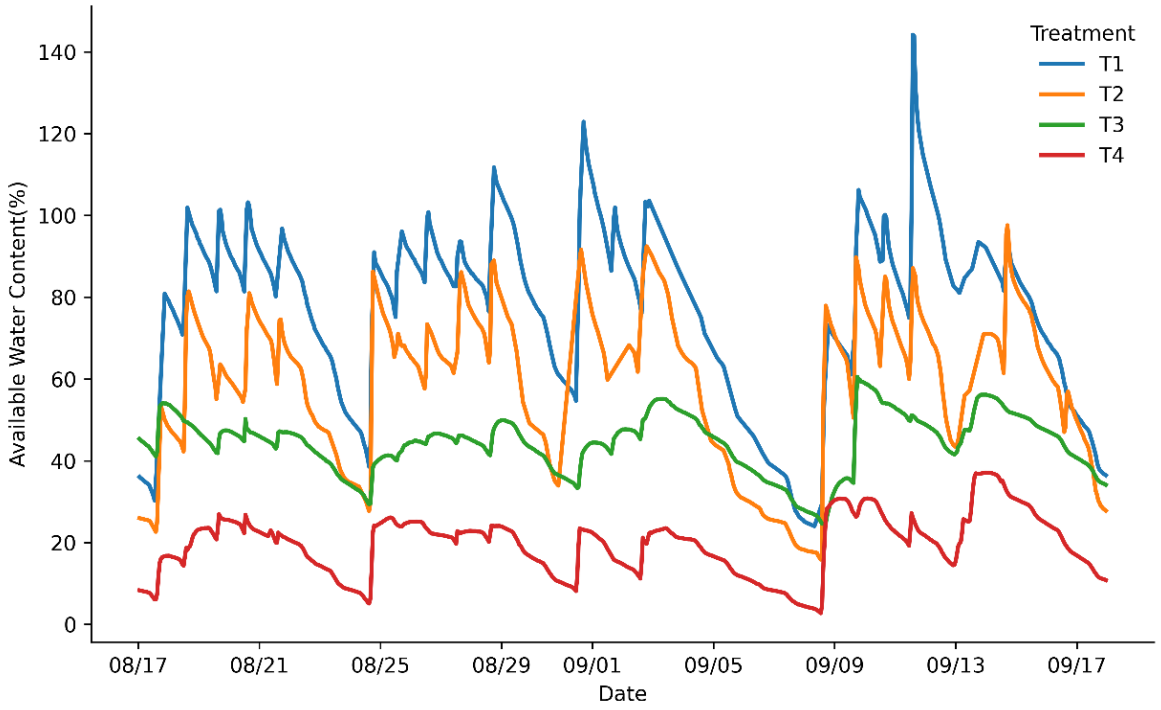


Figure 3. Available water content variation in the root zone (15–50 cm) during the treatment period.

Water applied by the soil water balance algorithm decreased from T1 to T4 (Table 1). These volumes cover only the period from system installation in mid-August to September 17, not the whole season. Before August 17, all EUs received the grower's standard irrigation. The amount of irrigation water applied did not decrease proportionally with the target AWC levels, with T2, T3, and T4 receiving approximately 77%, 44%, and 34% of the water applied to T1, respectively. These deviations can be attributed to differences in irrigation requirements among replicates, primarily driven by spatial variability in soil properties and associated differences in soil water retention and depletion rates, which resulted in varying irrigation frequencies across experimental units.

Table 1. Cumulative water applied by the automated system from installation (August 17) to September 17, 2026, for all the replicates in the respective treatments.

Treatment	AWC target (%)	Water applied (L)
T1	100	18296
T2	75	14122
T3	50	7974
T4	25	6249

Tree water status responded to the treatments about 10 days after they started (from August 27; Figure 4). Contrary to the common expectation that shrinkage increases with stress, MDS was highest in T1 (median ≈330 µm) and lowest in T4 (≈195 µm), and MDS increased with AWC ($r = 0.51$, $R^2 = 0.26$; Figures 5 and 6). Under more severe deficit, depleted water reserves in the trunk can reduce daily shrinkage, and lower daily recovery in T4 indicates incomplete overnight rehydration (Fernández and Cuevas, 2010). To quantify actual tree water stress and validate differences in water stress levels among irrigation treatments, midday stem water potential measurements will be collected during the summer of 2027.

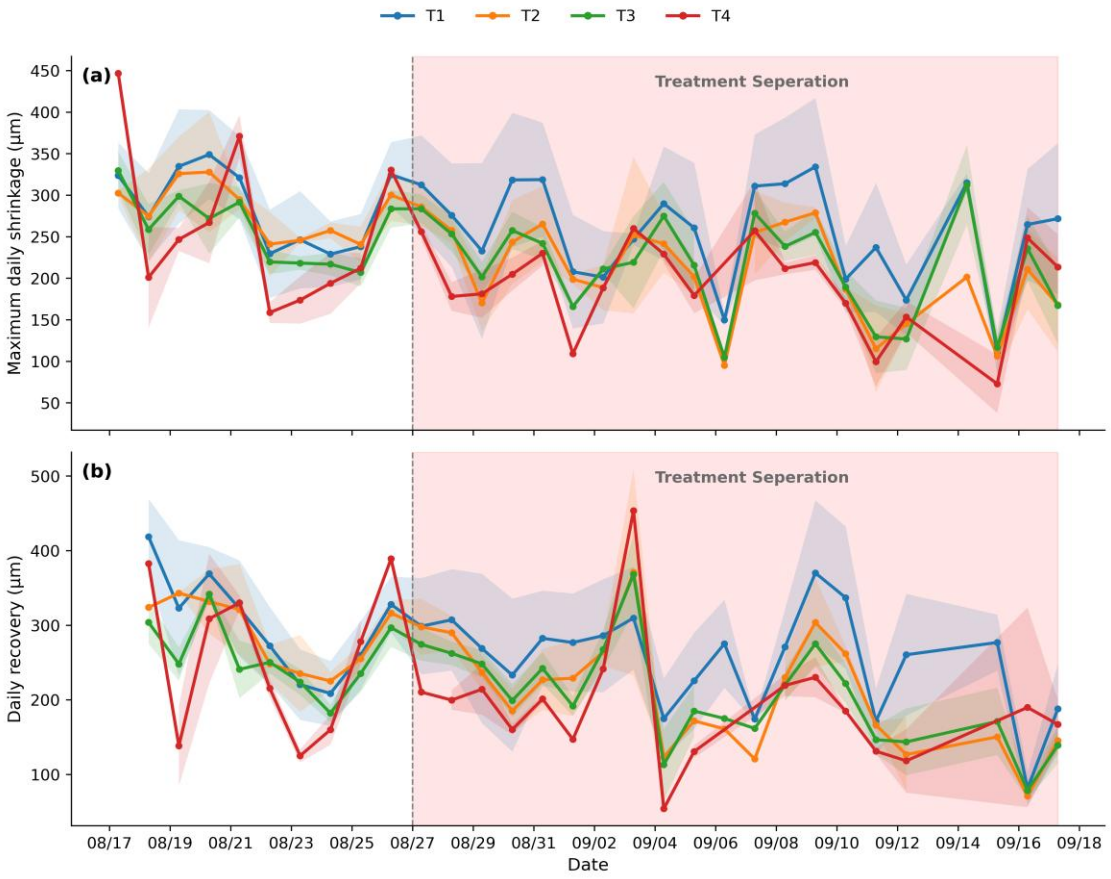


Figure 4. Temporal variation in dendrometer-derived stem diameter metrics under four irrigation treatments (T1–T4): (a) maximum daily shrinkage (MDS) and (b) daily recovery (DR). Shaded area: period of treatment separation.

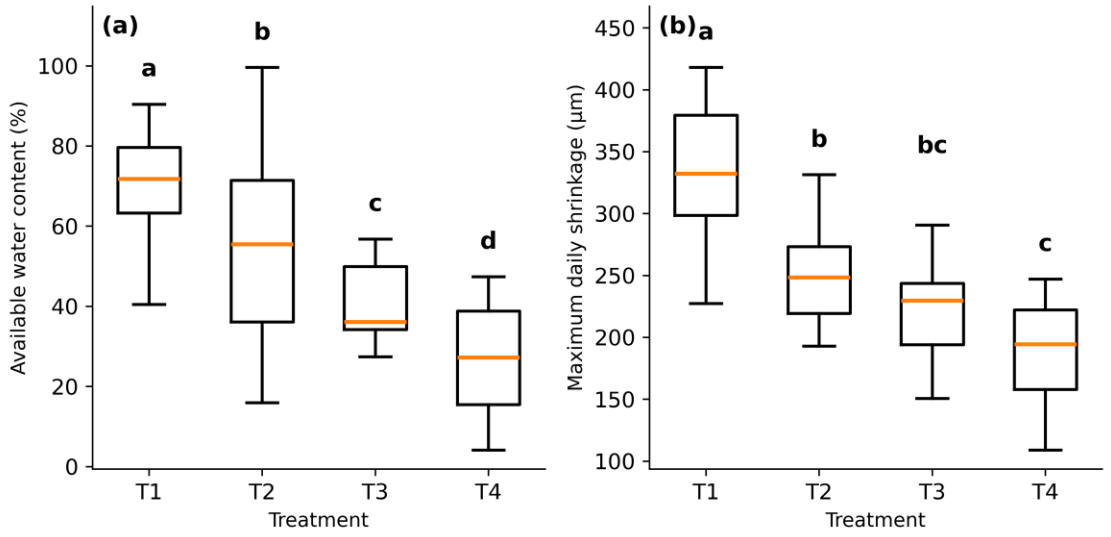


Figure 5. Treatment distributions of (a) available water content (AWC) and (b) maximum daily stem shrinkage (MDS). Boxes with different letters are significantly different (Tukey, $\alpha = 0.05$).

A moderate positive correlation was observed between soil AWC and MDS (r = 0.51, R^2 = 0.26), indicating that soil water availability explained approximately 26% of the observed variability in MDS. Unlike conventional deficit irrigation experiments, initiated under well-watered conditions, the trees in the present study were already experiencing water stress before the initiation of irrigation treatments. This was confirmed with the orchard management. Consequently, the observed trunk shrinkage responses likely reflected differences in recovery from pre-existing water stress and the subsequent levels of water availability (Huguet et al., 1992; Blanco and Kalcsits, 2024). The well-watered treatment (T1) generally exhibited greater MDS, potentially associated with the restoration of water uptake, transpiration, and diurnal trunk contraction following irrigation. In contrast, the severely deficit-irrigated treatment (T4) exhibited smaller MDS, which may be attributed to sustained water limitation, reduced stomatal conductance, and restricted transpiration, thereby limiting further daily trunk contraction. The intermediate treatments (T2 and T3) showed considerable overlap, suggesting varying degrees of physiological recovery and adaptation to water availability. Furthermore, the moderate correlation between AWC and MDS indicates that atmospheric evaporative demand, particularly vapor pressure deficit (VPD), and tree-specific physiological responses also influenced trunk diameter fluctuations. These findings suggest that MDS responses under prolonged water stress may differ from those observed during the initial development of water deficits in previously well-watered trees.

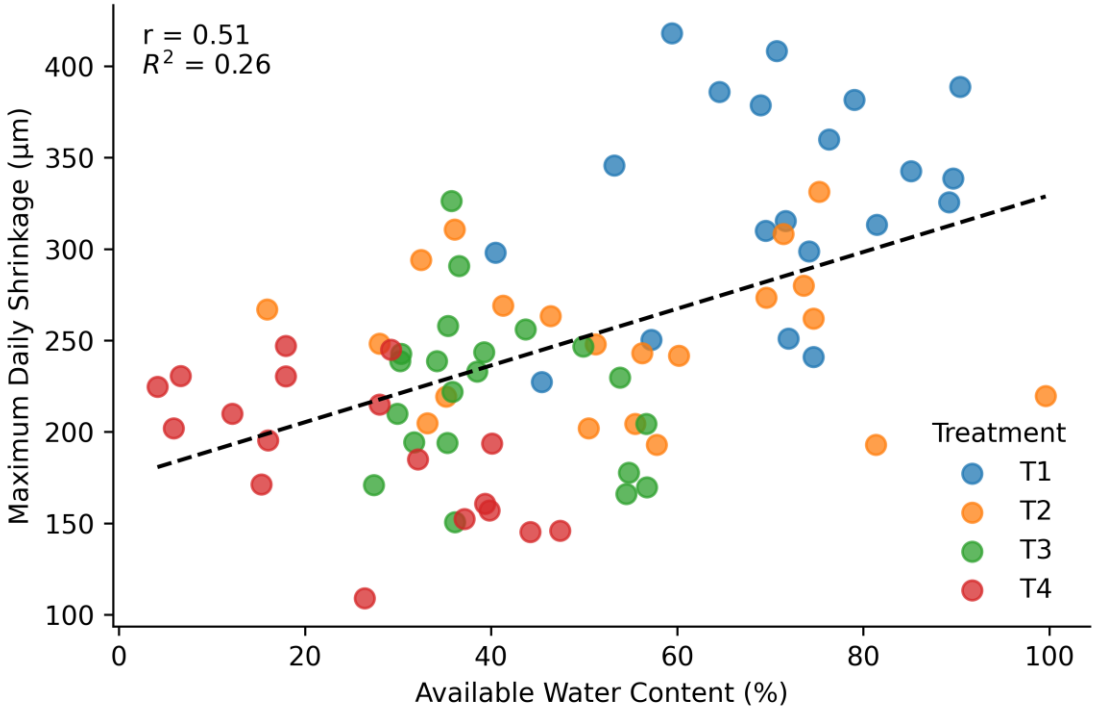


Figure 6. Relationship between available water content (AWC) and maximum daily stem shrinkage (MDS) across four irrigation treatments (T1–T4).

Objective 2. Soil water retention and validation of thresholds

To validate the thresholds, 10 random samples were collected from T1, T2, T3, and T4 for Hyprop water curves. Bulk density averaged 1.39 g cm^{-3} (1.27–1.49) and total porosity 47.5% (44–52%), typical of a silt loam. Water content at field capacity was similar among treatments (17.3–18.4%), so treatment effects are not confounded by soil differences.

The retention curves were steep near field capacity. Water content averaged 33.6% at −6 kPa (pF 1.8), 30% at −10 kPa, 17.2% at −33 kPa and 11.3% at −100 kPa. Most of the water available to the

trees is therefore held at low tension, and small changes in sensor readings near field capacity represent large changes in plant-available water. The 16 in root zone holds about 2.1 in of water between −10 and −33 kPa and 3.0 in between −10 and −100 kPa. PWP representative samples ranged from 2–8% (mean 4.1%) and AWC of 8.5–18% (mean 14.6%). The dry end of the curve, beyond the Hyprop range, is an estimation based on the adjusted curve.

The 2026 algorithm used the maximum and minimum sensor readings as limits, not the tension. In 2027, sensor readings will be converted to matric potential with each plot's retention curve, and targets will be checked and in kPa.

Objective 3.

Fruit weight, red color coverage, and soluble solids did not differ among irrigation treatments at the first harvest pass (Table 2). Mean fruit weight ranged from 130 g (T4) to 155 g (T2), red color from 17% to 19%, and soluble solids from 15.8 to 16.5 °Brix.

Table 2. Fruit quality of Honeycrisp apples at the first harvest pass under four irrigation treatments, Mattawa, WA, 2026. Means ± standard error (n = 4). Means with the same letter within a column are not different (Tukey, α = 0.05).

Treatment	AWC target (%)	Fruit weight (g)	Red color coverage (%)	Soluble solids (°Brix)
T1	100	136.4 ± 8.9 a	17.2 ± 1.4 a	16.5 ± 0.4 a
T2	75	155.2 ± 10.5 a	19.0 ± 1.3 a	15.8 ± 0.2 a
T3	50	138.2 ± 9.7 a	18.5 ± 2.0 a	16.1 ± 0.3 a
T4	25	129.7 ± 1.2 a	17.8 ± 0.4 a	16.3 ± 0.1 a

Treatments lasted about one month at the end of the season, and fruit was sampled at the first pass (≈10% of the crop). The lack of differences shows that no large effects occurred in this short period. Fruit in the adjacent block (171 g) were larger than in all treatments, including T1. According to the grower is due to a change in irrigation and overhead cooling strategy (from sprinklers to drip, and overhead R5 to foggers), leading to excessive stress in the treated area. Our monitoring system prior to treatment deployment confirmed very dry conditions and plant stress. Thus, these results should be interpreted with caution.

Objective 4

Project results and the automated irrigation system will be presented at the IRRIGATION TECHNOLOGY WEBINAR on November 4, 2026.

New No-Cost Extension Request

The project team requests a second no-cost extension through the 2027 growing season to complete one full season of RDI treatments, with plant and fruit quality measurements, using the automated irrigation system now fully operational under the AWN Smart Farms platform.

Implementation was delayed mainly by changes in project personnel and contracting. Contracting complications first prevented timely procurement and installation of the trial, and the contract with Phytech failed. For the 2026 NCE, responsibilities were reassigned and technologies changed: Dr. Lav Khot and Dr. Srikanth Gorthi joined the team to lead automation, sensing and data integration, building on the Smart Orchard and AWN Smart Farms platforms. In spring 2026, valves and the new sensing and control hardware were repaired and installed, but the soil moisture probes were on back order. By the time they were installed and tested in mid-June 2026, we learned additional changes were needed in the main pump system. Thus, full operational treatments would start on August 17, with a week used to validation, ground truth and logic model set up, providing about three weeks of treatment deployment before harvest. The 2026 season established and tested the system but did not allow a full-season evaluation of fruit quality.

The project now has a fully operational hardware, well-replicated experiment: four treatments in four randomized blocks (16 EUs) in a commercial Honeycrisp orchard. This experiment complements the Smart Orchard project with replicated, randomized design needed to quantify RDI effects. A second NCE builds on the investment already made by WTFRC and the team, allowing treatments to start after fruit set, as originally intended, and continue through harvest. The collaborating grower supports the extension of this project.

This request aligns with WTFRC's 2027 priorities on irrigation management, sensing and automation, and orchard water-use efficiency. No additional funds are requested.

Updated timeline

Table 4. Timeline of 2027 activities.

Activity	Jan–Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Refine AWC limits (Hyprop, 2026 sensor record)	X							
System recommissioning: valves, sensors, gateway, flow check		X						
RDI treatments (fruit set to harvest)				X	X	X	X	
Tree water status: dendrometers, AWC, stem water potential				X	X	X	X	
Fruit growth and color progression				X	X	X	X	
Harvest (all passes): yield, fruit count, quality							X	
Storage evaluation and disorders							X	X
Water use and benefit-cost analysis								X
Extension: field day, newsletter, webinar						X		X
Final report								X

Activities for 2027

1. **Prepare the system (Jan–May).** Replace failed sensors, check valve and line flow in each EU, confirm water-use measurement and ensure RDI plots are isolated from the grower's irrigation (Co-PI Khot, Gorthi).
2. **Refine thresholds.** Use Hyprop curves and the 2026 sensor record to set field capacity and wilting point for each EU, keeping the four AWC targets (PI Sallato, Khot, Gorthi).
3. **Standardize crop load.** Record fruit set and adjust crop load to a uniform level across EUs after June drop (PI Sallato).

4. **Impose RDI from fruit set to harvest.** Start after final thinning (about early June) and maintain through harvest with daily automated scheduling (Co-PI Khot and Gorthi).
5. **Monitor tree water status.** Continuous soil data, and midday stem water potential every two weeks and during heat events (PIs Sallato and Kalcsits).
6. **Evaluate yield and fruit quality.** Yield, fruit number and size distribution at each harvest pass; color, firmness, soluble solids, starch and sunburn at harvest; bitter pit, soft scald, soggy breakdown and other disorders after storage (Co-PI Kalcsits).
7. **Water productivity and benefit-cost.** Yield per unit of water applied, and cost of the sensing and automation suite versus water savings, yield and packout (PI Bierer and Sallato).
8. **Extension.** Field day at the site, *Fruit Matters* article and a webinar or grower presentation (all PIs).

Deliverables for 2027

- One full season of replicated data (4 treatments × 4 blocks) on soil water, tree water status, yield and fruit quality under RDI.
- A validated soil moisture–based RDI algorithm for Honeycrisp, with recommended AWC thresholds and timing.
- Fruit quality at harvest and after storage, including disorders, by treatment.
- Water applied and water productivity by treatment, and a benefit-cost estimate of the automated system.
- Extension: one field day, one *Fruit Matters* article and one webinar or grower presentation.
- Final report to WTFRC and a draft peer-reviewed manuscript.

Literature Review

Behboudian, M.H., and T.M. Mills. 1997. Deficit irrigation in deciduous orchards. Horticultural Reviews 21:105–131.

Fernández, J.E., and M.V. Cuevas. 2010. Irrigation scheduling from stem diameter variations: A review. Agricultural and Forest Meteorology 150:135–151.

Gorthi, S., Khot, L. R., Kiraga, S., Schrader, M. J., Keller, M., & Peters, R. T. (2026). LoRaWAN-based scalable wireless sensing networks for precision and automated tree fruit crop production management. [Submission ID: COMPAG-D-26-02121]. Computers and Electronics in Agriculture.

Naor, A., and S. Cohen. 2003. Sensitivity and variability of maximum trunk shrinkage, midday stem water potential, and transpiration rate in response to withholding irrigation from field-grown apple trees. HortScience 38:547–551.

Huguet, J.-G., Li, S. H., Lorendeau, J.-Y., & Pelloux, G. (1992). Specific micromorphometric reactions of fruit trees to water stress and irrigation scheduling automation. Journal of Horticultural Science, 67(5), 631–640. https://doi.org/10.1080/00221589.1992.11516293

Blanco, V., & Kalcsits, L. (2024). Relating microtensiometer-based trunk water potential with sap flow, canopy temperature, and trunk and fruit diameter variations for irrigated 'Honeycrisp' apple. Frontiers in Plant Science, 15, 1393028. https://doi.org/10.3389/fpls.2024.1393028

Proposal Title: Smart Apple Orchard: Technology Testbed and Demonstration Site
Report Type: Continuing Project Report

Primary PI: **Lav Khot**
Organization: Washington State University
Telephone: 509-786-9302
Email: lav.khot@wsu.edu
Address: 24106 N Bunn Rd.,
City/State/Zip: Prosser, WA 99350

Co-PI 2: Bernardita Sallato
Organization: Washington State University
Telephone: 509-789-9205
Email: b.sallato@wsu.edu
Address: 24106 N Bunn Rd.,
City/State/Zip: Prosser, WA 99350

CO-PI 3: Steve Mantle
Organization: Innov8Ag
Telephone: 509-795-1395
Email: steve@innovate.ag
Address:
City/State/Zip: Walla Walla, WA 99362

Co-PI 4: R. Troy Peters
Organization: Washington State University
Telephone: 509-786-9247
Email: troy_peters@wsu.edu
Address: 24106 N Bunn Rd.,
City/State/Zip: Prosser, WA 99350

Co-PI 5: Anantharaman Kalyanaraman
Organization: Washington State University
Telephone: 509-335-6760
Email: ananth@wsu.edu
Address: School of Electrical Engineering and Computer Science
City/State/Zip: Pullman, WA 99163

Cooperators: G***rower***: Sean Sahli (Columbia Farm Services, Mattawa, WA), Keith Veselka (NWFM, LLC, Zillah, WA); ***Private Industry:*** *See image below (in objective 1)*; *WSU*: G.-A. Hoheisel, Rui Liu.

Postdoc/Graduate students/Research Associates: Dr. Srikanth Gorthi, Dr. Dattatray Bhalekar, Juan Carlos Munguia Delacruz; Prassana Medarametla; Horacio Contreras, Members of Khot Precision Ag Lab and Sallato Lab

Project Duration: 3-Year
Total Project Request for Year 1 Funding: $75,901
Total Project Request for Year 2 Funding: $77,281
Total Project Request for Year 3 Funding: $77,206

Other related/associated funding sources: AI Institute for Transforming Workforce and Decision Support (Awarded)
Funding Duration: 2021 - 2025
Amount: $20 M
Agency Name: USDA NIFA
Notes: External funding for smart orchard project sustainability. In 2024 & 2025, the commercial Smart Apple Orchard testbed will be supported in parts by WSU AgAID Institute (PIs: Kalyanaraman, Khot, Sallato, Peters, Mantle). The support comes as 'WSU Smart Farm Engineer' helping team with initial installation and monitoring of the established sensing network, in collaboration with the grower cooperator and help our team to jointly organize field days, and outreach events and content creation on technology know-how. In 2024-2025, will identify key USDA NIFA and NSF grant programs and submit large project proposals on the themes of "Farms-of-the-Future", "Cybersecure Farms", etc. to have long-term funds to sustain the on-going efforts.

Budget 1
Primary PI: Lav Khot (PIs sub-awards have been done internally at WSU)
Organization Name: Washington State University
Contract Administrator: Hollie Tuttle
Contract administrator email address: mailto:Prosser.grants@wsu.edu **hollie.tuttle@wsu.edu; prosser.grants@wsu.edu**

Category/Object	Year 1	Year 2	Year 3
Salaries and Wages - 00 & 01	31,249	31,992	32,765
Purchased Services - 02	-	-	-
Goods/Services - 03	25,040	25,040	22,540
Travel - 04	9,696	9,696	5,993
Equipment - 06	-	-	-
Benefits - 07	7,088	7,725	7,967
Tuition (QTR) - 07QT	2,828	2,828	2,941
Scholarships and Fellowships - 08	-	-	-
Award Restrictions - 14	-	-	-
Total Direct Costs	75,901	77,281	72,206
F&A - 13	-	-	-
Total Costs	75,901	77,281	72,206

Footnotes: Year 3. Salaries ($18,979) with benefits ($2,469) are requested for part of spring & summer support of a PhD level graduate student to continue maintaining LoRAWAN at the testbed. Additional salaries ($13,786) with benefits ($4,743) are requested for a classified staff and summer intern to collect ground truth data throughout the season. Supplies of $22,540 include upkeep of LoRAWAN hardware nodes, with Gateway, soil moisture and flow sensors, stem-water quantification sensors, all-in-one weather station, and AWS Cloud storage costs. PI Mantle's services through Innov8Ag are estimated to be at $5,000. Travel costs include Khot, and Sallato team member travel from WSU IAREC to Mattawa/Zillah site ($0.70/mile).

Objectives.

1. Establish Smart Apple Orchard: Technology Testbed and Demonstration Sites in a commercial setting.
2. Integrate and evaluate technologies for WTFRC technology roadmap identified priority use cases including crop load mapping/management, irrigation heat stress management, and crop protection, nutrients, and weed management.
3. Conduct outreach and extension education through field days, workshops, know-how videos, fact sheets, etc.

Progress Update Year 1-3 & plan for NCE in Year 4

- *Testbeds.* Two operational Smart Apple Orchard testbeds; *Testbed 1*: Mattawa, WA (2024, 2025, 2026 season, management changed to Columbia Farm Services in 2025; Cultivar: Cosmic Crisp®); *Testbed 2*: Moxee, WA (added in 2026 season; managed by NWFM LLC; Cultivar: Organic Honeycrisp).
- *Use cases*. Heat stress automation efforts continued at Mattawa, WA Testbed, whereas Crop load monitoring and management, Irrigation Automation technology evaluation moved to Testbed 2 (Moxee, WA).
- *Partnerships and scaling up with extramural funding*. About 24 private industry partners have deployed and /or demonstrated their technology at these testbeds and the WSU team continues validation efforts. In 2026, members expanded scope to research alternate weed management (Liu, Sallato, Whiting, Khot, WSDA SCGB, $250K, 2026-2029) and have new testbed Smart Cherry Orchard (Whiting, Khot, Sallato, WSDA-SCGB, $211K). Team continued to seek extramural funding (e.g., $2M OREI proposal, not funded, three USDA NIFA SCRIs [~$4M] submitted).
- *Field day and FIRA USA 2026*. The 2026 Smart Orchard Field Day was held October 22 at Gilbert Orchards in Yakima, Washington, as the closing event of a three-day AgTech program aligned with FIRA USA 2026. It was fully funded by more than $8,000 in private sponsorships and drew over 250 national and international attendees. Groups rotated through three tracks (crop load and nutrient management, irrigation and heat stress, and robotics and autonomy) featuring roughly 24 research and industry demonstrations, followed by a sponsored social hour at Gilbert Cellars. At FIRA USA 2026, the team also had a Smart Orchard presence in the WSU Pavilion and organized three panels: “Smart Farms in America: University and Industry Prospective,” “Smart Irrigation: Rethinking Water Management with AgTech & Automation,” and “Transforming Crop Load Management.”
- *Outreach and dissemination*. The 2026 highlight was a WSU Smart Orchard exhibit in the “Our Food, Our Farms, Our Washington” pavilion at the Washington State Fair, which drew about 90,000 visitors over 20 days. The team continued updating the web portal with results from prior years and published articles in Fruit Matters. Testbed results were also shared at national forums (WSTFA 2025 Annual Meeting and Hort Show; USDA NIFA multistate meetings S1069 and W4009) and international forums (e.g., Virtual Orchard Meetup, IHC2026-Japan).
- *Heat Stress and Irrigation Automation*: We continued evaluating automated heat stress mitigation scenarios at Testbed 1 (Mattawa, WA). Like prior years, sensor guided heat stress mitigation used 65.2% less water without affecting fruit quality. Irrigation automation was moved to Moxee, WA site and was not successful due to limitations of the irrigation infrastructure.
- *Crop Load Monitoring and Management*: At Testbed 2 (Moxee, WA), ground (Vivid Machines) and aerial (Tyton Aviation with Outfield technologies, and Precision Agri Tech.) imaging-based mapping technology providers collected data in Year 3. Each technology provider mapped the orchard block for estimating various crop parameters, including apple blossom count, fruit size, and fruit count and WSU team validated the findings. Vivid Machines and Precision Agri Tech mapping results are in this report. Outfield Technology data was used to create variable rate prescription maps (blossom thinning, nutrient) and then use Red-Ant retrofit to realize panel-to-panel actuation. Collaborating PIs Sallato, Mantle and Hoheisel are leading these efforts, and detailed results can be found in those reports.

Methods and Results Summary (Year 3)

Objective 1. Establish the WSU Smart Apple Orchard: Technology Testbed and Demonstration Sites 1 and 2.

Testbed 1. The "WSU Smart Apple Orchard: Technology Testbed and Demonstration Site 1" was established at Mattawa, WA in 2024 (46.712803, -119.852839). This is a 'WA 38' orchard on M9 Nic29 and inter-plantings of Bud 9 rootstock, managed by Columbia Farm Services. The block is trained as tall spindle, at 12 ft by 3 ft spacing and by 1.5 ft spacing. The first commercial harvest was in 2024 season. The block is irrigated via drip, sprinklers and has an overhead fognet (fogging + netting) installed for heat stress mitigation.

Testbed 2. The "WSU Smart Apple Orchard: Technology Testbed and Demonstration Site 2" was established at Zillah, WA (46°25'18.5", -120°12'12.0") in 2025. The block was planted in 2021 with G41 rootstock over 8.89 acres and is managed by grower cooperator (NWFM LLC). The plants are trained as tall spindle at 10 ft by 4 ft spacing. The block is irrigated via drip, sprinklers and has an overhead fognet (fogging + netting) installed for heat stress mitigation. Due to management change, this testbed was moved to Moxee, WA in 2026. This is an organic Honeycrisp (on M106 rootstock) trained as tall spindle (10 x 4 ft spacing), established in 2011 by Moxee Valley Orchard LLC. The block is irrigated using under tree sprinklers and doesn't use overhead cooling from heat stress management.



WSU Smart Apple Orchard

Cooperators:

NWFM COLUMBIA FARM SERVICES

Partners

Objective 2.

Irrigation and Heat Stress Automation. Our team continues to evaluate soil-plant-atmosphere continuum sensing, climatic modeling driven decision support, and automated irrigation control for irrigation and heat stress management. As illustrated in Figure 1 and detailed at https://smartorchard.wsu.edu/automated-irrigation-and-heat-stress-automation/, we have demonstrated three scenarios that have been successfully deployed at the Testbed 1. Over the two years (2024-2025), ground-truthing has shown that sensor-guided automation saves 20.8% to 52.4% water for automated irrigation management use case without affecting fruit quality. Similarly, water savings were between 46.4% and 50.7% for temperature threshold driven evaporative cooling for heat stress management use cases. In year 3, heat stress management continued at Mattawa, WA site, and automated irrigation use cases were attempted at Moxee, WA site. Due to limitations with established irrigation system, without Variable Frequency Drive

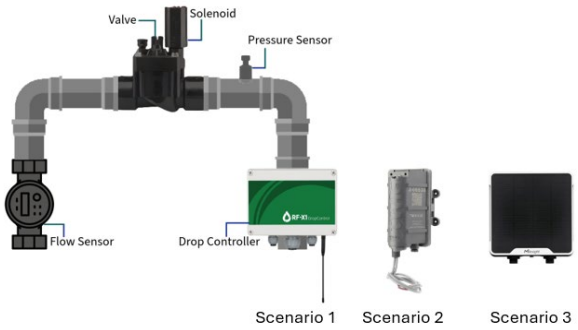


Figure 1. Smart apple orchard testbed scenarios for precision and automated irrigation and heat stress management.

(VFD), this turn-out to be unsuccessful implementation. The manual, the irrigator followed climate model guided irrigation schedule.

At the Mattawa, WA field site, automated heat stress management continued during the 2026 growing season using real-time fruit surface temperature (FST)-data feed. FST was monitored using thermistors (ST-200, Apogee Instruments, Inc.) inserted into west-facing, sun-exposed fruits approximately 2 m above ground level. Water consumption was monitored using inline flow meters (SW3L, Dragino Co., Ltd.) installed in the cooling lines. The automated cooling system operated from June through September 2026. The same solenoid valve controller was also used to manage under-tree irrigation through grower-defined schedules, with the water supply switched between overhead cooling and under-tree irrigation lines. Under-tree irrigation was scheduled after 7:00 PM, ensuring no overlap with daytime cooling operations, as confirmed by flow-meter observations.

Ground-truthing: In all blocks, WSU Precision Ag group has installed water flow meters (SW-3L, Dragino Inc.) to monitor and quantify water used for heat stress mitigation. This block also has micro-tensiometer probes (MT FloraPulse, Davis) inserted into the trunks for real-time plant water status monitoring along with soil moisture probes (TEROS 12, Meter Group Inc.) at 8 and 24 in. for soil moisture tracking. An all-in-one weather station (ATMOS 41, Meter Group Inc.) has been deployed inside and outside the orchard to quantify the orchard effects on weather variables. For evapotranspiration (ET) estimation and its comparison with weather data derived estimates, an eddy covariance based actual ET sensor (LI-710, LI-COR Environmental) has been deployed at 2-m (6 ft) above the canopy at Moxee, WA testbed. All the data gets collected through LoRaWAN (Long range wide area network) based wireless sensing network (WSN) developed by our team. In addition, Sallato lab has been doing ground truthing of canopy water stress, nutrient status, fruit size, and quality.

Results: During the monitoring period, automated cooling was active on 44 days, compared with 53 days under grower-managed (continue fogging throughout the day) cooling. The estimated operating duration was 109 and 309 hours for the automated and grower-managed blocks, respectively. Seasonal cooling water application was estimated at 8.54 and 24.54 inches for the respective treatments, representing a 65.2% reduction in under automated management. Such differences in water savings compared with previous years (46-51%) may be attributed to changes in cooling management strategies and operating schedules. In terms of fruit quality, it was evaluated across four locations. Two sites (Sites 1 and 2) received FST-driven automated cooling, while two sites (Sites 3 and 8) were managed using conventional grower-controlled cooling schedules, i.e., continuous fogging throughout the day. Five replicates were collected from each site, resulting in 10 replicates per treatment group. Automated cooling exhibited numerically higher mean fruit weight (267.9 vs. 258.3 g, Table 1), lower cull incidence (3.7% vs. 5.7%), and lower sunburn incidence (0.3% vs. 2.6%) than grower-control cooling. However, none of these differences were statistically significant ($p = 0.4171$, 0.2930, and 0.1434, respectively). Similarly, total harvested fruit weight, fruit count, and green spot incidence did not differ significantly between treatments ($p > 0.05$). These findings suggest that reduced cooling water application under automated management did not result in statistically detectable differences in the evaluated fruit quality attributes across the study sites. Note that irrigation was not an evaluated factor and was assumed random or grower management scenario.

Table 1. Comparison of fruit yield and quality characteristics between automated and grower-control cooling treatments during the 2026 growing season.

Parameter	Automation	Grower control
Total fruit weight (lbs)	59.90 ± 18.78[a]	49.28 ± 14.93[a]
Total fruit (no.)	102.6 ± 35.4[a]	86.8 ± 26.9[a]
Estimated fruit weight (g)	267.9 ± 26.2[a]	258.3 ± 25.3[a]
Green spot (%)	5.7 ± 9.2[a]	5.0 ± 6.3[a]

Culls (%)	3.7 ± 3.2[a]	5.7 ± 5.1[a]
Sunburn (%)	0.3 ± 0.6[a]	2.6 ± 4.7[a]

Objective 2. Provide a testbed for evaluation and validation of mapping technology.
Crop Load Mapping Technologies. Details of crop parameters mapping technologies explored at smart orchard testbed over the years are at https://smartorchard.wsu.edu/precision-crop-monitoring-techniques-at-wsu-smart-apple-orchard-testbed/ and shown in figure 2.



Figure 2. Crop monitoring technologies validated at the smart orchard testbed over the years.

In 2026, only four of those partners (Vivid, Tyton/Outfield, Precision Agri Tech, Aerobotics) tested their technologies at the testbed, and their technology details are as below.

The Vivid XV3 Vision System (Vivid Machines Inc., Canada) comprises a multispectral sensor capturing multiple bands in visible and near-infrared (VISNIR) spectral range, a GPS receiver, and an integrated proprietary data processing algorithm. This ground-based imagery system can be universally mounted on any farm vehicle with 2.2-4.5 m/s travel speed. The vision system can scan up to 20,000 trees/hour, processing and providing real-time insights. The system generates a variability map of estimated crop parameters at a tree-level resolution. The variability maps, data, and scanning reports can be accessed remotely using a smartphone or tablet installed with the Vivid Control app and cloud-based dashboards.

The Tyton Aviation (Tyton Aviation Pvt Co., United States) and Outfield Technologies (Outfield Technologies Ltd., England) collaboration uses an unmanned aerial vehicle (Mavic 3 Enterprise Multispectral, DJI Technologies) equipped with an integrated, gimbaled RGB (CMOS Hasselblad 20MP, DJI Technologies; resolution: 5280×3956 pixels) and multispectral (bands: Green, Red, Red-Edge, and Near-Infrared) sensors. During the flight campaigns at the smart orchard, the UAV was flown at an altitude of 7.6 m AGL and 5 m/s forward speed with 45° sensor orientation, providing a complete side-view of the tree from trunk to top. These flight parameters allow users to collect aerial imagery data at 16.2 ha/h which is post-processed using proprietary machine vision and deep learning algorithms to create variability maps. Outfield Technologies processes the acquired raw data using proprietary computer vision algorithms to create an orchard-specific variability map. The algorithm can detect fruits even in fields with overhead netting. For most applications, this technique generates maps of average estimated crop parameters,

displayed in a 5×5 m grid, based on sampling 60% of the trees. However, this technique can also generate tree-level data with 100% tree coverage for tree-level blossom or fruit-thinning applications.

Precision Agri Tech (Precision Agri Tech LLC, United States) is a Washington-based ag-technology company delivering drone-enabled, per-tree orchard intelligence for fruit growers. Using FAA-certified UAV flights, the company captures high-resolution RGB and infrared imagery, georeferenced with RTK GNSS for inch-level accuracy. Advanced computer vision and AI models process imagery to generate tree-level metrics, including fruit count, size, color, and spatial inventory. These outputs are delivered through Treelytics, a patent-pending in-field mobile app that enables tree-specific inspection, temporal trend analysis from repeat scans, and data-driven decisions for crop load management, yield forecasting, and harvest labor planning.

Aerobotics is a smartphone-based platform designed to support fruit yield estimation and crop monitoring through digital fruit counts and image-based fruit sizing. The platform uses artificial intelligence (AI) and computer vision algorithms to estimate fruit size from captured imagery. Its TrueFruit™ Size tool generates block-level reports at the time of data collection and provides forecasts of expected fruit size at harvest. The TrueFruit™ Bin feature estimates fruit size distribution at the bin level prior to packing operations, while the recently introduced TrueFruit™ Grade tool evaluates external fruit attributes such as color development and visible blemishes.

Ground-truthing: Like 2025, crop-load mapping campaigns were conducted at key growth stages throughout the season. Eight ground truth locations with five trees per location were selected. These locations were geotagged using a precise RTK device; however, these details were not shared with partners to perform blind ground truthing. Blossom count, fruit count, and fruit size per tree parameters were measured manually on these locations. Mapping campaigns and data collection was conducted on April 9, May 26, July 1, and September 9 in season 2026. This data was compared with estimates from mapping solutions.

Key outcomes. The data is being curated and analyzed through NCE, and results will be reported next year. As example, Vivid Machines generated fruit county variability data is shown in Figure 3. The Vivid Machines estimated an average of 112.3 blossom clusters/tree compared with 123.7 blossom clusters/tree from hand counts, indicating overall 9.2% absolute percentage error between two means. Other crop stage mapping data for Vivid and other partners is being analyzed and reported in 2027.

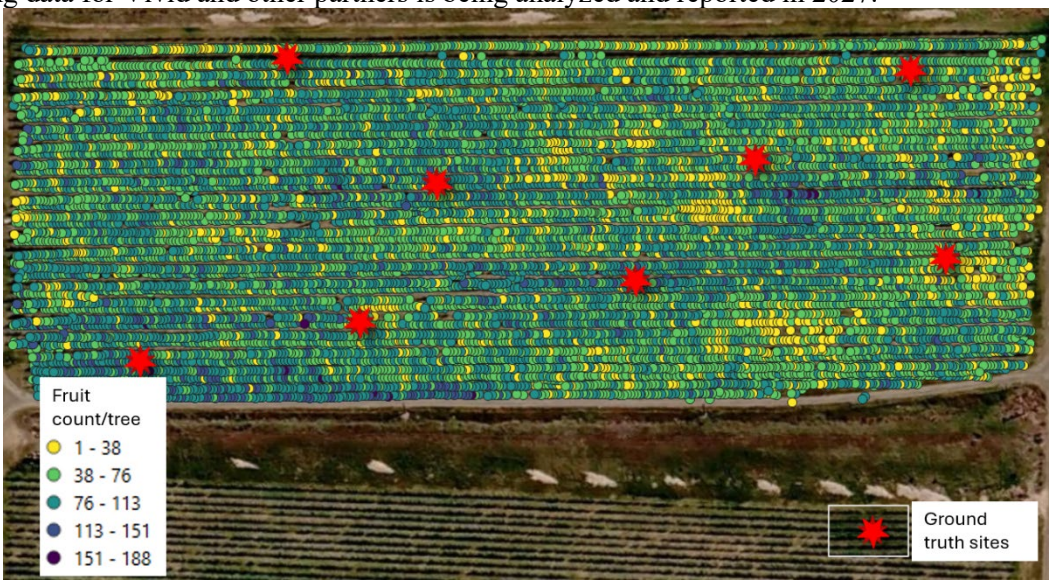


Figure 3. Tree level fruit count variability map generated by Vivid Machines and WSU ground truth sites within the testbed block, Moxee, WA during season 2026.

Objective 3. Outreach and extension education. In 2024, WSU Smart Apple Orchard Field Day was organized on August 2, 2024, with over 200 participants, highlighted in Good Fruit Growers and PNW Ag Network (https://pnwag.net/smart-orchard-nwfm-interview). We also have created a technology know-how video (https://youtu.be/KMmTDGGYu3U) on irrigation and heat stress automation. We created a website https://smartorchard.wsu.edu/, that is being kept up to date. We also have hosted several visits at the Mattawa smart orchard, including California Research Board (Sebastian Saa) and a technology transfer group from Chile.

In 2025, we conducted two Field days: Precision and Automated Irrigation Systems [July 25] and Precision Crop Load Management & Automation Technologies [Aug 1]) and observed over 200 in attendance. We have also created a technology know-how video (https://youtu.be/KMmTDGGYu3U) on irrigation and heat stress automation. The field days and related technologies were highlighted in media reports Report 1 and Report 2. We also continue to maintain the WSU smart orchard website, updating current information on evaluated technologies and results. We also have hosted several visits at the Mattawa smart orchard from Polish fruit industry, South Africa, Chile, and Dutch groups.



In 2026, Smart Orchard Field Day was held October 22, 2026, at Gilbert Orchards in Yakima, Washington, closing a three-day AgTech program aligned with FIRA USA 2026 (>2500 participants from 20 countries). Fully funded by $8,000+ in private sponsorships, it drew more than 250 national and international attendees. Groups rotated through three tracks (crop load and nutrient management, irrigation and heat stress, and robotics and autonomy), which together featured roughly 24 research and industry demonstrations. The day ended with a sponsored social hour at Gilbert Cellars. The web portal has also been continually updated with results from prior years.



Besides field days, team had heavy involvement in FIRA USA 2026 with a Smart Orchard footprint in WSU Pavilion, and in organization and coordination of three key panels, 1) Smart Farms in America: University and Industry Prospective, 2) Smart Irrigation: Rethinking Water Management with AgTech & Automation, and 3) Transforming crop load management using AgTech. The team also shared the research outcomes from the testbed at Lightning Talks and Poster sessions at FIRA. Throughout the year, team members have also pushed articles in Fruit Matters as well shared results from testbed at national (WSTFA 2025 Annual Meeting and Hort Show, USDA NIFA Multi-state meetings- S1069, W4009) and international forums (e.g. Virtual Orchard Meetup, IHC2026). Key highlight of 2026 was a WSU Smart Orchard exhibit at WA State Fair 2026's "Our Food, Our Farms, Our Washington" pavilion. Approximately, this event drew over 85,000 visitors over 20 days.

Project Title: New Strategies for Precision Plant Nutrient Application

Report Type: Continuing report Year 2

PI: Bernardita Sallato C.
Organization: Washington State University
Telephone: (509) 786-9205
Email: b.sallato@wsu.edu
Address: 24106 North Bunn Road
City/State/Zip: Prosser, WA 99350

Co-PI (2): Lav R. Khot
Organization: Washington State University
Telephone: (509) 786-9302
Email: lav.khot@wsu.edu
Address: 24106 North Bunn Road
City/State/Zip: Prosser, WA 99350

Co-PI (3): Dattatray Bhalekar
Organization: Washington State University
Telephone: (509) 778-8646
Email: dattatray.bhalekar@wsu.edu
Address: 24106 North Bunn Road
City/State/Zip: Prosser, WA 99350

Co-PI (4): Jim McDougall
Organization: Outfield Technologies
Telephone: +44 7763 058842
Email: jim@outfieldtechnologies.com
Address:
City/State/Zip:

Cooperators: Steve Mantle (Innov8Ag), Agrocares, Croptix, North West Farm Management, Columbia Farm Services, Wilbur Ellis, Red Ant

Total Project Request Year 1: $34744
Total Project Request Year 2: $14990
Total Project Request Year 3: $15245

Organization Name: Washington State University
Telephone: (509) 335-2885
Station Manager: Naidu Rayapati

Contract Administrator:
Email address: arcgrants@wsu.edu
Email address: naidu@wsu.edu

Item	2025	2026	2027
Salaries			
Benefits			
Wages[1]	5000	5000	5000
Benefits	500	500	500
Services	6144	6390	6645
Supplies[2]	2500	2500	2500

Travel	600	600	600
Miscellaneous			
Plot Fees			
Total	**14744**	**14990**	**15245**

Footnotes:

[1] Wages: hourly support for sample collection at $19/hour for 263 hours + 10% benefits

[3] Supplies: laboratory analyses of 64 soils @ $36/sample, 128 tissue, 32 fruitlet and 32 fruit @ $20 / sample.

Organization Name: Jim McDougall **Contract Administrator:**

Telephone: +44 7763 058842 **Email address: jim@outfieldtechnologies.com**

Item	**2025**	**2026**	**2027**
Salaries	20,000		
Benefits			
Wages[1]			
Benefits			
Services			
Supplies[2]			
Travel			
Miscellaneous			
Plot Fees			
Total	**20,000**		

OBJECTIVES

Our specific focus within the 'smart orchard project' is to assess mapping technology for plant stress, soils, vigor and fruit quality, and testing methods for variable nutrient management.

1. **Validate tools to determine precision and variable nutrient demand.**

2. **Integrate layers of information to create prescription mapping for different nutrient requirements**

3. **Evaluate the impact of variable rate nutrient management**

SIGNIFICANT FINDINGS

- Similar to 2025 season, leaf N in July was above the recommended range at all sites (2.40–2.77%) in 2026.
- Variable rate nitrogen (N) application was completed in Mattawa Cosmic Crisp® smart orchard testbed in June 2026, using drone-based N demand prescription map (panels of 30 ft) and RedAnt spreader managed by Wilbur-Ellis.
- The spatial pattern of crop load is stable between seasons: yield at the eight monitoring sites in 2026 was strongly correlated with 2025 yield ($r = 0.84$, $p < 0.01$), which supports using the previous season's crop-load map to set N rates.
- The SoilOptix OM map was verified in spring 2026 with 18 soil samples from three low-OM and three high-OM areas. Laboratory OM was moderately correlated with the mapped OM ($r = 0.56$, $p = 0.02$). SoilOptix overestimated OM by ≈0.3 percentage points (measured 0.2–0.8% vs. mapped 0.57–0.96%), and one high-OM area tested as low as the low-OM areas.
- Mattawa site had very low organic matter (0.2–0.8%) and mineral N (nitrate-N 0.6–1.3 ppm); thus, the soil supply was fixed at ≈3 lbs N/acre (1.4–5.6 lbs N/acre) for the entire block, and integrating the soil OM map was not needed.
- Ground truth during prescriptive spreading confirmed that no-N panels received no urea and that standard and double panels differed as expected relative to each other. Absolute values were not confirmed.
- The variable-rate prescription used ≈12% less urea than a uniform rate based on 2025 maps.
- Estimated N removal in 2026 crop averaged 11.6 g N per tree (≈44 lbs N/acre on average). Variability in N demand within sites (CV 14–32%) was about as large as variability among sites (CV 27%). A per-panel rate would use the same N as a single average rate but redistribute ≈4 lbs N/acre; it saves product (8–34%) only compared with a single rate. A tree-level rate would add ≈4 lbs N/acre of redistribution, similar to a ±10% map error, and is not justified on product savings.
- Leaf and soil samples were collected for validation of Agrocares™ and Croptix™ technologies. No results have been returned yet, and validation is expected to start in 2027.
- Extension: Smart Orchard Field day and evening social was conducted after FIRA USA, October 22nd, with aprox. 300 participants; partners, growers, students, international visitors.

METHODS

1. Validate tools to determine precision and variable nutrient demand

In 2026 the work continued in the Mattawa Cosmic Crisp® orchard testbed (GRCC1; M9-Nic 29 and Bud 9 interplanted, planted 2020; managed by Columbia Farm Services), where the variable-rate (VR) application was implemented. The Zillah Smart Apple Orchard (Envy™) was no longer available and was replaced with a new orchard; Moxee Smart Apple Orchard (Block 11, Honeycrisp, managed by NWFM LLC.).

Mattawa. The same eight monitoring sites selected in 2025 (five trees per site, 40 trees) were followed in 2026 (Figure 1). Sites 4 and 5 are located east of the farm road, in a grower-managed section outside the 19.6-acre VR prescription area.

- **Soil (April 16):** six areas were selected from the SoilOptix OM map (2024 survey; Figure 5): three in the lowest OM classes (blue, 0.57–0.70%) and three in the highest (orange–red, 0.83–0.96%). Three samples per area (18 samples, 0–12 in) were analyzed for pH, organic matter (OM), nitrate-N, ammonium-N, Olsen P, K, Ca, Mg, S, Zn, Fe, Mn, Cu, B and soluble salts following standard procedures for Western soils (Gavlak et al., 2005).
- **SoilOptix validation:** laboratory OM at each sample was compared with the OM class mapped by SoilOptix at the same location (Pearson correlation, n = 18), and the N supplied by OM was estimated from the laboratory OM values.
- **Leaf:** Composite samples from each monitoring site were collected on five dates June 30, July 14, July 28, August 13 and September 3 for total N, P, K, Ca, Mg, S, Zn, Fe, Mn, Cu and B (Soil Test Laboratory, Moses Lake, WA) and for Croptix™ technology (detailed below)
- **Harvest:** all 40 monitored trees were harvested individually. Total fruit weight and fruit number were recorded, mean fruit weight was estimated, and fruit were sorted into clean, green spot (GS), culls and sunburn.

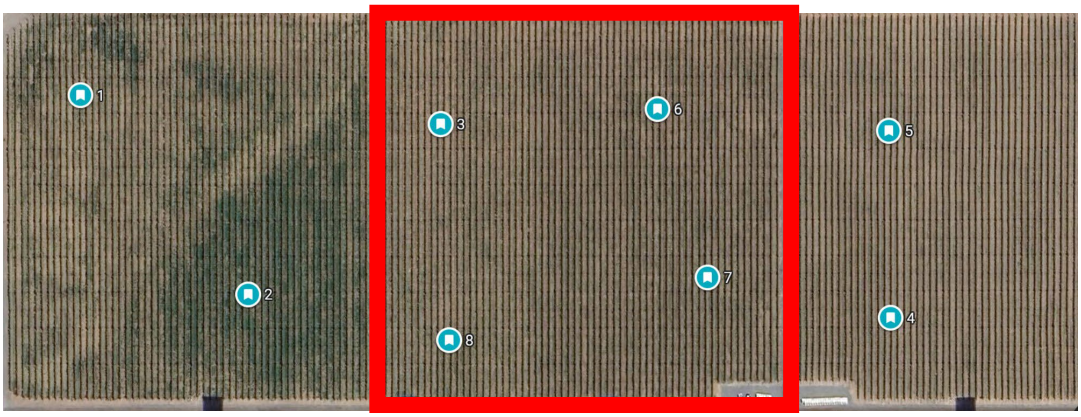


Figure 1. Monitoring sites (1–8) in the Mattawa Cosmic Crisp® orchard, followed in 2025 and 2026.

Moxee. Eight monitoring sites (rows 4, 9, 14, 16, 25, 28, 38 and 40; five trees per site) were established. Bloom clusters were counted on April 9 and fruiting clusters before June drop on May 26 to calibrate drone counts (from Outfield Technologies). Soils were sampled on June 2 (three samples per site, 0–12 in; 24 samples) and leaves on July 15 and September 3.

Sensor tools. At every leaf sampling time, paired samples were collected for standard leaf tissue test; consisting on total mineral content in the leaf blade and petiole, utilizing combustion method for N

and S, and ICP-EOS for all other elements, and for Croptix™. In addition, the same set of samples were scanned with Agrocares™, half of the samples were dried and sent to Canada for internal analysis. In 2026, we included samples from other orchards where WSU monitors nutrients to widen the range of nutrient status (orchards with deficiencies), among them an SCBG-funded trial evaluating soil amendments at replanting. Both companies are using these samples and results from nutrient test to develop and improve their calibration models.

2. Integrate layers of information to create prescription mapping for different nutrient requirements

Nutrient management decisions vary widely among growers. For nitrogen, strategies may include a flat rate adjusted by visual vigor, spring soil tests of available N (NO_3-N and NH_4-N), sap analysis or leaf analysis, among others. In this project, we used the WSU recommended approach (Sallato et al., 2019) for consistency and reliability, in which the N rate is calculated as: N rate = (crop demand − soil supply) / application efficiency, where crop demand is the N removed by the crop and soil supply is the N released from soil organic matter and residual mineral N.

Aerial surveys were conducted by Tyton Aviation and Outfield Technologies. At Mattawa, a hand-launched DJI drone was flown by a Tyton pilot following Outfield's autonomous flight plans. At Moxee, a drone-in-a-box system (DJI Dock 2) installed ≈2 miles from the orchard flew fully autonomous, remotely monitored surveys, with results available ≈4 hours from launch. The number of campaigns and data layers for each site are summarized in Table 1.

Table 1. Drone survey campaigns and data generated at each site (Outfield Technologies).

	Mattawa (GRCC1) 2025 and 2026	**Moxee (Block 11) 2026**
Surveys reported	4	39 (daily blossom surveys Apr 19 – May 3)
Platform	Hand-launched drone (Tyton), Outfield flight plans	DJI Dock 2 drone-in-a-box, fully autonomous
Tree coverage per survey	≥58% (best flight ≈95% of trees in 25 min)	≥89% (NW corner avoided, power lines)
Data layers	Blossom load; calibrated crop load; canopy fill %; Vegitation indices-NDVI, NDWI, SAVI, NDRE, CHI	Blossom emergence and load; crop load from fruitlets; calibrated counts; canopy fill %
Map resolution	30 ft panels (2,601 panels; ≈9 trees/panel)	16 ft grid (4 trees); tree-level (4 ft) demo
Ground truth for calibration	WSU tree counts during the season, fruit count and fruit quality at harvest (8 sites)	WSU tree counts during the season, fruit count and fruit quality at harvest (8 sites)
Use in 2026	VR urea prescription (RedAnt spreader)	VR lime sulfur bloom thinning (RedAnt sprayer retrofit) – *report by Mantle, Hoheisel and Khot*

Layers of information

Demand: crop load was compared between years to choose the approach. Alternate bearing was ruled out for the Mattawa Cosmic Crisp® block; therefore, the N rate was based on the previous season's crop removal (2025). If alternate bearing had been confirmed, the N rate would have been based on the predicted 2026 yield.

Soil supply: estimated from soil samples collected in the low- and high-OM areas mapped by SoilOptix (Figure 5), which were also used to validate the SoilOptix OM map.

Therefore, the final rate was based on crop removal because (1) leaf N was adequate in 2025, so a maintenance rate equal to crop removal is justified (Sallato et al., 2019), (2) N supplied by soil

organic matter was negligible, and (3) crop load was stable: the ranking of sites by yield was consistent between years (r = 0.84 between 2025 and 2026; r = 0.62–0.66 with 2024), and ground-truth assessment confirmed no alternate bearing.

Rate: Calibrated crop load (kg of fruit per 30-ft panel) from the 2025 pre-harvest survey was multiplied by 0.55 g N per kg of fruit to estimate the N removed (reported in 2025). Panel rates were grouped into three rates: 0, 22 and 45 lbs N/acre (Table 2; Figure 2). The grower had applied 30 lbs N/acre in fall 2025, and a high N dose close to harvest was not desired. Therefore, the rate was adjusted to about half the calculated dose and, for an easy conversion, used the N values directly as urea rates: 0, 22 and 45 lbs urea/acre, equal to 0, 10 and 21 lbs N/acre (urea = 46% N). The prescription was exported as a GeoJSON file (GRCC1_VariableRateUrea_V3) and uploaded to the RedAnt Agri web app (SmartNode configuration). Because the spreader drives along one side of each tree row and the controller works in lbs per acre of its treated width, Outfield set the controller to 80 and 160 lbs urea/acre for the standard and double tiers. This value was calculated for the 30-ft panel (≈319 ft² per panel, ≈11-ft rows), considering a ≈28% of the orchard area being covered; i.e., a band of ≈3 ft wide.

Table 2. Variable-rate prescription and urea applied in the 19.6-acre Mattawa Cosmic Crisp® block.

Tier	Panels (n)	Block (%)	Calculated N (lbs N/acre)	Urea applied (lbs/acre)	N applied (lbs N/acre)	Urea used (lbs)[1]
None	596	23	0	0	0	0
Standard	1,730	66	22.3	22.3	10.3	291
Double	275	11	44.6	44.6	20.5	92
Block	**2,601**	**100**	**19.6**	**19.6**	**9.0**	**383**
Flat rate equiv	2,601	100	22.3	22.3	10.3	437

[1] Expected product, from the area in each tier. Block values for rates are area-weighted means.

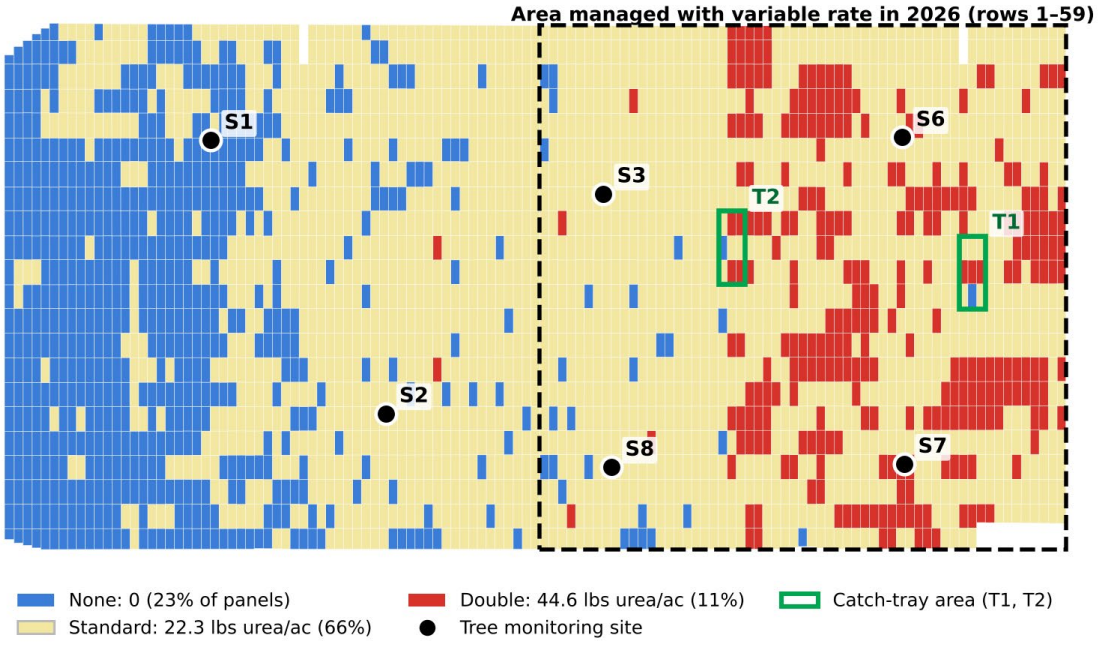


Figure 2. Variable-rate prescription for 30-ft panels in the Mattawa block. The dashed outline is the area managed with variable rate in 2026 (rows 1–59, counted from the farm road), and green boxes are the catch-tray areas (T1, T2). Black dots are the tree monitoring sites within the prescription area.

Application check (June 16): two areas inside the variable-rate area were selected where, according to the Outfield prescription, consecutive panels were assigned the double, standard, and no-N rates (T1 and T2; Figure 2). Catch trays were placed in the panels around each center, on the east and west sides of the tree row and north and south of the reference post (84 trays), and the product in each tray was weighed. Panels were also inspected visually and photographed after the pass (Figure 3).



Figure 3. Left: Catch trays placed in the panels in six positions, 3 on each side of the trees (east and west) totalling (84 trays). Right; Wilbur Ellis (team meber: Paolo) driving Red-Ant variable spreader at Mattawa Cosmic crisp® orchard.

3. Evaluate the impact of variable rate nutrient management

The goal of variable-rate N is a better distribution according to demand and, over time, a reduction of orchard variability, expected as a long term response of variable rate management. Therefore, the 2026 leaf, yield and fruit quality data are treated as a baseline, and the response will be assessed in the following seasons by comparing variability between the area managed with variable rate (rows 1–59) and the rest of the block managed with a uniform rate.

Single rate versus per-panel rate: tree-level N demand (crop removal) of the 40 harvested trees in 2025 and 2026 was used to separate variability within sites (five trees) from variability among sites (one-way ANOVA, coefficient of variation). Each site represents the proportion of low, medium, high rate of the 19.6-acre block. Total N and urea were then calculated for a single rate (grower standard) and for a per-panel rate (site mean), including a ±10% error in the panel estimate, and cost of Urea at $674 per ton (DNT).

RESULTS AND DISCUSSION

1. Validate tools to determine precision and variable nutrient demand

Mattawa site soils are alkaline (pH 7.6–8.5), with very low OM (0.2–0.8%), reflected also in very low mineral N (nitrate-N 0.6–1.3 ppm; ammonium-N 0–0.8 ppm) (Table 3). Soil B (0.02–0.29 ppm) was low in all zones, and Olsen P, Zn and K varied two- to tenfold between zones. Moxee site soils had higher OM (1.1–2.6%), higher nitrate-N (1.3–62 ppm) and much higher K (459–1,216 ppm) (data not shown). Given the low soil O.M at Mattawa site, the supply of N for the rate calculation can be ignored, while should not be ignored for Moxee site.

Table 3. Soil properties in three low-OM and three high-OM areas of the Mattawa block selected from the SoilOptix map (April 16, 2026; mean of three samples).

Zone	pH	OM (%)	NO_3-N (ppm)	NH_4-N (ppm)	Olsen P (ppm)	K (ppm)	S (ppm)	Zn (ppm)	B (ppm)
Low 1	8.0	0.4	0.7	0.6	8	91	2.7	0.3	0.03
Low 2	8.1	0.3	0.7	0.3	28	143	8.9	1.9	0.20
Low 3	8.3	0.5	0.9	0.4	16	124	2.6	1.3	0.07
High 1	7.8	0.7	0.8	0.5	22	74	14.2	3.2	0.07
High 2	7.9	0.6	1.0	0.6	22	98	6.5	2.5	0.08
High 3	8.4	0.3	0.7	0.5	11	77	3.3	0.3	0.08
Block mean	**8.1**	**0.5**	**0.8**	**0.5**	**18**	**101**	**6.4**	**1.6**	**0.09**

In July, leaf N was 2.40–2.77% at Mattawa and 2.37–2.88% at Moxee, above the recommended range for apple (1.7–2.2%; Sallato et al., 2019) at every site (Figure 4), consistent with 2024 and 2025 results.

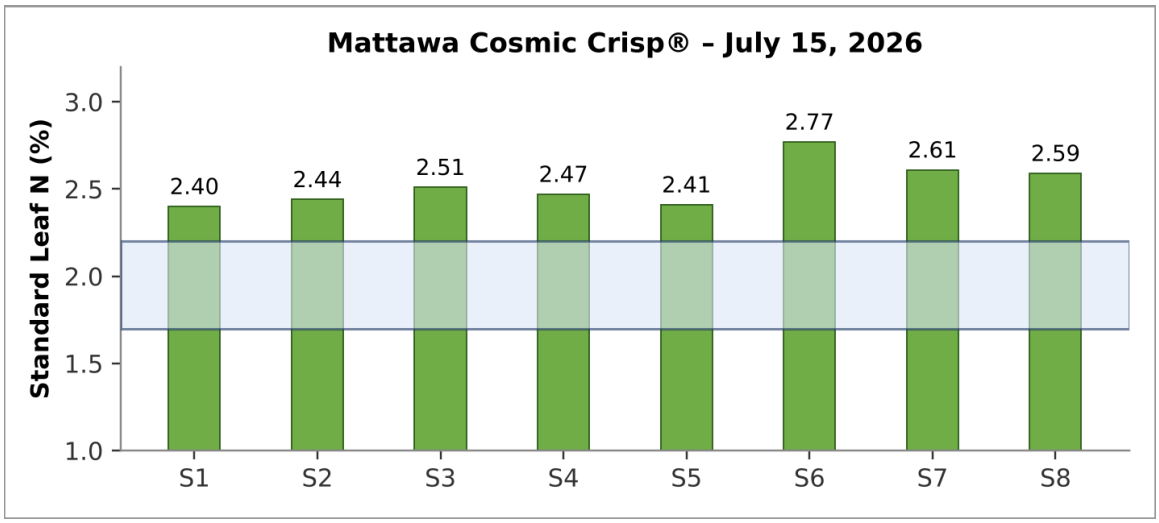


Figure 4. Leaf N levels in Mattawa apple orchard sites, July 15, 2026 (one composite sample per site). Overlayed box reflects recommended N ranges for apples (Sallato et al., 2019).

For Mattawa site, yield ranged from 14 to 90 lbs/tree (mean 46.6 lbs/tree) and differed among sites ($p < 0.001$), while mean fruit weight (204–310 g; mean 257 g) did not ($p = 0.36$) (Table 4). On average, 88% of the fruit was clean, with 4.3% green spot, 5.2% culls and 2.9% sunburn. Green spot was half of the 2025 level (8.6%), while sunburn was similar (2.6% in 2025). Site 5 had the lowest packout (71%), driven by sunburn (12.7%) and culls (12.5%). Mean yield was 18% lower than in 2025 (56.7 lbs/tree).

Table 4. Yield and fruit quality at the eight Mattawa monitoring sites (mean of five trees), with 2025 yield for comparison.

Site	Yield 2025 (lbs/tree)	Yield 2026 (lbs/tree)	Fruit (n/tree)	Fruit wt (g)	Clean (%)	GS (%)	Culls (%)	Sunburn (%)
1	62.5	49.3	82	273	86	9.6	3.8	0.4
2	86.5	70.5	123	263	95	1.7	3.6	0.1
3	69.7	40.1	70	258	78	8.6	8.1	5.2
4	37.6	32.4	57	264	93	1.2	2.7	2.9
5	34.2	35.6	67	242	71	3.7	12.5	12.7
6	44.7	36.2	62	264	91	5.1	3.3	0.7
7	48.1	50.0	97	234	92	3.0	4.0	0.7
8	70.2	58.5	103	259	95	1.4	3.3	0.1
Mean	**56.7**	**46.6**	**83**	**257**	**88**	**4.3**	**5.2**	**2.9**

Using 0.55 g N per kg of fruit, the 2026 crop removed 11.6 g N per tree on average (3.6–22.5 g). Per acre, this was ≈44 lbs N/acre on average across sites (19–92 lbs N/acre across trees), considering 1,210 trees/acre in the west section and 2,420 trees/acre in the interplanted section (Sites 4–7). The trees received 30 lbs N/acre in fall 2025 plus 0–20.5 lbs N/acre with the variable-rate urea (mean ≈9), a total of 30–50 lbs N/acre (mean ≈39). This is close to, but below, the average removal, and the gap is largest in high-crop, high-density areas: Site 7 removed ≈67 lbs N/acre and received ≈50, and Site 2 removed ≈47 and received ≈40. With very low soil OM and mineral N at Mattawa, little of that gap can be covered by the soil, so fall N applications were added at a tree level in high-cropping / low vigor trees.

Nutrient sensors

Croptix™ and Agrocares™ system supports immediate scanning of samples collected from the field. However, Croptix™ sensor was not available on-site. Instead, samples were shipped to Croptix, where samples were subsequently processed and scanned. For both technologies, measurements and their ground truth with standard and sap (only Croptix™) collected during the season supports ongoing apple model development.

2. Integrate layers of information to create prescription mapping for different nutrient requirements

Soil supply and SoilOptix validation.

Six soil sampled areas aligned with SoilOptix low and high O.M classes (Figure 5). Laboratory OM had a moderate positively correlated with the mapped OM ($r = 0.56$, $p = 0.02$, $n = 18$), and the high-OM areas averaged 0.54% OM compared with 0.39% in the low-OM areas ($p = 0.06$). However, SoilOptix overestimated OM by 0.29 percentage points on average (0.2–0.8% measured vs. 0.57–0.96% mapped), and one high-OM area (High 3) tested 0.30%, as low as the low-OM areas; this point lies at the edge of a small high-OM patch, so a small location error may explain the mismatch. Regardless, the N released from OM corresponds to ≈3 lbs N/acre (1.4–5.6 lbs N/acre), and the difference between low- and high-OM areas was ≈1 lb N/acre. SoilOptix data were therefore ingested but not used to adjust rates, given the negligible contribution (< 6 lbs N/acre).

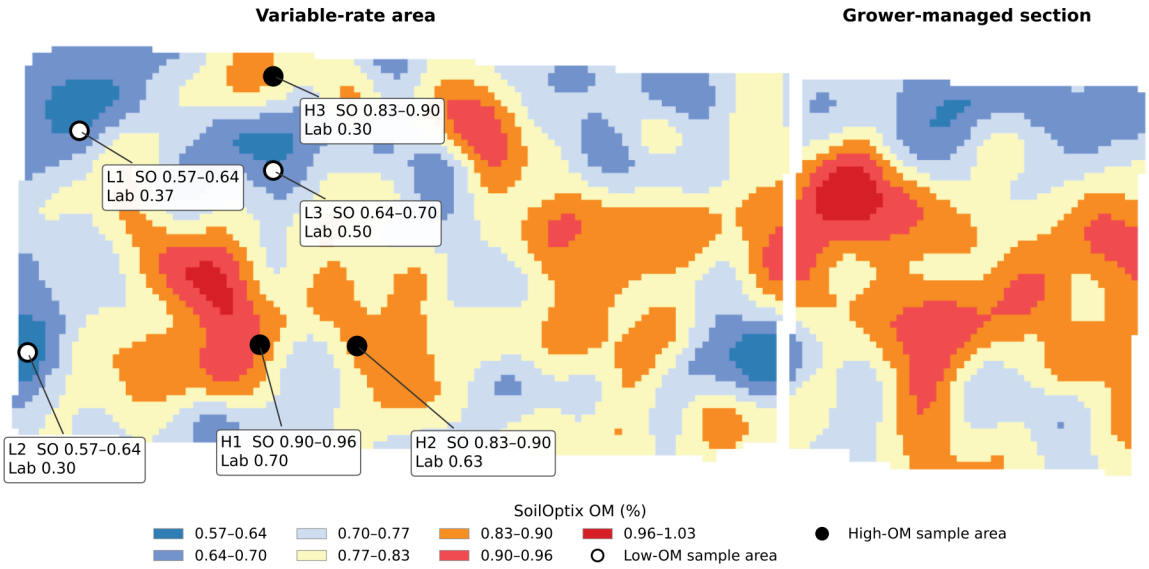


Figure 5. SoilOptix organic matter map (2024 survey) of the Mattawa smart orchard, with the soil sampling areas used for validation in spring 2026. Labels show the OM range mapped by SoilOptix (SO) and the laboratory OM (mean of three samples) at each area. Sampling areas are placed by row number and GPS and are approximate.

Compared with uniform rate application over the whole block, the VR prescription required ≈54 lbs (12%) less urea (Table 2). Across the eight sites, 2026 yield was strongly correlated with 2025 yield ($r = 0.84$, $p < 0.01$), and Sites 2 and 8 were the highest-yielding sites and Sites 4, 5 and 6 the lowest in both years (Table 4). In 2024, when trees carried a lighter crop (4th leaf) (10–38 lbs/tree; seven sites), the pattern was similar but had weaker correlation ($r = 0.66$ with 2025 and 0.62 with 2026). The stable cropping between 2025 and 2026 supports the use of the previous season's map and confirms that there is no alternate bearing in this block. The only exceptions were Site 1, which produced 62.5 lbs/tree in 2025 (fourth highest) but fell in a no-N panel, and Site 7, which produced 48.1 lbs/tree (fifth) but fell in a double-rate panel. Possible causes include spreader geo-positioning error in the site location relative to 30-ft panels or the difference in scale between a 5-tree site and a ≈9-tree panel.

Variable Rate Technology Validation.

Urea (46-0-0) was applied on June 16–17, 2026 by Wilbur-Ellis with a spreader (unit RASS 1) fitted with the RedAnt Agri SmartNode stepper-motor controller, which changed the rate on the go, panel by panel, according to the prescription (Figure 6a). The spreader drove along one side of each tree row, and the as-applied path was logged by the controller (Figure 6b).

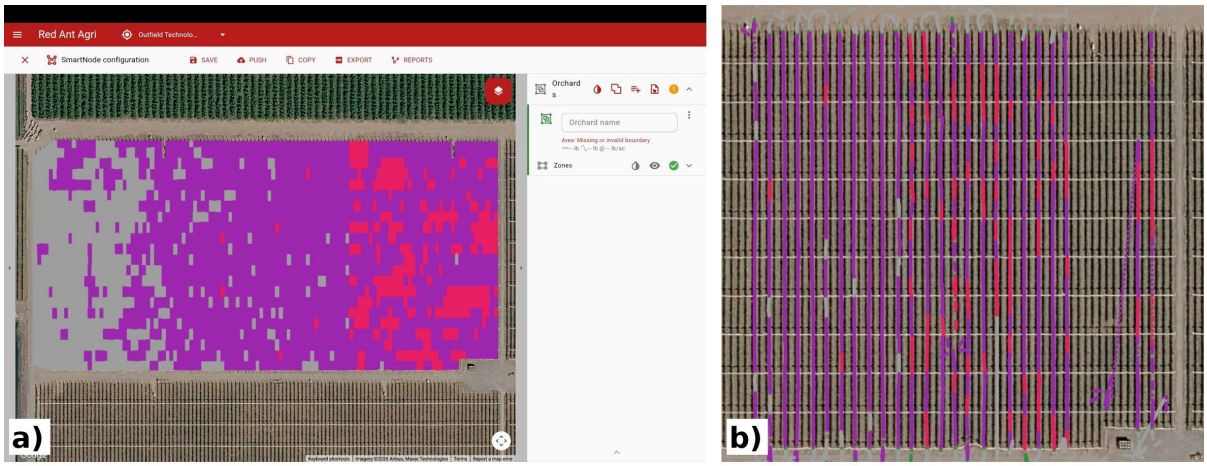


Figure 6. a) Prescription loaded in the RedAnt Agri controller (gray: no N; purple: standard; pink: double rate). b) As-applied log from the spreader (June 17, 2026).

Visual inspection and photos confirmed that panels prescribed no N received no urea on the ground, and that standard and double panels differed as expected relative to each other. The actual rates could not be quantified with the catch trays because they were placed on both sides of the tree row while the spreader delivers to one side only, so half of the trays were outside the treated band and the catch in the others was very small to weigh reliably. In 2027, trays (or collection pans across the full swath) will be placed only within the treated band, and the controller log and total product used will be checked against the prescription.

3. Evaluate the impact of variable rate nutrient management

Variability of N demand within sites and across the orchard.

Nitrogen demand was calculated for each harvested tree as fruit removal (kg fruit × 0.55 g N per kg) and expressed per acre using the planting density of each section: 1,210 trees/acre for Sites 1–3 and 8, and 2,420 trees/acre for Sites 4–7 (interplanted section). In 2026, tree-level N demand averaged 11.6 g per tree and ranged from 3.6 g in low-cropping trees to 22.5 g in high-cropping trees, equivalent to 19–92 lbs N/acre (average of sites ≈44 lbs N/acre). In 2025, demand was higher (14.7 g per tree; 31–144 lbs N/acre; average ≈54 lbs N/acre), in line with the 18% higher yield that season (Table 5; Figure 7).

Site means ranged from 27 to 67 lbs N/acre in 2026 season (2.5-fold) and from 40 to 81 lbs N/acre in 2025 season (2.0-fold). Per tree, the ranking was similar in both years (Sites 2 and 8 highest, Sites 4, 5 and 6 lowest), but per acre the highest demand was in the high-density section (Sites 6 and 7), where twice as many trees share each acre. Differences among sites were significant in both years ($p < 0.01$).

Variability within a site was large. The coefficient of variation (CV) among the five trees of a site averaged 24% in 2026 (14–32%) and 19% in 2025 (8–48%), compared with a CV among site means of 27% and 25%, respectively.

Table 5. Nitrogen demand per tree and per acre at each monitoring site (mean of five trees), and variability within the site, in 2025 and 2026.

Site	2025 N (g/tree)	2025 N (lbs/acre)	2025 CV (%)	2026 N (g/tree)	2026 N (lbs/acre)	2026 range (lbs/acre)	2026 CV (%)
1	15.2	40.5	16	12.3	32.8	19–43	29
2	22.9	61.0	15	17.6	46.9	34–60	25
3	17.4	46.5	13	10.0	26.7	21–34	20
4*	9.3	49.7	9	8.1	43.2	19–52	32
5*	8.5	45.2	20	8.9	47.3	36–59	18
6*	12.3	65.7	11	9.0	48.2	39–54	14
7*	15.1	80.8	48	12.5	66.6	47–92	26
8	16.8	44.7	24	14.6	38.9	28–46	26
Block	**14.7**	**54.3**	**35**	**11.6**	**43.8**	**19–92**	**34**
CV among site (%)		**25**			**27**		

* Interplanted section, 2,420 trees/acre; all other sites 1,210 trees/acre. Block values are the mean of sites; block CV is the CV among all 40 trees.

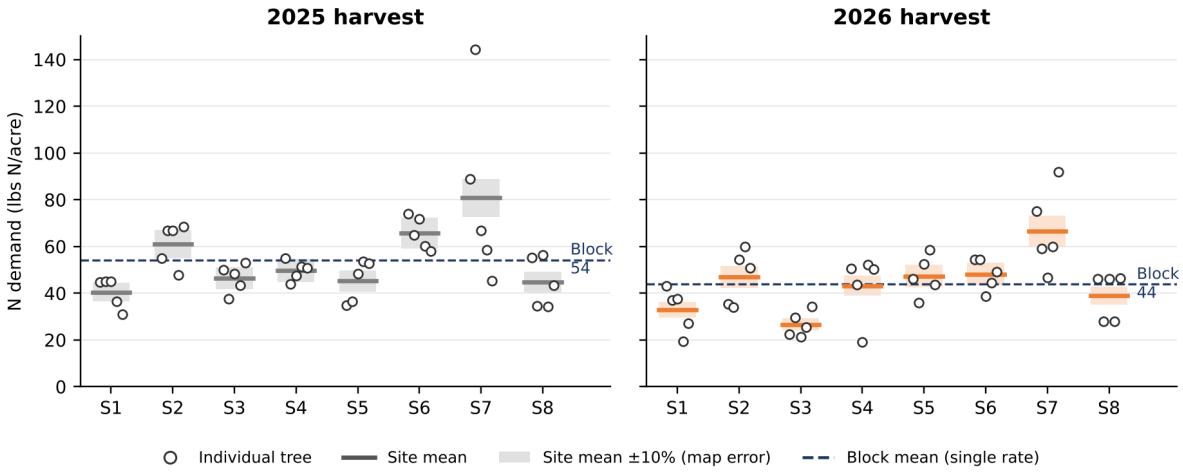


Figure 7. Nitrogen demand of individual trees (circles) and site means (bars) at the Mattawa monitoring sites in 2025 and 2026. Shaded boxes show ±10% around each site mean, the assumed error of a drone-based map; the dashed line is the block mean that a single uniform rate would apply.

Single versus per-panel rate. Following the approach described in Methods, we compared applying the exact N estimated for each panel (site mean) with a single (uniform) rate for the whole block (Table 6). When the single rate equals the block average, the total N is the same as with per-panel rates (859 lbs N or 1,867 lbs urea in 2026). Overall, the single rate puts ≈4.2 lbs N/acre (10%) in excess in low-demand areas and leaves the same amount short in high-demand areas. In 2025 this redistribution was ≈5.6 lbs N/acre (10%).

Product savings appear only when the single rate is set to cover the more demanding areas (high load). Covering the highest-demand site with a single rate would have required 1,304 lbs N (2,836 lbs urea) in 2026; the per-panel rate would have saved 446 lbs N (34%), ≈970 lbs urea or ≈$326 for the block ($16.6/acre at $674 per ton of urea; DTN, October 2026). The 2025 data gave similar results (33% and 13% savings, ≈$381 and ≈$114).

Table 6. Nitrogen and urea required for the 19.6-acre block under a single rate or a per-panel rate, based on 2026 crop removal.

Strategy	N rate (lbs N/acre)	N block (lbs)	Urea block (lbs)	Urea cost ($)	Short in high areas (lbs N/acre)
Single rate = block mean	43.8	859	1,867	629	4.2
Single rate = highest site	66.6	1,304	2,836	956	0
Per panel, exact	43.8	859	1,867	629	0

Urea = 46% N; $674 per ton (DTN, second week of October 2026). Application costs not included.

Moving from a per-panel rate to a tree-level rate would redistribute another ≈4.1 lbs N/acre in 2026 (9% of the average demand), but would not reduce the total amount of N. At current urea prices, this is worth ≈$3 per acre even if all of it were saved. This gain is also the same size as a ±10% map error (up to 4.4 lbs N/acre) and it is below the resolution of a spreader that delivers along a ≈3-ft band in 30-ft panels. Therefore, a tree-level N rate is not justified on product savings; the panel (≈30 ft) is a practical resolution for soil-applied N in this block.

The main value of variable-rate N here is not lower product use but better placement: avoiding excess N in low-crop areas, where it can promote vigor and reduce fruit quality, and avoiding shortages in high-crop areas, with the long-term goal of reducing variability across the orchard. We will continue to evaluated variability the following seasons by comparing the area managed with variable rate with the area managed with a uniform rate.

Plans for 2027. Include Moxee, WA and new site in Yakima, WA for 2027 prescriptions.

Outreach. The smart orchard and project specific technologies were demonstrated at the Smart Orchard Field Day organized on October 22, 2026 (Gilbert Orchards, Yakima), which closed FIRA USA's three-day event. This event was attended by over 300 participants. Results from the VR application were also summarized in the poster "Variable-Rate Fertilizer from Drone Surveys".





The project outcomes were also shared at the Columbia Tree Fruit Grower Club meeting held in Kennewick on June 23, 2026. Our team also organized and moderated a panel discussions at FIRA USA 2026, perticularly on, "how agtech is transforming crop load management.", where grower insights on variable rate application technologies were disscued. This year's findings will also be published as extension articles.

Project Title: Int'l collab: Advancing global harvest automation with open-source digital orchards

Report Type: Continuing Project Report

Primary PI: Joseph Davidson
Organization: Oregon State University
Telephone: 541-737-9193
Email: joseph.davidson@oregonstate.edu
Address: 236 Rogers Hall
Address 2: 2000 SW Monroe Ave
City/State/Zip: Corvallis, OR 97331

Co-PI 2: Cindy Grimm
Organization: Oregon State University (same address as Primary PI)
Email: grimmc@oregonstate.edu

CO-PI 3: Jochen Hemming
Organization: Stichting Wageningen Research
Telephone: +31 653174569
Email: jochen.hemming@wur.nl
Address: Droevendaalsesteeg 1, 6708 PB Wageningen, the Netherlands

Co-PI 4: Richard Oliver
Organization: Bioeconomy Science Institute
Telephone: +64212210189
Email: Richard.Oliver@plantandfood.co.nz
Address: Private Bag 3230, Waikato Mail Centre, Hamilton 3240, New Zealand

Co-PI 5: Francisco Rojo
Organization: Bioeconomy Science Institute (same address as Co-PI 4)
Email: Francisco.Rojo@plantandfood.co.nz

Cooperators: Allan Brothers Fruit, Arjan Vroegop (Wageningen University & Research), and Pieter van Dalfsen (Wageningen University & Research)

Project Duration: 2-Year

Total Project Request for Year 1 Funding: $166,003
Total Project Request for Year 2 Funding: $133,997

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

Budget 1
Primary PI: Joseph R. 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	2026	2027
Salaries	$25,587.00	$24,093.00
Benefits	$12,144.00	$11,553.00
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies	$2,519.00	
Travel	$3,253.00	$3,351.00
Plot Fees		
Miscellaneous	$17,500.00	
Total	$61,003.00	$38,997.00

Footnotes:
[1]Salaries include 0.5 months per year for Joe Davidson and Cindy Grimm.
[2]Supplies include consumable materials for field experiments.
[3]Miscellaneous expense in Year 1 is for a handheld LiDAR scanner needed to image orchards in Washington.
[4]Travel budget is requested to support mileage, trailer rentals, and lodging for data collection and field experiments.

Budget 2
Co PI 2: Jochen Hemming
Organization Name: Stichting Wageningen Research
Contract Administrator: Tom Molthof (Finance & Control)
Telephone: +31634510679
Contract administrator email address: tom.molthof@wur.nl

Item	2026	2027
Salaries	$50,000.00	$44,000.00
Benefits		
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies	$4,000.00	
Travel	$500.00	$500.00
Plot Fees		
Miscellaneous	$500.00	$500.00
Total	$55,000.00	$45,000.00

Footnotes:

Budget 3
Co-PI 3: Richard Oliver
Organization Name: Bioeconomy Science Institute
Contract Administrator: Katie Sizeland
Telephone: +64 21 221 0189
Contract administrator email address: Katie.Sizeland@plantandfood.co.nz

Item	2026	2027
Salaries	$44,000.00	$44,000.00
Benefits		
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies	$5,400.00	$5,400.00
Travel	$600.00	$600.00
Plot Fees		
Miscellaneous		
Total	$50,000.00	$50,000.00

Footnotes:

Introduction: In this project we are developing an open-source, publicly available robot simulation environment with sufficient example data, both real and synthetic, to support commercial development of harvest automation technology for apples, pears, and cherries. Despite decades of research and development, there are still no commercial harvesters available for the fresh tree fruit market. One large challenge facing companies is the lack of realistic simulation environments for orchards – most commercial ventures develop their own custom software tools and collect and label data, often starting from scratch. This cycle of constantly 'reinventing the wheel' is slow, inefficient, and wastes valuable resources.

Our focus is on creating digital trees with deformable, prunable limbs and fruit that can be picked virtually. While not our main priority, an added benefit of this work is that because the trees will also look realistic, the software tool can also be used to generate synthetic data for training computer vision algorithms for detecting fruit and branches. Notably, we will create simulation environments of several popular high-density systems. Ultimately, our long-term goal is to create the digital infrastructure that reduces the entry barrier for large agricultural equipment companies (e.g. CNH, John Deere, etc.) into orchard harvest automation. To accomplish our goals, we have defined the following four research objectives:

1. Collect high-resolution sensor data of high-density apple, sweet cherry, and pear orchards during harvest, and pre-post pruning, from three international locations.
2. Develop a robot simulation environment with deformable trees and parameterized physics.
3. Validate the orchard simulation using a combination of manual measurements and sensor data.
4. Share the simulation environment with the international tree fruit community at a publicly available repository and advertise/showcase the simulation at Ag Tech forums such as the Smart Orchard Field Day and NW Hort Expo.

This Continuing Report summarizes research results from the performance period of Spring 2026 to Fall 2026. During the first year of the project, we made substantial progress across all research objectives.

Significant Findings

- Canopy, limb, and fruit scans (e.g. meshes and Gaussian Splats) were captured from multiple commercial orchards in Washington. Similar scans in New Zealand are planned for November 2026.
- Oregon State University's (OSU) L-Py tree creation software was updated to support user-defined pruning algorithms at any growth stage, explicit control of wire placement and tying algorithms, visualization of proposed cuts, and other changes.
- The Bioeconomy Science Institute (BSI) initiated development of a next-generation plant architecture and growth modelling platform designed to support modular, extensible simulations of plant development.
- The project team adopted NVIDIA Isaac Sim 6 as the simulation platform. Wageningen University and Research (WUR) developed a virtual orchard generator that generates a world from individual 3D assets, such as trees, poles, support wires, irrigation drip lines, etc. The first example data sets from all three geographical locations (US, New Zealand, The Netherlands) have been exchanged and successfully imported.
- A joint research workshop was held with UC Davis on October 28th, 2026 to exchange knowledge, share data, and identify collaboration opportunities

Methods

<u>Task 1: In-field data collection and model validation (OSU lead; BSI and WUR participants)</u>

This year the OSU team procured a new Lixel K2 handheld LiDAR scanner from Xgrids. Note, this is the same scanner used by the University of Tokyo for the WTFRC-funded robotic pruning project (PI Davidson is also a collaborator on that project). The sensor was used to scan four unique locations in Washington during the 2026 apple harvest season (early October):

- *Location*: Prosser / commercial orchard; *Orchard system*: V-trellis; *Variety*: 'Envy'
- *Location*: WSU Roza / research orchard; *Orchard system*: Bi-axe; *Variety*: 'Cosmic Crisp'
- *Location*: WSU Roza / research orchard; *Orchard system*: UFO; *Variety*: 'Sunflare'
- *Location*: Pasco / commercial orchard; *System*: Tall spindle; *Variety*: 'Envy'

There were three treatments applied to the Cosmic Crisp block to vary the level of occlusion and fruit visibility in the orchard scans. These treatments were summer pruning + cluster thinning, summer pruning with no cluster thinning, and the control section (i.e. no summer pruning or cluster thinning). All LiDAR scans were postprocessed into 3D Gaussian Splats (3DGS) using Lixel CyberColor (LCC) Studio, a proprietary software from Xgrids that converts raw LiDAR and camera scans into photorealistic, navigable 3D environments. Figure 1 shows an example of one of the 3DGS from the Cosmic Crisp row. All data was shared with project partners to support the project's other research tasks. The data was also shared with the research team at UC Davis.



Figure 1. Visualization of the 3DGS reconstruction of the bi-axe Cosmic Crisp row.

Apples were collected and scanned on a high resolution scanner. Meshes were created both with and without stems and spurs (Figure 2), and downsampled to create low resolution meshes (25 Envy, 10 Pink Lady, 10 Cosmic Crisp). These are meant to serve as exemplars for automatic geometry generation algorithms.

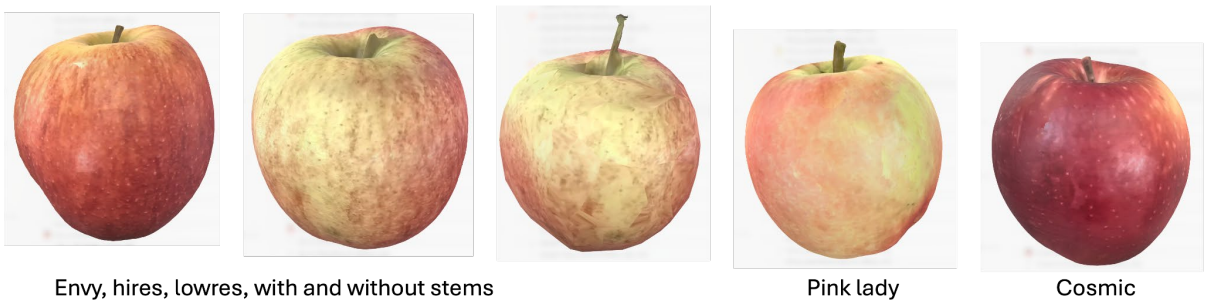


Figure 2. Scans of individual apples collected from commercial orchards in Washington.

Using the same scanner, we also captured individual branches, spurs, stem spur attachments, both in the field (full structure) and in the lab (individual branches). Figure 4 shows an initial example of generating "random" apple meshes in Blender. These assets are not necessarily accurate, but can be used to robustly train algorithms to, eg, recognize apples within a canopy.

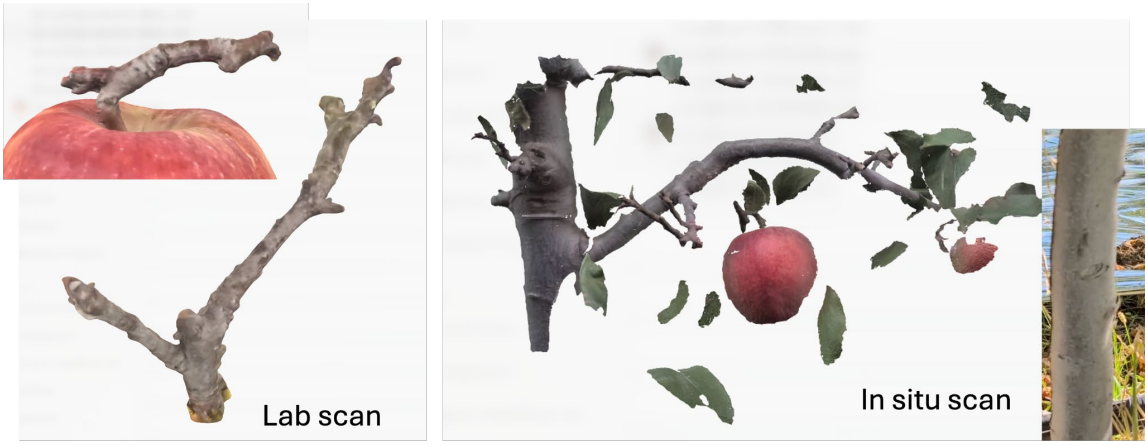


Figure 3. Example 3D scans of limbs and spurs.



Figure 4. Apple meshes generated in Blender.

The New Zealand growing season is opposite to Washington's. Flowering is under way in many apple cultivars. The BSI team is working with commercial growers in Hawke's Bay, one of New Zealand's major apple regions, to select three to five blocks covering the 2D systems relevant to Washington production systems and robotic applications in Royal Gala and Envy™. Each block will be captured before and after hand thinning and before harvest, so the data will support fruitlet detection, thinning and harvest tasks. A capture during dormancy in May–June 2027 will give clear branch structure for building collider bodies. We have identified a cherry grower who expects to begin harvest in mid-November, continuing through early December. We are also seeking pear blocks for additional captures.

Captures use a purpose-built ten-camera photogrammetry rig towed by a Peek Robotics autonomous ground vehicle (Figure 5). It records 160 geolocated images per linear metre of canopy per side, allowing reconstruction at a minimum of five to ten million splats per cubic meter of canopy volume.



Figure 5. Ten-camera photogrammetry rig towed by a Peek Robotics autonomous ground vehicle. The rig is towed at 0.5 m s^{-1} with a set of 10 images captured about every 62 mm along the canopy wall.

Each capture will be reconstructed as a 3D Gaussian splat model (Figure 6) and segmented into trunk, branches, leaves, fruitlets and fruit using a method of transferring 2D segmentations to the model. This gives class and instance for each splat in the model providing digital trees for testing orchard-robotics vision systems. Gaussian splats can be rendered in NVIDIA Isaac Sim™, the project's target platform, but they have no physical surface for a simulated robot to touch. We are therefore trialling ways to generate collider bodies. Trunks and branches would be represented as meshes or fitted cylinders, while leaves may stay visual-only (splat) elements. We will compare these approaches on geometric accuracy and simulation performance and report a recommended method.



Figure 6. Example of Gaussian splat generated from the ten-camera rig. Royal Gala, pre-harvest, planar-cordon.

Task 2: Plant structural modeling (BSI lead; OSU participant)

Leveraging parallel work funded by the AI Institute for Transforming Workforce & Decision Support (AgAID), the OSU team continued to develop its open-source library, built on LPy, for generating geometrically realistic pruned fruit trees (see Figure 7). LPy is a python-based, open-source package developed for modeling plant growth and is part of a larger package for modeling plants (OpenAlea). The LPy geometry can be incorporated into robot simulation environments (such as Isaac Sim, MuJoCo, or PyBullet) to create an infinite variety of trees. Specific updates this year include:

- Revising the wire/training architecture to better support, and generalize, the pruning and tying procedures
- Revising the tree-growth software to support testing and developing pruning algorithms
    - Implementation of pruning rules at different time points (eg, winter, summer)
    - Pre and post visualization of pruning cuts (e.g., which branches were marked for cutting and why)
    - Geometric queries to support pruning decisions (e.g., trunk to limb ratios, number of fruiting spurs within a given area)
- Annotation of the output geometry to support training computer vision algorithms, collision detection, and simple physics simulations (instance segmentation, cylinders with joints)
- Output of geometry in ply, obj, and Universal Scene Descriptor formats to enable input into simulation platforms

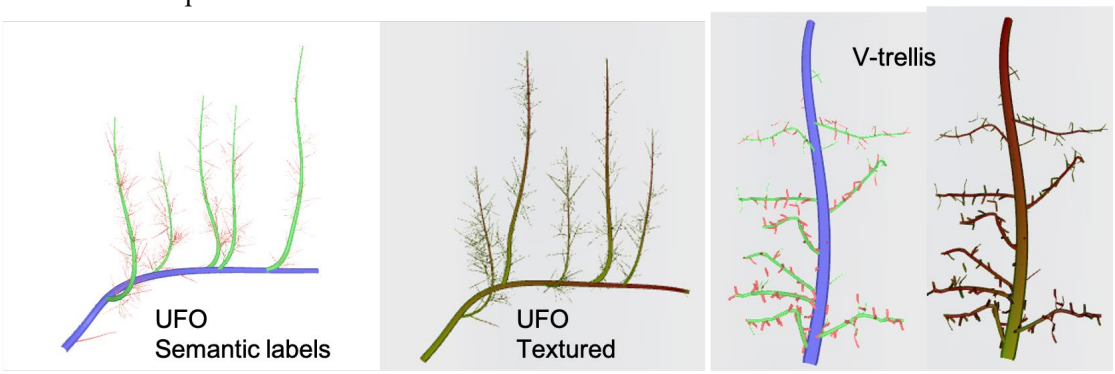


Figure 7. Images of our modified L-Py tree creation software. The software was modified to support 1) running user-defined pruning algorithms at any growth stage, 2) explicit control of wire placement and tying algorithms, 3) visualization of proposed cuts, 4) varying levels of vigor at the plant level, 5) labeling of tree components for semantic segmentation (eg, trunk, branch, spur), 6) phyllotaxis placement of buds, 7) generating a simplified collision structure for use in contact modeling, 8) generation of assets for use in Isaac Sim (universal scene descriptor format), 9) multiple trunks from one rootstock.

Virtual orchard assets can also be generated using the Bioeconomy Science Institute's Tree Generator, a MATLAB-based stochastic modelling platform for creating digital representations of apple trees and orchards. The model combines field-derived statistical distributions of segment length, diameter and orientation with architectural constraints that reproduce planar-cordon tree structures while preserving natural variability. Trees are represented as hierarchies of connected segments, with explicit allocation of vegetative and floral buds supporting seasonal development through the generation of annual shoots, leaves and fruit. User-defined parameters control tree dimensions, branching density and orchard layout, including tree spacing and row orientation, enabling representations ranging from winter dormancy to fully foliated, fruiting canopies.

Tree Generator outputs were used to create two representative planar-cordon apple tree assets: a dormant winter tree and a fully foliated summer tree (Figures 8 and 9). CSV outputs describing the generated geometry and connectivity were used to construct OpenUSD (USD) assets, establishing a pathway from tree architecture modelling to simulation environments such as NVIDIA Isaac Sim™. These assets provide a foundation for visualisation, sensor simulation, robotics development and future digital twin applications.

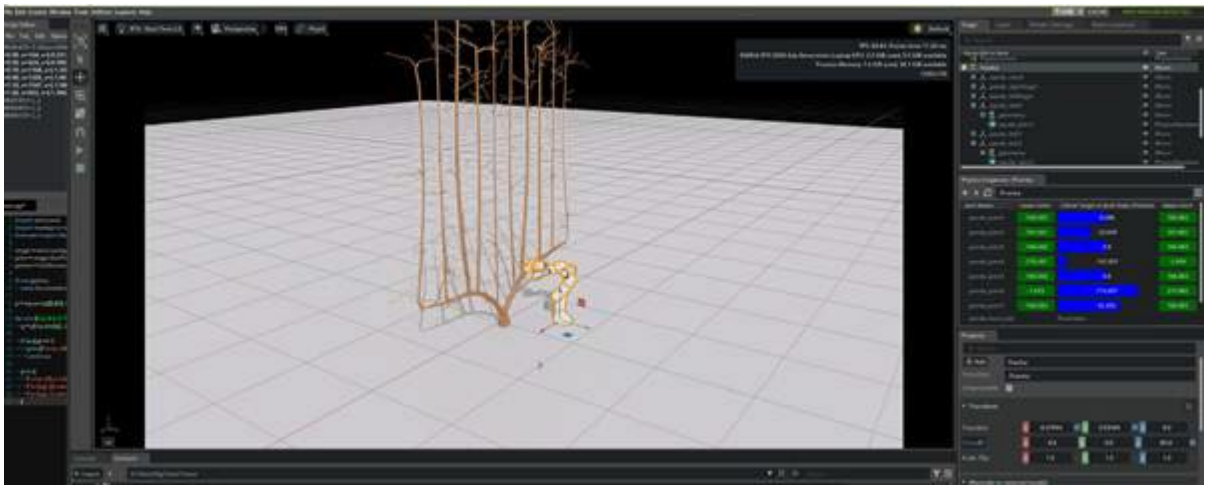


Figure 8. Stochastically generated tree at winter dormancy, simulated using the Tree Generator and visualised in NVIDIA Isaac Sim.

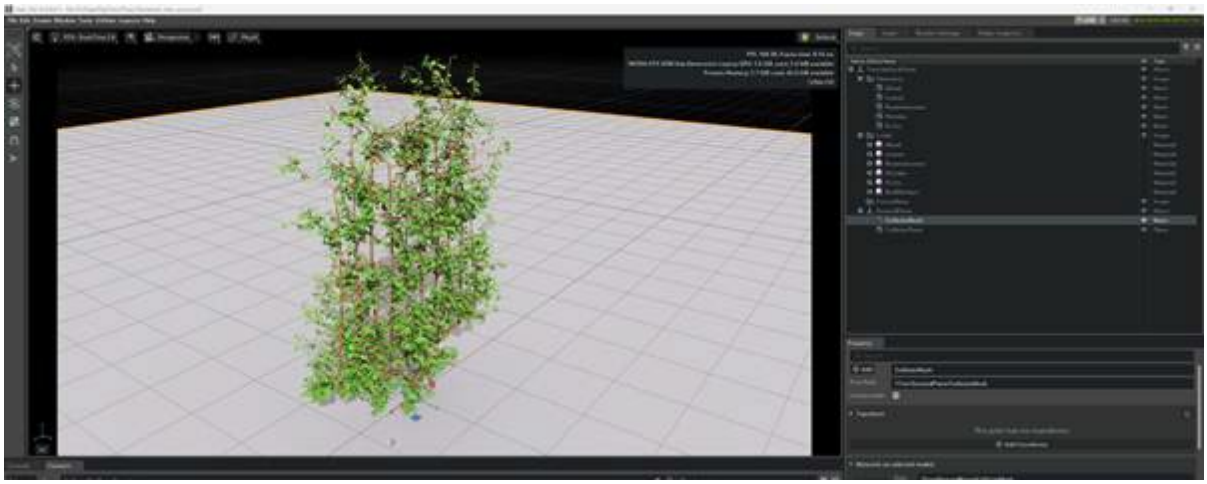


Figure 9. Stochastically generated tree with foliage, simulated using the Tree Generator and visualised in NVIDIA Isaac Sim.

Building on this work, the Bioeconomy Science Institute is developing a next-generation plant architecture and growth modelling platform designed to support modular, extensible simulations of plant development. The platform integrates shoot elongation, branching topology, bud placement and secondary (radial) growth within a coherent biological framework, supported by configurable growth rules and integrated 3D visualisation (Figure 10). Current work focuses on implementation verification and assessment of biological consistency, establishing a foundation for increasingly complex tree architectures and future digital twin applications. The platform's structured outputs also provide a pathway to generating OpenUSD assets for use in NVIDIA Isaac Sim™, opening opportunities for future robotics and physics-based simulations.

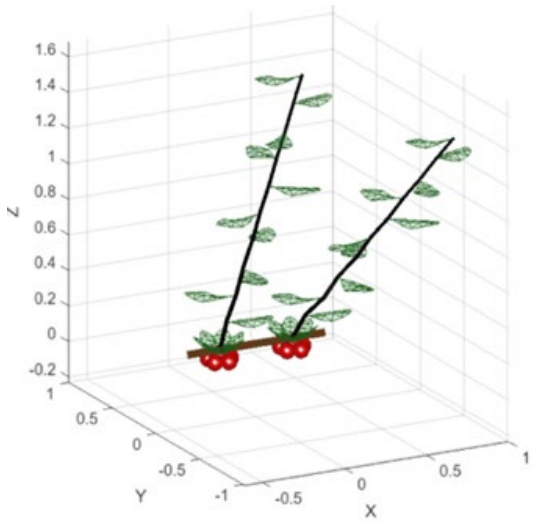


Figure 10. Annual shoot development simulated using the next-generation plant architecture and growth modelling platform.

Task 3: Robot simulation development (WUR lead)

While the main activities for this task are scheduled for the second year of the project, the project team has agreed on the type and format of tree data that will be imported and used in the simulation software. We have adopted NVIDIA Isaac Sim 6 as the simulation platform. Isaac Sim is a scalable robotics simulation platform and synthetic data generation tool built on the NVIDIA Omniverse platform. This platform enables the simulation of photorealistic environments, robots and sensors and has advanced physics engines. Isaac Sim is connected to the Robot Operating System (ROS 2) middleware that enables the simulator to behave like a real robot. We have developed a virtual orchard generator that generates a world from individual 3D assets, such as trees, poles, support wires, irrigation drip lines, etc. The assets have been created using Blender and then exported in the OpenUSD (Universal Scene Description) file format. Geometry of trees are either based on 3D data recorded from real trees (Task 1), but can also originate from structural plant modelling (Task 2). Stem properties (thickness, texture) and leaves and eventually fruits can be added to the tree structure. Using real orchard properties, such as the number of rows, row length and width, tree spacing, pole spacing, etc., a Python script generates a master OpenUSD file that hierarchically arranges the different assets in a virtual world (Figure 11). 3D models of robots (Figure 12) and sensors can also be added. Environmental parameters such as sky conditions, light quality, and light intensity can be set as needed.



Figure 11: Example views of a virtual apple orchard in Isaac Sim.

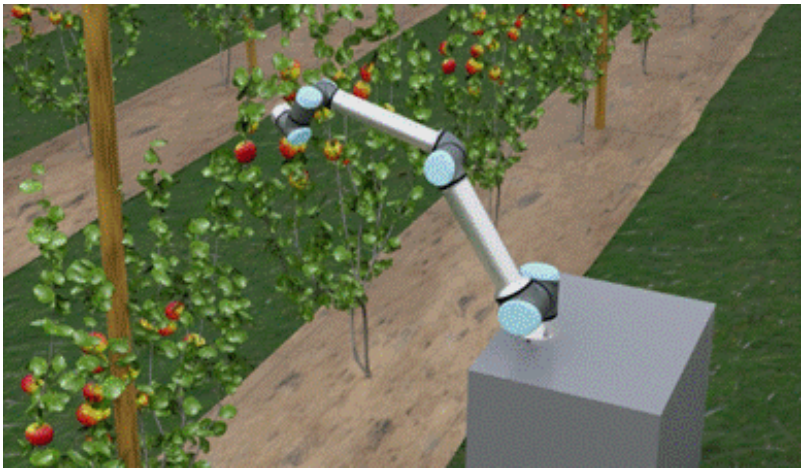


Figure 12: Integration of simulated robotic arm to the virtual orchard.

The first example data sets from all three geographical locations (US, New Zealand, The Netherlands) have been exchanged and successfully imported. A script-based software pipeline to add physics and to parametrize the physical properties of the trees is under development.

Task 4: Simulation validation (OSU and WUR co-lead)

While we have not conducted any formal simulation validations (yet), the newly re-designed LPy models (UFO and V-trellis architectures) were informally reviewed by two growers for their suitability for explaining automated pruning algorithms. Prototype software was developed to show simulated trees before and after pruning, with the cuts explicitly visualized/marked on the trees. The feedback was given as part of a bigger conversation around what forms of automation would be most beneficial. Reception was generally positive.

Project Title: Robotic Harvesting: Multi-Camera Fruit Detection Under Heavy Occlusion

Report Type: Continuing Project Report

Primary PI: Stavros Vougioukas
Organization: University of California, Davis. Dept. of Biological and Agricultural Engineering
Telephone: 530-7521890
Email: svougioukas@ucdavis.edu
Address: 1 Shields Ave.
Address 2:
City/State/Zip: Davis, CA 95616

Co-PI 2: Brian Bailey
Organization: University of California, Davis. Dept. of Plant Sciences
Telephone: 530-7521890
Email: bnbailey@ucdavis.edu
Address: 1 Shields Ave.
Address 2:
City/State/Zip: Davis, CA 95616

Co-PI 3: Zhaodan Kong
Organization: University of California, Davis. Dept. of Mechanical and Aerospace Engineering
Telephone: 530-7521890
Email: zdkong@ucdavis.edu
Address: 1 Shields Ave.
Address 2:
City/State/Zip: Davis, CA 95616

Cooperators: Lodi Farming (Jeff Colombini)

Project Duration: 2-Year

Total Project Request for Year 1 Funding: $ 100,036
Total Project Request for Year 2 Funding: $ 104,730

Other related/associated funding sources: None

WTFRC Collaborative Costs: None.

Budget 1
Primary PI:
Organization Name: University of California, Davis
Contract Administrator: Kathryn Olson
Telephone: 530-754-3077
Contract administrator email address: kkolson@ucdavis.edu
Station Manager/Supervisor:
Station manager/supervisor email address:

Item	2026	2027
Salaries	$76,871	$79,177
Benefits	$19,365	$20,553
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies	$2,800	$1,000
Travel	$1,000	$4,000
Plot Fees		
Miscellaneous		
Total	$100,036	$104,730

Footnotes: The Co-PIs are from the same Organization and share the budget.

Objectives

1. **Create a High-fidelity Synthetic Apple Orchard**
2. **Develop a Multi-Camera Active Vision System**
3. **Evaluate the Active Vision System in Simulations and in Orchards**

Significant Findings

Tree and apple fruit scans were captured in a V-trellised Pink Lady apple orchard in Lodi, CA. More scans are planned when the leaves drop. The data are being processed.

Physics were added to the HELIOS plant-growth simulator, and tree models were exported to NVIDIA Isaac Sim.

HELIOS generates precise instance segmentation masks for fruits and other objects in canopies and infrastructure, enabling model training without manual labeling.

A joint research workshop with OSU, WUR, and BSI was held on October 28, 2026, to exchange knowledge, share data, and identify collaboration opportunities.

Multi-camera active vision approaches were identified in the manufacturing literature and are examined alongside published work in the agricultural domain that uses a single camera.

Methods

OBJECTIVE 1. Create a High-fidelity Synthetic Apple Orchard

Apple Scans Data Collection
On 29 September 2026, we collected 33 apples of the local variety at Lodi Farms in Lodi, California (38.0768° N, 121.1806° W), brought them to the lab, and scanned each one on a turntable with a Revopoint MetroY Pro in two scanning sessions.

We scanned each apple as a complete object so we could measure its shape and full skin color, including the stem cavity and calyx end. Because a single turntable pass only sees the side facing the scanner and leaves the resting patch unseen, each apple was scanned in two passes. In the first scan, the apple was placed vertically on the turntable. It was then repositioned horizontally for the second scan so surface regions hidden or in contact with the turntable during the first orientation could be captured from a different viewpoint. Apples were scanned in two sessions: 11 apples on day 1 (apple_1 to apple_11) and 23 on day 2 (apple_12 to apple_33), for 33 apples in total.

Methodology

1. Scan setup and acquisition mode: Each apple was scanned using the Revopoint MetroY Pro in Feature Scan mode with the Auto Turntable enabled and Color acquisition turned on. For the first scan, the apple was positioned upright on the turntable. For the second scan, the apple was rotated by approximately 90° and scanned again. This change in orientation exposed surface regions that were hidden or in contact with the turntable during the first scan and improved overall surface coverage (Figure 1).



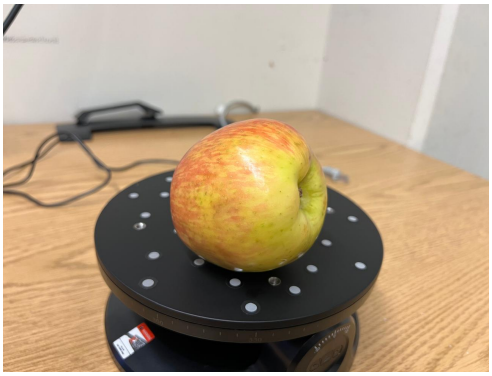


Figure 1. Revo Scan setup to scan the apple from two angles.

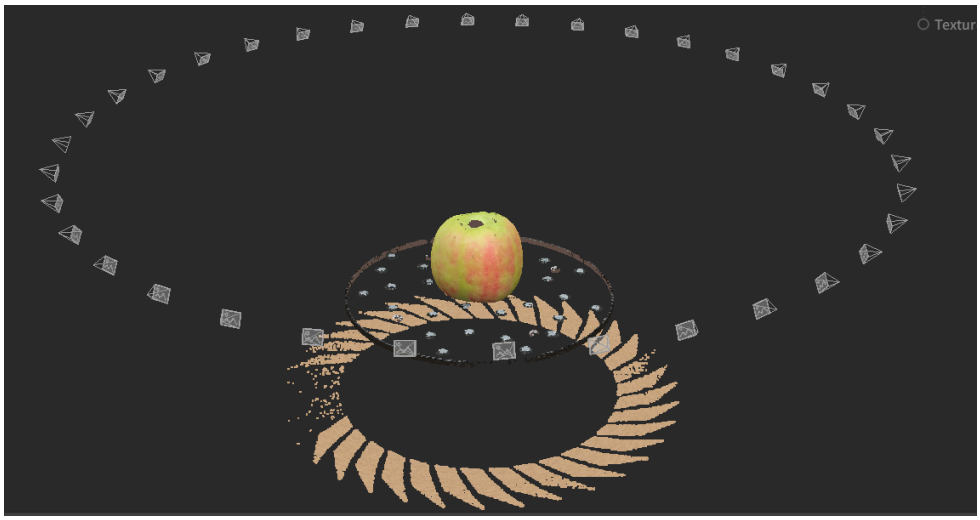


Figure 2. Revo Scan's one complete scan of an apple.

2. Initial scan processing in Revo Scan. After acquisition, each scan was processed individually in Revo Scan. The raw scan was first fused using a point distance of 0.1 mm. A high-quality mesh was then generated using a 0.02 mm grid size, followed by applying the captured color texture image to the mesh. This processing was performed separately for both apple orientations before the scans were subsequently aligned and merged.
3. Exported per pass: the raw preview cloud (68 k to 86 k points in millimeters, each with position, surface normal, and RGB color), the full fused cloud (about 3 million points), a fused mesh with vertex colors, and Revo Scan's screenshot of the pass (Figure 2). The turntable disc and its registration markers are still in the frame of every export.
4. Scan session folder: Lodi_apple_scan_29_09_2026 (29 September 2026); working copies under DATASET/apple_scan/lodi_apples_raw/day_1 and day_2.

Data processing

All processing is done with our own Python code (appletex/cloud.py, run by scripts/cloud_to_spherical.py). The central idea is to work in a spherical coordinate frame: an apple is star-shaped around its stem-calyx axis, so every ray from the center hits the skin exactly once, and the whole fruit can be stored as two flat images over (θ, φ), one for radius (shape) and one for color (texture). Every apple then lands on the same 512 × 256 grid, making apples comparable pixel by pixel and the equirectangular image a ready-made UV texture for the final mesh.

Steps per apple

1. Segmentation: A RANSAC plane fit finds the turntable; points more than 4 mm above it and within 60 mm of the robust center are kept. Grey marker fragments are removed by saturation.

2. Per-pass de-lighting: The scanner's lamp is fixed to its sensor, so the shading on a pass depends only on the surface normal. A second-order spherical-harmonics fit of the Lab color against the normals is subtracted, removing the shading gradient while preserving the real red and yellow of the skin.
3. Registration: The passes are aligned to each other by multi-start point-to-plane ICP followed by colored ICP; a radial outlier filter removes stray points after alignment.
4. Stem-calyx axis: Found by a simple search: the direction whose two poles show the deepest dips in radius. The turntable normal is not the axis, because the apples lie on their side.
5. Spherical maps: Each pass is binned into a 512 × 256 (θ, φ) grid of median radius, mean color, mean normal, and point count.
6. Texture steps: (a) Seam leveling: a smooth per-pass Lab correction is estimated in the overlap so that the passes agree, then the maps are blended with a feathered seam. (b) Hole filling: pixels with no pass saw (stem cavity floor, resting patch) are filled by wrap-aware normalized convolution, and the filled pixels are marked. (c) For the texture library, a final Telea inpainting removes small dark flecks left by marker fragments; the resulting texture set is shown in Figure 4.
7. Mesh: The filled radius map is turned into a mesh on the equirectangular grid (131 k vertices) with UV = (φ / 2π, 1 − θ / π); the filled color map is its texture (Figure 3). Output per apple: OBJ + MTL + PNG, plus the radius, normal, and count arrays and a report image.



Figure 3. Extracted texture of apple_23 (left; stem at the top, calyx at the bottom, azimuth left to right) and the same map wrapped back onto the apple's own mesh, rendered without shading so only the extracted colours are visible.

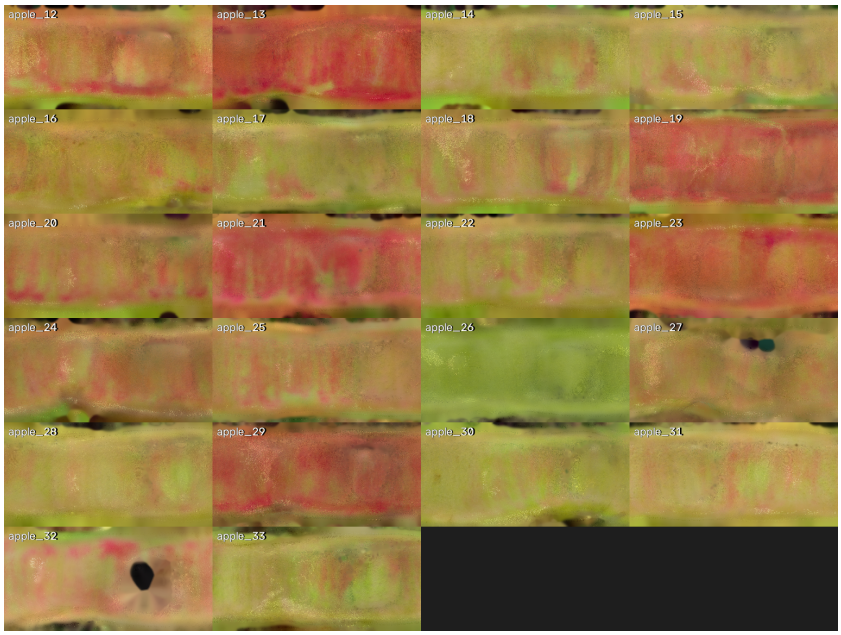


Figure 4. The extracted textures of the day-2 set. The black patches mean that overlap was not good enough

Apples on a Helios tree

Both the scanned and the generated apples load into Helios as textured OBJ files at true scale. A library apple tree (PlantArchitecture, age 1080 days, 3.5 m tall, about 3,400 leaves) had all 85 of its fruit replaced by generated apples, each with a random azimuth and a small random tilt (Figure 5a). A low-polygon version of the apples (9,216 triangles each) keeps the tree renderable; the scanned skin texture survives at full resolution (Figure 5b). A fly-in video and 17 high-resolution stills were produced.



(a) (b)

Figure 5. (a) The Helios apple tree with 85 generated apples. (b) Close view of the same tree: the generated apples keep the scanned skin texture at full resolution.

Tree Scans

On the morning of 29 September 2026 we drove to Lodi Farms in Lodi, California (38.0768° N, 121.1806° W), an apple block of three rows with twelve trees each. Most trees are the farm's main variety, noted as Lady Pink (LP) in our field sheet, with two green-fruited trees and one crab apple in the first row. From 08:45 to 12:55, we walked the rows with a RIEGL VZ-1000 terrestrial laser scanner on a tripod mounted on a cart (Figure 6), recording 66 scan positions along and between the rows so that every tree was captured from several sides, each scan sweeping a full circle at a 0.06° step.



Figure 6. Scanning the orchard using the RIEGL VZ-1000 on a tripod mounted on a garden cart with its battery, pushed along the row between the trees.

The 66 laser scans are individual point clouds, each in its own scanner frame, with ground, neighboring trees, the cart, and the ground cover mixed in with the tree we want. We plan to use the Phytograph software for post-processing. Phytograph is a desktop application for processing terrestrial laser scans of plants: it reads the RIEGL .rxp files directly, registers the scans of a tree to each other without targets (Auto-Register Clouds), lets us crop a box around one tree, stitches the cropped scans into a single cloud, and separates wood from leaves with its Segment Wood / Leaf tool.

Fitting the Tree Model to LiDAR Scans

To make simulated trees structurally realistic, we fit the Helios plant architecture model to laser scans of real trees. Apple scans suitable for this are not yet available, so we first developed the process on existing LiDAR scans of seven-year-old almond trees of three varieties (Nonpareil, Aldrich and Independence; four trees each). Phytograph converted each scan into a 3D model of the tree’s woody structure. We then calibrated each variety’s growth parameters by comparing groups of simulated trees against the scanned trees on measures such as height, crown size, trunk diameter, and branching.

The fitted model can generate any number of new, unique trees that resemble a given variety rather than copy a scanned tree (Figure 7). Averaged by variety, simulated tree height was within 10% of the

scanned trees and crown radius within about 15%. Fine branching and some crown-shape details still differ and continue to be refined.

This fitting has not yet been done for apple. Leaves hide much of the branch structure in the 29 September scans, so we will collect leaf-off scans this winter and then apply the same process to fit the apple model.

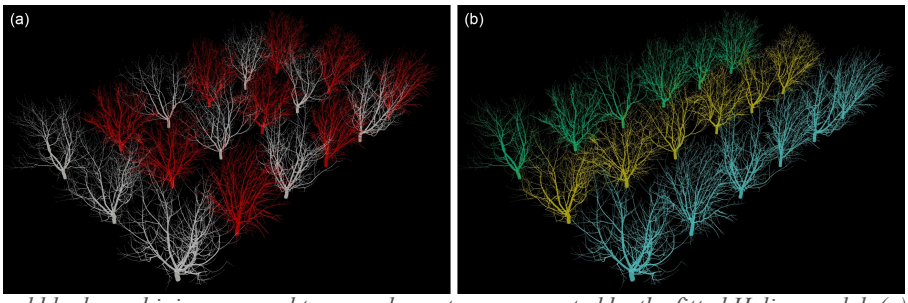


Figure 7. Almond block combining scanned trees and new trees generated by the fitted Helios model. (a) Scanned trees in red and Helios generated trees in white. (b) The same trees colored by variety: Aldrich (blue), Nonpareil (gold) and Independence (green).

Physics Simulation of Trees for Robotics

Robot arms and cameras moving through a canopy can push branches and leaves aside, which may change what the cameras see. To allow this to be simulated, we connected Helios to two physics simulators widely used in robotics.

Isaac Sim: The current version of Helios can export any plant architecture model to Isaac Sim (supported by NVIDIA), with branches, leaves, and fruit that move in response to physical forces. We verified this by moving a solid object through the crown of a simulated apple tree. The branches bent out of the box's path and returned to position after it passed (Figure 8a).

MuJoCo: We also demonstrated a prototype Helios plug-in that runs the open-source MuJoCo physics engine (supported by Google DeepMind) directly within Helios, and repeated the same test (Figure 8b). This plug-in is not yet part of the main Helios release.

These tests show that Helios trees work in both simulators. We have not yet tested them with a robot model, and branch stiffness and fruit weight have not yet been calibrated to measurements of real apple trees.



Figure 8. A simulated Helios apple tree responding as a solid box moves through its crown, (a) in NVIDIA Isaac Sim and (b) in MuJoCo running inside Helios. Frames are in time order from left to right.

Synthetic Image Generation

Helios can generate simulated camera images of the virtual orchard, which will be the visual perception component of the simulator used to train the robotic harvesting models. Because every object in the scene is known, each simulated RGB image comes with an exact instance segmentation mask of every apple, outlining the visible part of each fruit without any manual labeling (Figure 9a). Helios can also simulate images in other wavebands, such as near-infrared (NIR; Figure 9b).

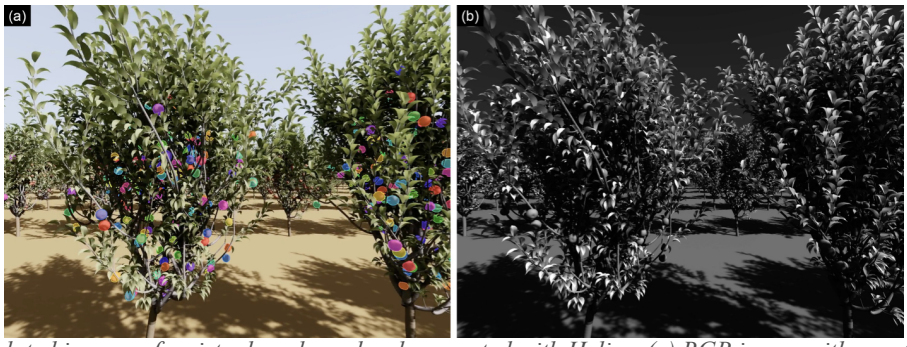


Figure 9. Simulated images of a virtual apple orchard generated with Helios. (a) RGB image with exact instance segmentation masks of the apples, each apple shown in a different color. (b) NIR image.

OBJECTIVE 2. Develop a Multi-Camera Active Vision System

A literature review has begun to collect articles on active vision methods for plant sensing. All articles found so far in the agricultural domain use a single camera. However, researchers have proposed and are investigating multi-camera approaches in the manufacturing domain. The comprehensive literature review will be continued in the following 2-3 months.

Work has also started on building a two-degree-of-freedom pan-and-tilt mechanism that will carry a camera at the tip of a linear arm. Once the design is validated, we will build and install two more pan-and-tilt mechanisms on the multi-arm robot shown in the figure below.

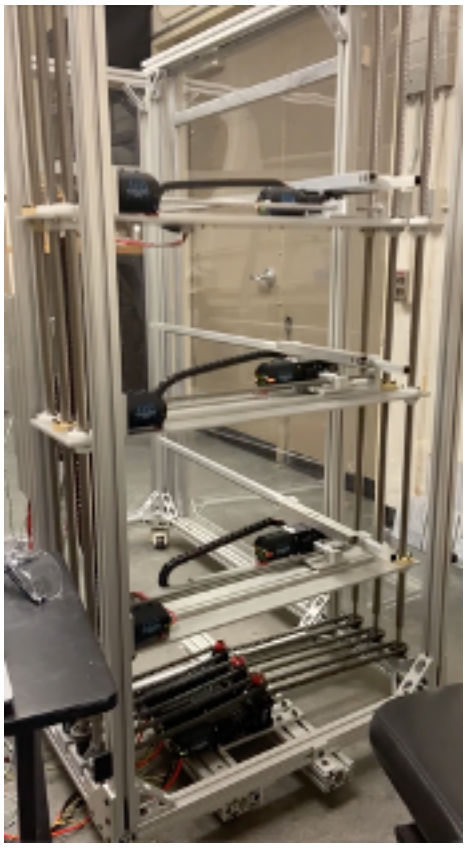


Figure 7. A multi-arm robot that will be used for experiments in active vision. A camera will be attached to a pan-and-tilt mechanism at the end of each linear arm.

Literature Review

Bailey, B.N., 2019. Helios: A scalable 3D plant and environmental biophysical modeling framework. *Frontiers in Plant Science*, *10*, p.1185.

Burusa, A. K., van Henten, E. J., & Kootstra, G. (2024). Attention-driven next-best-view planning for efficient reconstruction of plants and targeted plant parts. Biosystems Engineering, 246, 248-262.

Burusa, A. K., Scholten, J., Wang, X., Rapado-Rincón, D., van Henten, E. J., & Kootstra, G. (2024). Semantics-aware next-best-view planning for efficient search and detection of task-relevant plant parts. Biosystems Engineering, 248, 1-14.

Cañadas-Aránega, F., Border, R., Moreno, J. C., & Blanco-Claraco, J. L. (2026). Active perception for robotic harvesting: 3D reconstruction and localisation of tomatoes hidden within clusters in a Mediterranean greenhouse. arXiv preprint arXiv:2609.18738.

Jose, A. I., Pan, S., Zaenker, T., Menon, R., Houben, S., & Bennewitz, M. (2025, October). Go-vmp: Global optimization for view motion planning in fruit mapping. In 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 1825-1832). IEEE.

Lauri, M., Pajarinen, J., Peters, J., & Frintrop, S. (2020). Multi-sensor next-best-view planning as matroid-constrained submodular maximization. IEEE Robotics and Automation Letters, 5(4), 5323-5330.

Lei, T., Graefe, J., Mayanja, I.K., Earles, M., and Bailey, B.N., 2024. Simulation of Automatically Annotated Visible and Multi-/Hyperspectral Images Using the Helios 3D Plant and Radiative Transfer Modeling Framework. *Plant Phenomics*, *6*, p.0189.

Menon, R., Zaenker, T., Dengler, N., & Bennewitz, M. (2023, October). Nbv-sc: Next best view planning based on shape completion for fruit mapping and reconstruction. In 2023 IEEE/RSJ international conference on intelligent robots and systems (IROS) (pp. 4197-4203). IEEE.

Sun, T., Zhang, W., Gao, X., Zhang, W., Li, N., & Miao, Z. (2024). Efficient occlusion avoidance based on active deep sensing for harvesting robots. Computers and Electronics in Agriculture, 225, 109360.

Villacrés, J. and Vougioukas, S., 2024. Assessing a multi-camera system to enhance fruit visibility for robotic harvesting in a V-trellised apple orchard. *Computers and Electronics in Agriculture*, *224*, p.109164.

Wang, X., Burusa, A. K., Rapado-Rincón, D., Versmissen, T. A., van Henten, E. J., & Kootstra, G. (2025). Multiple object tracking with multi-view active vision to effectively find plant nodes in a cluttered tomato greenhouse. Computers and Electronics in Agriculture, 234, 110266.

Zhang, Z., Deng, J., Xie, H., Wang, Y., Gao, X., Tan, Q., & Li, C. (2026). A comprehensive analysis of multi-robot collaborative 3D measurement technologies. Robotics and Computer-Integrated Manufacturing, 100, 103271.

Project Title: AWN Smart Farms: LoRaWAN Platform for Precision Heat Management

Report Type: Continuing Project Report

Primary PI: **Lav Khot**
Organization: Washington State University
Telephone: 509-786-9302
Email: lav.khot@wsu.edu
Address: 24106 N Bunn Rd.,
City/State/Zip: Prosser, WA 99350

Co-PI 2: Bernardita Sallato
Organization: Washington State University
Telephone: 509-789-9205
Email: b.sallato@wsu.edu
Address: 24106 N Bunn Rd.,
City/State/Zip: Prosser, WA 99350

Cooperators: Keith Veselka (NWFM, LLC, Moxee, WA), Garret Henry (Douglas Fruit Co, Pasco, WA), Seth Hayden (Hayden Farms Inc., Pasco, WA), Sean Sahli (Columbia Farm Services), Paul Catchcart (WA Fruit Co, Yakima, WA), Keith Oliver (Olsen Brother Ranches, Inc., Benton City, WA), Sam Godwin (Box Canyon Fruit, LLC, Tonasket, WA), Clay Divis (Zirkle Fruit Company, Okanogon, WA), Allyana Martinez (S Martinez Fruit LLC, Moxee, WA), Mike Burns (Zirkle Fruit Company, Mattawa, WA), Ethan Flory (Gilbert Orchards, Inc., Yakima, WA), Jeff Cleveringa (Columbia Fruit, LLC, Ephrata, WA), Hans Groenke (Bigfork Orchards, Mattawa, WA), Shawn Tweedy (Chiawana Orchards Inc., Yakima, WA), Paul Carter (McDougall & Sons, LLC, Quincy, WA), Jeremy (Stemilt Growers LLC, Mattawa, WA).

Researchers: Srikanth Gorthi (Postdoctoral Research Associate), Horacio Contreras (Smart Farm Engineer), Prasanna Medarametla (Agricultural Research Technologist), Dheeraj Vurukuti (Natural Resource Scientist 2), Sanjita Bhavirisetty (Application System Analyst/Developer).

Project Duration: 3 Year

Total Project Request for Year 1 Funding: $100,025
Total Project Request for Year 2 Funding: $ 69,169
Total Project Request for Year 3 Funding: $78,693

Budget 1
Primary PI: Lav Khot (PIs sub-awards have been done internally at WSU)
Organization Name: Washington State University
Contract Administrator: Hollie Tuttle

Contract administrator email address: mailto:Prosser.grants@wsu.edu **hollie.tuttle@wsu.edu; prosser.grants@wsu.edu**

Salaries	$36,000.00	$37,440.00	$38,938.00
Benefits	$12,636.00	$13,141.00	$13,667.00
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	$41,589.45	$8,788.42	$16,288.42
Travel	$9,800.00	$9,800.00	$9,800.00
Plot Fees			
Miscellaneous			
Total	$100,025.45	$69,169.42	$78,693.42

Footnotes: Year 1. Salaries ($36,000) with benefits ($12,636) are requested for a 6-month postdoc support to deploy LoRaWAN at the testbeds and improve the AWN Smart Farm and CropAI app functionalities. Supplies of $41,590 include LoRaWAN hardware for automating heat stress mitigation of 18 orchard blocks. Travel costs include Khot and Sallato team member travel from WSU IAREC to 18 site ($0.7/mile). **Year 2.** Salaries ($37,440) with benefits ($13,141) are requested for a 6-month postdoc support to maintain LoRaWAN at the testbeds and improve the AWN Smart Farm and CropAI app functionalities. Travel costs include Khot and Sallato team member travel from WSU IAREC to 18 site ($0.7/mile). **Year 3.** Salaries ($38,938) with benefits ($13,667) are requested for a 6-month postdoc support to maintain LoRaWAN at the testbeds and improve the AWN Smart Farm and CropAI app functionalities. Travel costs include Khot and Sallato team member travel from WSU IAREC to 18 site ($0.7/mile). $7,500 is requested for cost-benefit analysis by WSU CAHNRS Economics faculty in collaboration with Sallato and Khot.

Objectives. Project objectives include:

1. Scale AWN Smart Farm Platform to support sensor-driven, block-level precision and automated heat stress management using real-time fruit/canopy temperature data.
2. Enhance the dashboard through grower-informed iterative improvements, including bilingual interface support and the development of user-friendly instructional videos.
3. Advance weather-guided fruit surface temperature modeling by leveraging crowdsourced data from 18+ spatiotemporally distributed orchard blocks across Washington.
4. Cost-benefit analysis of the AWN-Smart Farm platform driven automated heat stress management and extension education.

Significant Findings Y1 (2026)

1. AWN Smart Farms has been successfully piloted on 18 commercial blocks across key apple production regions, each instrumented with a localized private sensing network.
2. Ten of the 18 blocks have been automated for temperature threshold-driven actuation of cooling systems (cultivars: Cosmic Crisp®, Honeycrisp, Gala, Wild Twist, and Fuji).
3. Due to field irrigation system limitations, the remaining nine blocks are instrumented to monitor the efficacy of grower-managed (cyclic on/off) cooling.
4. Based on the grower feedback, the AWN Smart Farms platform interface has been improved to support block-level monitoring and time- and sensor-based valve control.
5. The web platform is now bilingual (English and Spanish) for greater accessibility.
6. Crowdsourced spatiotemporal data from the 18 networks, along with 1,500 grower-collected radiometric thermal-RGB images, have been curated to improve the baseline weather-driven fruit surface temperature (FST) model.
7. Harvest yield and fruit quality data from grower operations are being curated and analyzed.
8. The team has conducted on-site, hands-on training in sensor deployment and maintenance.

Methods and Results Summary

Objective 1. Scale AWN Smart Farm Platform to support sensor-driven, block-level precision and automated heat stress management using real-time fruit/canopy temperature data.

Cooperator recruitment and site selection. During the winter meetings and early spring of 2026, our team presented the AWN Smart Farm automated heat stress mitigation concept to valley-specific grower networks/clubs, WTFRC, and WSTFA. Through this outreach, 18 commercial apple blocks were enrolled (Table 1). The blocks are located in the Columbia Basin (Mattawa, Pasco, Quincy, Ephrata), the Yakima Valley (Moxee, Naches, Benton City), and the Okanogan Valley (Okanogan, Tonasket). Cultivars include Honeycrisp, Cosmic Crisp®, Fuji, Gala, Granny Smith, Envy™, and Wild Twist. Existing heat mitigation practices range from overhead sprinklers and micro-sprinklers to fogging, and fogging combined with shade netting. Some sites do not use evaporative cooling. Each cooperator received a one-page participation guide covering hardware responsibilities, installation, the automation approach (Figure 1), and ground-truthing protocols.

Table 1. List of grower cooperators participating in the deployment of AWN Smart Farms sensors network for apple heat stress monitoring and mitigation across WA State.

Farm/LLC	Location, WA	Cultivar	Mitigation
S Martinez Fruit, LLC	Moxee	Honeycrisp	No Cooling
Zirkle Fruit Company	Okanogan	Honeycrisp	Fogging
Stemilt Growers LLC	Mattawa	Honeycrisp	Overhead Sprinklers
Gilbert Orchards, Inc	Naches	Honeycrisp	Overhead Sprinklers
Douglas Fruit Company	Pasco	Cosmic Crisp®	Fogging
Bigfork Orchards LLC	Mattawa	Grany Smith	Overhead Sprinklers

Farm/LLC	Location, WA	Cultivar	Mitigation
Columbia Fruit LLC	Ephrata	Fuji	Overhead Micro sprinklers
Olsen Brother Ranches Inc	Benton City	Envy™	Overhead Sprinklers
Northwest Farm Management LLC	Moxee	Honeycrisp	No Cooling
Zirkle Fruit Company	Mattawa	Wild Twist	Overhead Micro sprinklers
McDougall & Sons LLC	Quincy	Honeycrisp	Fogging
WA Fruit Co	Benton City	Gala	Overhead Sprinklers
Box Canyon Fruit LLC	Tonasket	Honeycrisp	Overhead Sprinklers
Columbia Farm Services	Mattawa	Cosmic Crisp®	Fogging + Netting
Hayden Farms Inc	Pasco	Honeycrisp	Overhead Sprinklers
Chiawana Orchards LLC	Naches	Fuji	Overhead Sprinklers

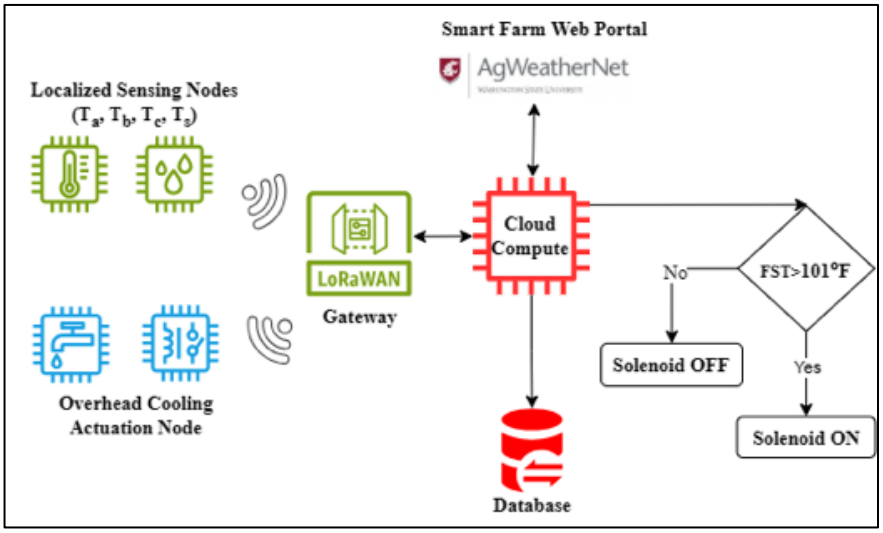


Figure 1. Schematic of the automated heat stress mitigation system integrating real-time, in-field fruit surface temperature (FST) monitoring, cloud-based decision-making, and solenoid valve actuation for precision cooling control.

Network deployment and training. A private LoRaWAN-based wireless sensing network was deployed across all 18 apple orchard blocks (Figure 2). At each site, a LoRaWAN gateway (RAK7289, RAKWireless Inc.) was installed at a suitable location with continuous power supply and internet connectivity, except at four grower sites situated in remote ranch locations where connectivity infrastructure was limited. Ten blocks were configured for temperature threshold-driven automated actuation with cultivars namely Honeycrisp [n = 5 sites], Cosmic Crisp® [3 sites], Gala [1 site], Fuji [1 site], Wild twist [1 site]. In these automated cooling blocks, two thermistors (ST-200, Apogee Instruments Inc.) were installed to continuously monitor apple FST, and an air temperature and relative humidity probe (ATMOS-14, Meter Group Inc.) was installed to monitor the orchard microclimate. Additionally, infrared thermometers (SPIP-IRT, Dynamax Inc.) were deployed to measure canopy/fruit temperature. These sensors were integrated with LoRaWAN-enabled multi-interface controllers (UC501, Milesight IoT) for real-time data acquisition and wireless transmission. In addition to microclimate monitoring, soil moisture sensors were installed at selected sites (per grower participation) to characterize soil water availability. Water flow meters (SW3L, Dragino Inc.) and pressure switches (TDPS 4-10 Series, Transducers Direct) were integrated into the cooling systems to monitor water consumption and verify valve actuation, respectively. To evaluate water-use efficiency and quantify potential water savings associated with automated cooling, an additional comparison block equipped with an equivalent cooling system was instrumented with a water flow meter to enable comparative assessment of water consumption. Across the deployed networks, packet delivery rates exceeded 90% at a five-minute data acquisition interval during the monitoring period

beginning in June 2026. Continuous monitoring, sensor maintenance, and data collection remain ongoing to support long-term assessment of network reliability, communication performance, and scalability across geographically distributed orchard environments.



Figure 2. Field deployment of sensors (e.g., Dynamax IRT, thermistor insert into fruit, temp/RH [Left image]) and LoRaWAN gateway [right image] to realize private sensing networks for effective heat stress management in apple orchards.

For the automated cooling blocks (n = 10), LoRaWAN-enabled solenoid valve controllers (UC511, Milesight) were integrated with existing solenoid valves installed on the cooling system control lines. These controllers were connected to a cloud-based analytics engine that continuously evaluated heat stress conditions using real-time apple FST measurements and grower-defined temperature thresholds to automatically initiate or terminate cooling events. To ensure operational reliability, a fallback control strategy was implemented using canopy or air temperature measurements when FST data were unavailable or unreliable, thereby maintaining cooling functionality during sensor or communication failures.

The remaining eight blocks were operated under grower-managed cooling schedules, as automation was constrained by existing irrigation infrastructure limitations, including the absence of variable frequency drive (VFD) pumps, shared irrigation mainlines, and restricted water availability. At these sites, the same wireless sensing network was deployed without solenoid valve controllers to continuously monitor FST, canopy temperature, and ambient microclimatic conditions during conventional grower-defined cyclic ON/OFF cooling operations. This deployment strategy enabled consistent environmental monitoring across both automated and non-automated blocks, providing a common sensor-based framework for evaluating differences in cooling effectiveness, temperature dynamics, and operational practices across diverse cultivars and irrigation system configurations.

Fruit thermal exposure and cooling efficiency (preliminary) analysis. Spatial distribution of LoRaWAN-based wireless sensing networks deployed for monitoring and automated heat stress management across Washington State, including the Yakima, Wenatchee, and Okanogan valleys and Columbia Basin is shown in figure 3. Orchard blocks are categorized by three cooling strategies:

continuous cooling (fogging), cyclic cooling (overhead sprinklers), and no cooling. Percentages displayed within the markers represent the proportion of duration with fruit surface temperature exceeded 90°F between 11:00 AM and 7:00 PM for 2026 summer season. Higher percentages indicate greater exposure of fruit to elevated temperatures and potentially increased sunburn risk.

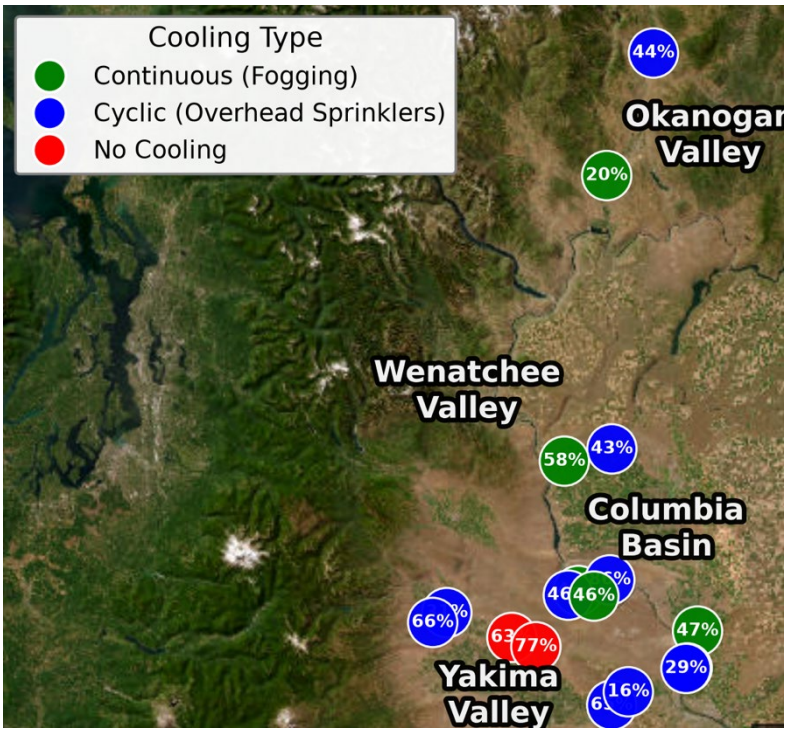


Figure 3. Statewide distribution of LoRaWAN-based wireless sensing networks and fruit surface temperature exposure.

Figure 4 represents mean FST exceedance percentage across orchard blocks implementing continuous cooling (fogging), cyclic cooling (overhead sprinklers), and no cooling. This FST exposure was quantified as the percentage of valid 15-minute monitoring intervals during which FST exceeded 90°F under ambient air temperatures ≥85°F, between 11:00 AM and 7:00 PM in July 2026. The ambient air temperature threshold was used to facilitate comparisons across geographically distributed orchards experiencing different climatic conditions. Values represent the means of block-level exceedance percentages within each cooling category, with higher percentages indicating greater exposure to elevated fruit temperatures. Overall, fogging seems to be effective, followed by cycling cooling across the regions. Fruit quality and packouts can shed more light on this and will be reported in Y2.

Objective 2. Enhance the dashboard through grower-informed iterative improvements, including bilingual interface support and the development of user-friendly instructional videos. Grower cooperators gave us extensive feedback during the installation and maintenance visits throughout the season. Based on the feedback, AWN team has developed and modified the AWN Smart Farms interface with block-level monitoring of sensors and valve actuations (Figures 5 and 6). Valve control now supports both time-based scheduling and sensor-based thresholds. The full web platform is now available in English and Spanish, so bilingual farm crews can view data and manage alerts directly.

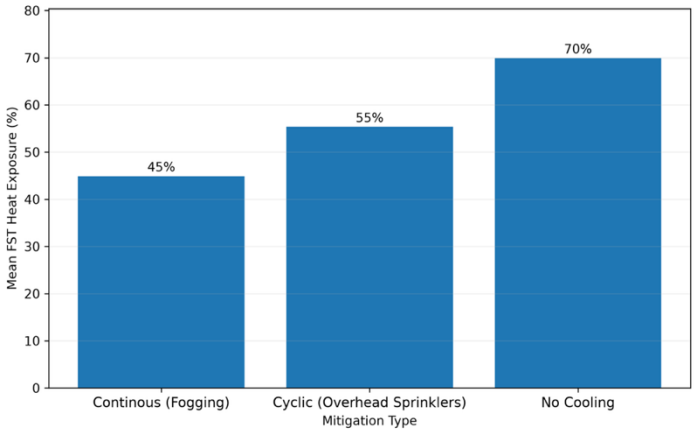


Figure 4. Comparison of mean fruit surface temperature (FST) heat exposure across multiple cooling strategies evaluated across the State of Washington (WA) for July 2026, using LoRaWAN-based wireless sensing network.

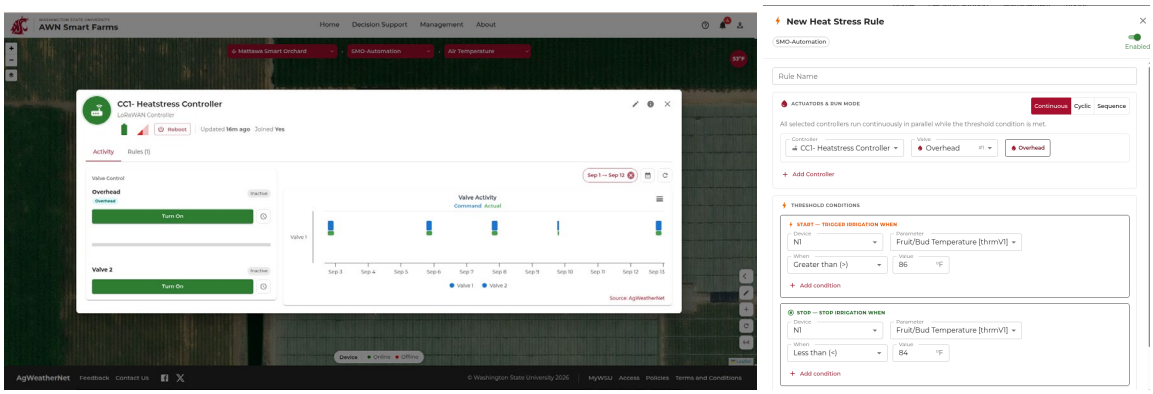


Figure 5. AWN Smart Farms web platform with insert pop-up showing irrigation controller scheduling interface for growers to decide temperature-threshold based controller actuation.

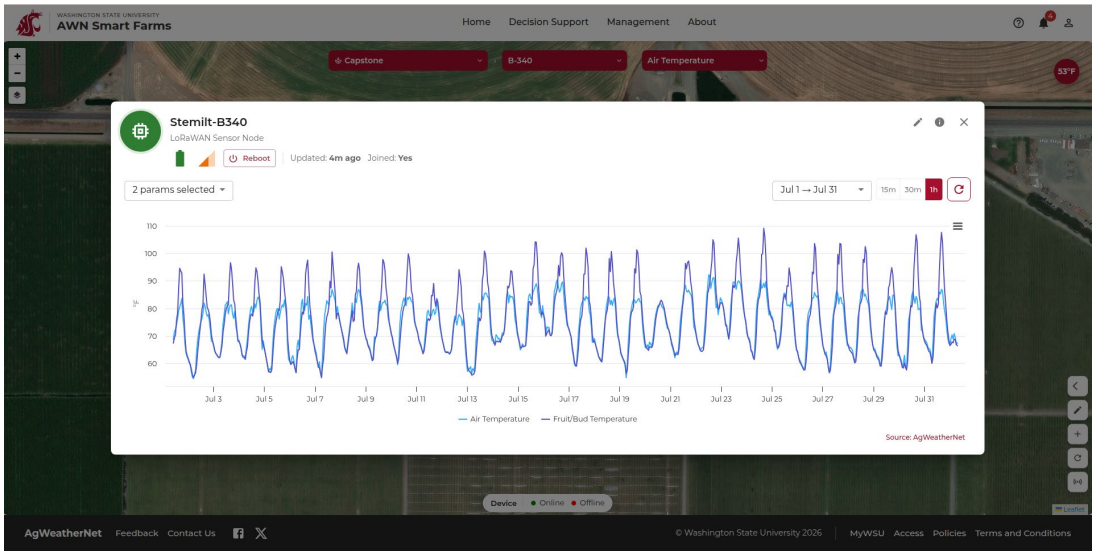


Figure 6. Web platform functionality showcasing hindcast monitoring of air and fruit temperature for growers to understand if heat stress mitigation was effective.

Objective 3. Advance weather-guided fruit surface temperature modeling by leveraging crowdsourced data from 18+ spatiotemporally distributed orchard blocks across Washington. *Ground-truthing and data curation.* Besides the spatiotemporal FST data at 5-min resolution from these 18 sites, cooperators collected thermal-RGB ground truth with the AWN CropAI app, following the SOP to collect imagery. The imagery data was collected on days with air temperature above 80 °F and between 11 am and 5 pm. By season end, cooperators had uploaded 1,500 radiometric thermal-RGB images. These images have been quality-screened and paired with concurrent thermistor, IRT, and weather data from the 18 networks. The combined dataset has been curated to re-train and validate the baseline weather-driven FST model.

Evaluation (in progress). Cooling water use is being quantified from flow meter records at the automated blocks and from estimated run times at the grower-managed blocks. Harvest yield and fruit quality data, including sunburn incidence and severity, color, and packout, are being collected from cooperator operations. This data will be used to compare automated and grower-managed cooling and will feed into the cost-benefit analysis under Objective 4.

Objective 4. Cost-benefit analysis of the AWN-Smart Farm platform driven automated heat stress management and extension education.

Extension Outreach. In early 2026, the team presented the AWN Smart Farm heat stress mitigation concept at regional grower club meetings. Cooperators received a participation guide and hands-on, on-site training in sensor deployment, maintenance, and CropAI imaging, delivered in English and Spanish. Year 1 efforts were shared during the 2026 Virtual International Orchard Meetup (June 25, 2026) and demonstrated at the annual Smart Orchard Field Day 2026 (attended by over 230 participants), and the WA State Fair 2026. Progress on this topic will be shared as a flash talk in 2026 WSTFA annual meeting and NW Hort Expo.

Cost-benefit analysis. Data is being collected, curated, and team has nothing to report on cost-benefit aspect in Y1.

Proposal Title: Robotic renewal pruning of fruit tree orchards
Report Type: Interim Report

Primary PI: Wei Guo
Organization: The University of Tokyo
Telephone: +81-80-3520-1527
Email: guowei@g.ecc.u-tokyo.ac.jp
Address: 1-1-1 Midoricho
City/State/Zip: Nishi-Tokyo city, Tokyo, Japan

Co-PI 2: Joseph Davidson
Organization: Oregon State University
Telephone: 541-737-9193
Email: joseph.davidson@oregonstate.edu
Address: 204 Rogers Hall
Address 2: 200 SW Monroe Avenue
City/State/Zip: Corvallis, OR 97331

Co-PI 3: James Burridge
Organization: The University of Tokyo
Telephone: +81-70-6442-9514
Email: burridge-j@g.ecc.u-tokyo.ac.jp
Address: 1-1-1 Midoricho
City/State/Zip: Nishi-Tokyo city, Tokyo, Japan

Cooperators: Dave Allan, Allan Bros. Fruit Co.; Olsen Brothers Ranches, Inc.; Dr. Matt Whiting, Washington State University

Project Duration: 3 years

Total Project Request for Year 1 Funding: $100,000
Total Project Request for Year 2 Funding: $100,000
Total Project Request for Year 3 Funding: $100,000

Other related/associated funding sources: None
WTFRC Collaborative Costs: None

Budget 1
Primary PI: Wei Guo
Organization Name: The University of Tokyo
Contract Administrator: Ryuzo ARITA
Telephone: 0081-03-5841-5032
Contract administrator email address: arita.ryuzo@mail.u-tokyo.ac.jp

Item	2024	2025	2026
Salaries	$43,900	$43,900	$43,900
Benefits			

Wages			
RCA Room Rental			
Shipping			
Supplies	$9,700	$16,100	$6,500
Travel	$6,400	$3,200	$9,600
Plot Fees			
Miscellaneous			
Total	$60,000	$60,000	$60,000

Footnotes:

[1]UTokyo salary costs are based on 30% of the current salary standard for two senior researchers and 50% for two junior researchers.

[2]The travel budget supports flight and lodging for data collection and field experiments. The calculation of travel costs is based on UTokyo standards. The budget covers two person trips in 2024, one trip in 2025 and three person trips in 2026 from the UTokyo team. If necessary, the UTokyo team will leverage funds to support two additional trips per year.

[3]Supplies include consumables such as fittings for hardware, electronics, stock materials and off-the-shelf sensors.

[4]In the Japanese academic system assistant professors, such as James Burridge and Pieter Blok, are subordinates of the Associate professor, Wei Guo, and do not have independent budgets.

Budget 2
Co-PI 2: 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	2024	2025	2026

Salaries	$17,715	$25,567	$26,334
Benefits	$5,968	$9,297	$10,103
Wages			
RCA Room Rental			
Shipping			
Supplies	$14,393	$3,154	$1,522
Travel	$1,925	$1,983	$2,042
Plot Fees			
Miscellaneous			
Total	$40,000	$40,000	$40,000

Footnotes:

[1]Salaries include a Graduate Research Assistant on a 6-month, 0.40 FTE appointment in year 1 and a 9-month, 0.40 FTE appointment in years 2-3 (no tuition). Salaries also include 0.25 months per year for Dr. Joe Davidson.

[2]Supplies includes an $11,500 allotment in year 1 to cover 50% of the purchase price of a Farm-NG ground robot (the remaining 50% will be provided by other sources). The remaining supplies budget includes actuators and consumables such as fittings, raw stock, and off-the-shelf sensors.

[3]Travel budget is requested to support mileage and lodging for data collection and field experiments in Prosser, Washington (for 2 travelers each year of the project).

Objectives

Pruning is a laborious operation required to maintain fruit yield and quality and to keep the orchard healthy. In addition to being labor intensive, pruning requires a certain amount of expertise and training, further complicating matters for labor-limited orchard managers. Currently, there are no commercially available robotic pruners. Two major challenges for automated pruning is hardware and training environments Our goal is to develop a prototype robotic pruner that will accomplish simpler tasks in dormant season renewal

pruning in UFO cherry and bi-axe Cosmic Crisp. We will also develop a segmentation and annotation tool that will catalyze robotic training capabilities at the community level.

In the first year of research we evaluated several LiDAR scanning products in Washington and Japanese orchards. In year two we focused on 1) robot development and navigation and 2) collecting LiDAR data using two platforms in multiple orchards before and after pruning and 3) began work on a object segmentation pipeline. In year three we focused building a branch deformation model, planning pruning point approach paths, publishing the segmentation tool so that other researchers can contribute datasets and addressing difficult object segmentation cases.

To reiterate, our overall objective remains to develop and test an autonomous robot that can perform dormant season renewal pruning. We have divided this into 3 sub-objectives.

1. Collect data from fruit tree orchards in Washington State and optimize data processing pipeline
2. Develop algorithms to determine renewal cut locations for the robotic pruner
3. Develop, deploy and evaluate a first robotic pruner prototype in Washington apple and cherry orchards

Significant Findings

1. Collected real orchard data using handheld LiDAR platforms.
2. Published semi-automatic annotation tool to segment support posts, trellis wires and individual trees.
3. Developed deformable tree model.
4. Testing methods for the robot arm to approach pruning points.

Methods

1. *Orchard scanning, data extraction,* post-processing, segmentation
2. *Machine learning of pruning points* using pre and post pruning scans
3. *Robotic arm path planning* and training in virtual environment

Results and discussion

Major accomplishments: deformable tree model, pruning point approach, instance aware scene decomposition pipeline.

OSU

Over the past year the OSU team has made substantial progress on the development of deformable, digital tree models. A typical model of woody trees, shrubs, etc. considers all branches to be completely rigid and fixed, and thus algorithms used to train pruning robots in simulated environments avoid colliding with the plant's structure during task execution. However, this assumption of rigidity is overly restrictive and prevents the robot from performing any task in which a branch would have to be moved out of the way to aid task completion. We posit that physics simulations for robotic pruning should not just look visually realistic, they should also accurately represent force-displacement behavior as the robot physically interacts with a limb.

Leveraging parallel work on digital plant models funded by the USDA AI Institute for Transforming Workforce and Decision Support (AgAID), we have constructed pseudo-rigid body models of trees in MuJoCo, an open-source physics engine developed for robotics. Each tree is discretized into connected chains of cylindrical rigid bodies connected by spring-loaded joints. The architecture of the tree is 'grown' using L-Py systems. We can currently create models of dormant UFO and V-trellis systems; Figure 1(*left*) shows a MuJoCo visualization of an example UFO tree. To set the mechanical properties of the simulated plants (e.g. limb compliance), we have been performing materials testing of limbs on a materials testing machine (Figure 1(*right*)).

These simulated tree models designed for training pruning robots will only be useful if they are physically realistic. We recently validated our methodology in blueberries, which have simpler limb structures with fewer major branching junctions compared to trees, via in-field measurements with a physical robot. The results were promising and demonstrate that the simulation provides reasonable physics, meaning forces and displacements from robot-limb interaction in the simulation were similar to what was measured in the real world. We will extend our approach to trees during the upcoming year of the project.

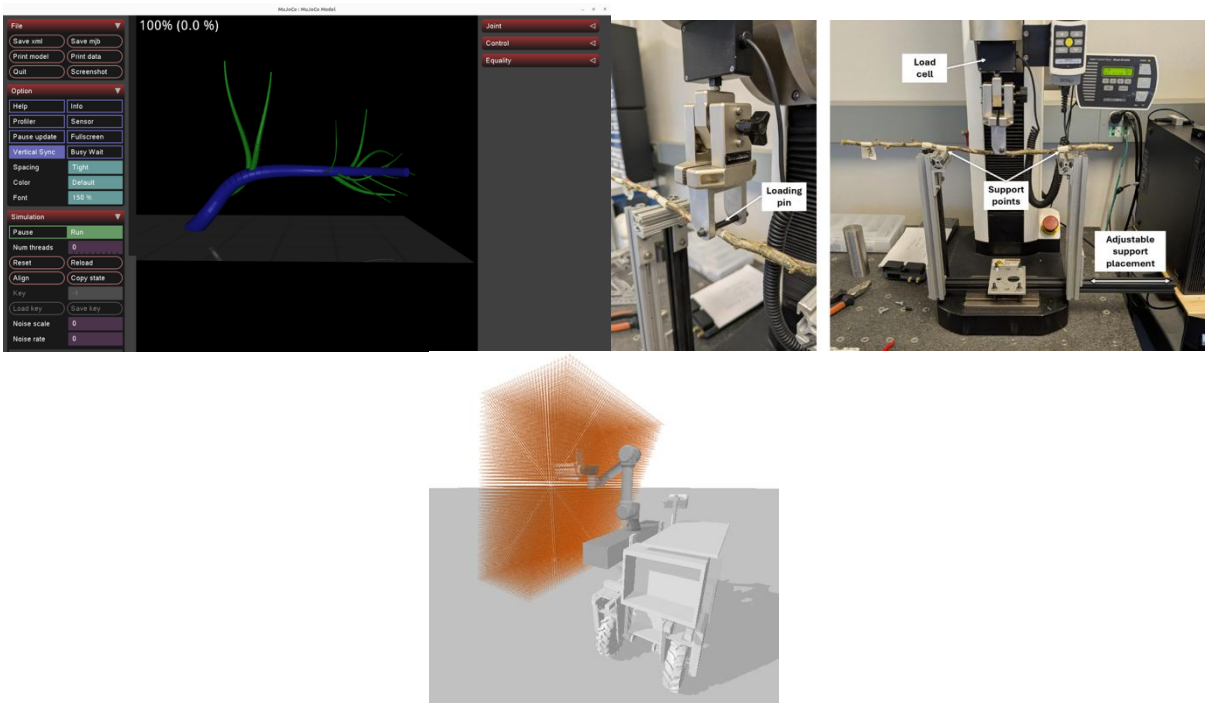


Figure 1. MuJoCo visualization of pseudo-rigid body model of UFO tree (left), materials testing of limbs (middle and right) and using apriori knowledge to plan for pruning point approach (bottom).

The OSU team also continued to develop the software for its physical robot, focusing on a pre-computed 'lookup table' for all *possible* reachable pruning points in the canopy. Planning a safe motion from scratch for every cut takes time. However, the robotic arm always works from the same spot on its vehicle, with the same canopy zone in front of it. Our approach is to use this *a priori* knowledge to plan ahead - we discretize the reachable canopy space (Figure 2) and compute the best motion to each individual cell before the robot ever reaches the orchard. Every stored motion keeps the arm from hitting itself or its vehicle, and favors poses where the arm is most nimble / dexterous. When pruning in the orchard, the robot simply looks up the motion for its target. The end-result is that since no online planning is required, selecting a motion takes a fraction of a second while planning ahead produces human-like movement.

UTokyo

Publication of semi-automatic segmentation workflow: A publication describing the segmentation workflow was re-submitted to the top tier journal CompAg after two demanding revisions. The title is *From 3D Gaussian Splatting to Simulation-Ready Orchard Digital Twins: An Instance-Aware Scene Decomposition Pipeline* and the core contribution is the ability to segment an orchard scene into components such as support post, trellis wires and individual trees. This will enable robots to learn to navigate and execute tasks such as pruning. We now expect acceptance and plan to publicize the workflow, as well as an online repository so new users can contribute annotated datasets.



Figure 2. From left to right; visualization of the bi-level closed-loop scanning trajectory designed for complete spatial coverage of the UFO architecture, instance-isolated meshing preserves actual physical gaps, successful simulation with accurate representation of path allowing collision avoidance and instance level manipulation.

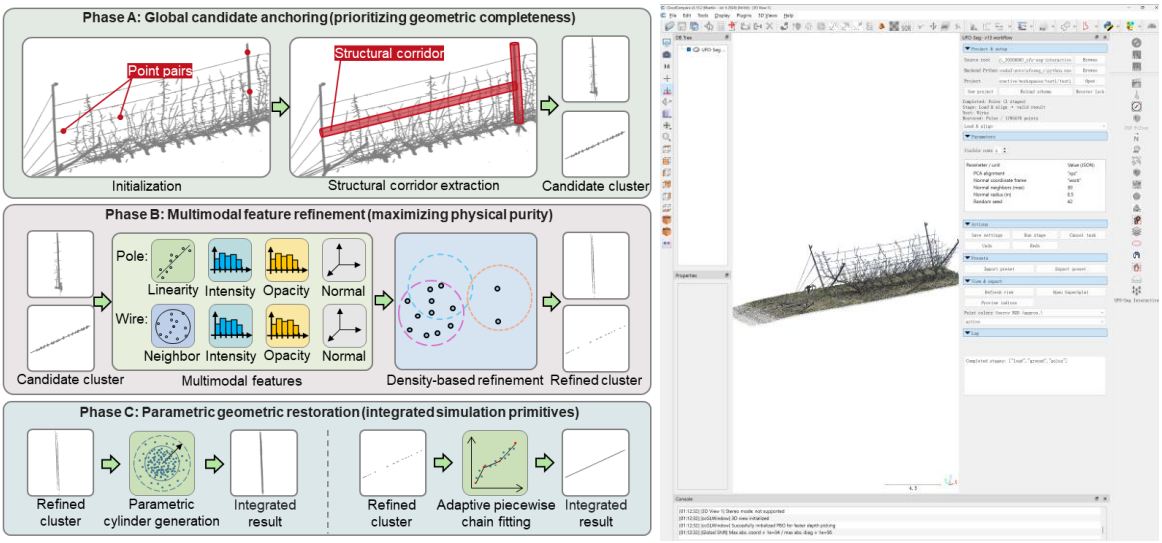


Figure 3. Left; workflow of the instance aware scene decomposition pipeline. Right; the pipeline running on the recently developed CloudCompare plugin.

Recent semi-automatic segmentation progress: The entire workflow now runs through a convenient CloudCompare plugin, and provides a single interface to run components, adjust parameters and inspect intermediate results. There are several improvements over the previous version including; in-browser access to 3DGS rendering, ability to repeat processing stages (i.e. for a new row in the same orchard) without starting a new project and a tool to correct tree assignments.

2026 orchard data: 3DGS reconstruction and visual inspection of the results have been completed for all scans. The instance aware segmentation workflow is being run on all datasets and performance on non-UFO orchards will be examined closely and appropriate adjustments to the workflow will be made.

Tasks for no-cost-extension period

Test robotic pruning point approach and cut execution in simulation and real environments. Now that OSU has developed a means to use *a priori* knowledge to simplify pruning point approach and UTokyo has developed the means to prepare simulation ready environments, training a robot to approach a pruning point and execute a cut should be more accessible.

Improve the segmentation workflow's performance in difficult cases (heavy overlap of structure, wires and trees) and include a streamlined tool for interactive manual corrections when necessary. We will continue testing on diverse US and Japanese orchards to promote generalizability.

Resolve the branch deformation pre/post pruning issue, in other words, branches that change position due to pruning or training pose a classification challenge for the existing pipeline (Figure 4). We are exploring

if this can be solved by extracting precisely aligned pre and post scan branch centerlines and topology then matching by length, topology and insertion point.

Continue developing robotic dog capacity. A custom LiDAR and onboard computer mount for a robotic dog was constructed and now the dog can perform repeat scanning along a taught route, which required solving issues related to navigation, velocity and wireless control in the field. Capacity to scan at multiple heights will be developed using a robotic arm (reBot Arm B601-DM).

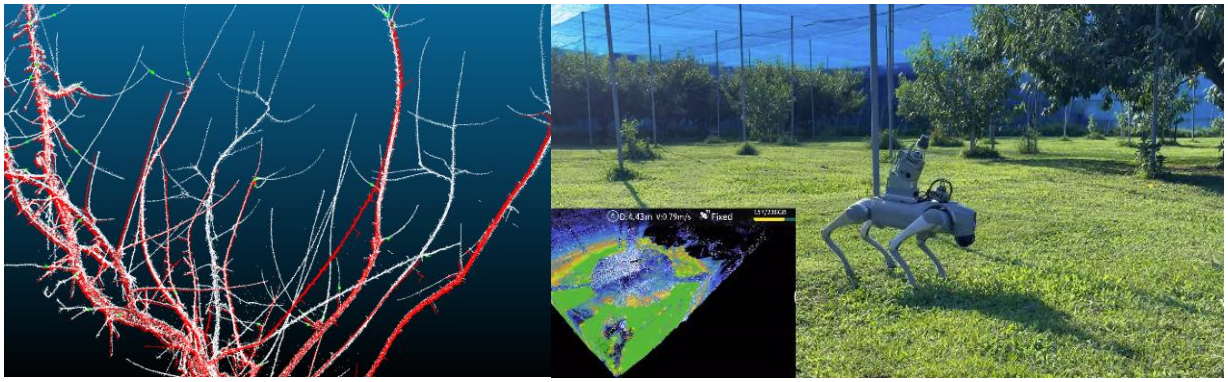


Figure 4. Left; example of problematic branch deformation in pre (white) and post (red) scans. Right; a robotic dog mounted with LiDAR scanner performing a scan along a taught route at the UTokyo orchard.

Literature review

The usefulness of a simulation environment depends largely on the quality of its scene representation. Traditional representations, such as photogrammetric meshes or raw point clouds, often struggle to reconstruct the thin, complex geometry of orchard vegetation, resulting in broken topology or sparse representations that degrade simulation realism (Mhamed et al., 2024). Recently, 3D Gaussian Splatting (3DGS) (Kerbl et al., 2023) has emerged as an effective approach to scene reconstruction.

In modern trellised orchards, artificial support structures, mainly rigid poles and deformable trellis wires, are essential for shaping and maintaining the structure of fruit trees. During autonomous robotic operations, these elements are obstacles that must be identified for safe collision avoidance and accurate pruning (Li et al., 2023; Bhattarai et al., 2024).

Existing research largely relies on supervised deep learning frameworks for this extraction. For instance, Tong et al. (2023) and Williams et al. (2023) used fully annotated RGB and RGB-D datasets to isolate trellis wires using segmentation models. Similarly, You et al. (2023) and Kok et al. (2025) reduced the manual annotation burden by synthesizing orchard images to train instance segmentation networks. However, these data-driven approaches are limited by annotation cost and often generalize poorly across orchard layouts. In practice, they frequently require manual intervention during field trials, such as pre-pruning branches to avoid collisions with undetected wires (You et al., 2023). In high-density systems such as the UFO architecture, branches and artificial supports are often closely intertwined, creating complex occlusions in which purely geometric or visual approaches fail. These conditions call for a multimodal method that isolates heavily occluded supports without deep-learning training data and reconstructs them as simulation primitives directly from their rendering and geometric attributes.

Individual tree segmentation is a prerequisite for generating interactive tree instances within a digital environment. With the advancement of deep learning, supervised models have demonstrated high accuracy in disentangling point clouds of broadleaf plantations or dormant cherry trees (Borrenpohl and Karkee, 2023; Liu et al., 2023). However, building sufficiently large, high-quality annotated 3D datasets for every new orchard architecture is labor-intensive. In addition, Sun et al. (2025) noted that even supervised

networks often fail to separate overlapping canopies in very densely planted scenes and incorrectly merge adjacent trees.

To avoid dependence on training data, unsupervised geometric and spatial clustering methods are widely used (Miao et al., 2023). For example, Münzinger et al. (2022) and Wilkes et al. (2023) used terrain models and graph-based shortest-path algorithms to extract individual canopies. These geometric and distance-based techniques work well where trees are spatially separated but degrade in clustered stands. For instance, Münzinger et al. (2022) reported that branch overlap reduced accuracy from 72% to 31%, and Wilkes et al. (2023) reported failures in which interlaced branches created false connections between trees. Even topology-aware approaches (Qiu et al., 2024a) struggle when artificial supports interrupt spatial continuity. In systems such as the UFO architecture, the vertical branches of adjacent trees overlap extensively, so that the canopies intertwine and clear physical boundaries between trees are largely absent. Separating such canopies requires a topology-guided, biologically inspired segmentation approach that goes beyond Euclidean distance metrics.

Research in this third year has addressed the gap between photorealistic 3DGS orchard reconstruction and simulation-ready digital orchards and brought effective robotic training closer to reality.

Bhattarai, U., et.al. 2024. Design, integration, and field evaluation of a robotic blossom thinning system for tree fruit crops. J. Field Robot. 41, 1366–1385. https://doi.org/10.1002/rob.22330

Borrenpohl, D., Karkee, M., 2023. Automated pruning decisions in dormant sweet cherry canopies using instance segmentation. Comput. Electron. Agric. 207, 107716. https://doi.org/10.1016/j.compag.2023.107716

Kerbl, B., et.al. 3D Gaussian Splatting for Real-Time Radiance Field Rendering. ACM Trans Graph 42, 139:1–139:14. https://doi.org/10.1145/3592433

Li, H., et.al., 2023. Automatic Branch–Leaf Segmentation and Leaf Phenotypic Parameter Estimation of Pear Trees Based on Three-Dimensional Point Clouds. Sensors 23, 4572. https://doi.org/10.3390/s23094572

Liu, Y., et.al. 2023. Study on Individual Tree Segmentation of Different Tree Species Using Different Segmentation Algorithms Based on 3D UAV Data. Forests 14. https://doi.org/10.3390/f14071327

Mhamed, M., et.al. 2024. Advances in apple's automated orchard equipment: A comprehensive research. Comput. Electron. Agric. 221, 108926. https://doi.org/10.1016/j.compag.2024.108926

Miao, Y., et.al. 2023. A single plant segmentation method of maize point cloud based on Euclidean clustering and K-means clustering. Comput. Electron. Agric. 210, 107951. https://doi.org/10.1016/j.compag.2023.107951

Münzinger, M., et.al.., 2022. Mapping the urban forest in detail: From LiDAR point clouds to 3D tree models. Urban For. Urban Green. 74, 127637. https://doi.org/10.1016/j.ufug.2022.127637

Qiu, T., et.al. 2024a. AppleQSM: Geometry-Based 3D Characterization of Apple Tree Architecture in Orchards. Plant Phenomics 6, 0179. https://doi.org/10.34133/plantphenomics.0179

Sun, Z., et.al. 2025. Canopy3D-Net: Semantic segmentation of fruit tree canopies based on 3D point clouds. Smart Agric. Technol. 12, 101673. https://doi.org/10.1016/j.atech.2025.101673

Tong, S., et.al. 2023. An image-based system for locating pruning points in apple trees using instance segmentation and RGB-D images. Biosyst. Eng. 236, 277–286. https://doi.org/10.1016/j.biosystemseng.2023.11.006

Wilkes, P., et.al. 2023. TLS2trees: A scalable tree segmentation pipeline for TLS data. Methods Ecol. Evol. 14, 3083–3099. https://doi.org/10.1111/2041-210X.14233

Williams, H., et.al., 2023. Modelling wine grapevines for autonomous robotic cane pruning. Biosyst. Eng. 235, 31–49. https://doi.org/10.1016/j.biosystemseng.2023.09.006

You, A., et.al. 2023. Semiautonomous Precision Pruning of Upright Fruiting Offshoot Orchard Systems: An Integrated Approach. IEEE Robot. Autom. Mag. 30, 10–19. https://doi.org/10.1109/MRA.2023.3309098

Proposal Title:
Training Vision Systems to Detect Little Cherry Disease in Orchards

Report Type: No Cost Extension / Continuing Project Report

Primary PI: **Charlie Wu**
Organization: Orchard Robotics
Telephone: +1 (607) 269-8838
Email: charlie@orchard-robotics.com
Address: 1522 Western Ave
Address 2: STE 24269
City/State/Zip: Seattle, WA 98101

Co-PI 2: Dr. Scott Harper
Organization: Washington State University
Telephone: +1 (509) 786-9230
Email: scott.harper@wsu.edu
Address: 24106 North Bunn Road
City/State/Zip: Prosser, WA 99350

Cooperators: Suzanne Bishop (Allan Bros., Inc.) Garrett Bishop (G.S. Long Co., Inc.) Tobin Northfield (Washington State University)

Project Duration: 2-Year (plus one year No Cost Extension)

Total Project Request for Year 1 Funding: $ 54,321.00
Total Project Request for Year 2 Funding: $ 15,314.00

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

Budget 1
Primary PI: Charlie Wu
Organization Name: Orchard Robotics
Contract Administrator: Charlie Wu
Telephone: +1 (509) 239-1598
Contract administrator email address: charlie@orchard-robotics.com

Item	2025	2026
Salaries[1]	$35,000.00	
Benefits		
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies		
Travel		
Plot Fees		
Miscellaneous[2]	$5,000.00	
Total	$40,000.00	$0.00

Footnotes:
[1] The total cost of engineering salaries for data labeling from Orchard Robotics is estimated to be at least $75,000 during 2025. The project's listed expense will likely cover about 1/3 of the total cost of the engineering salaries, and Orchard Robotics will contribute the remainder (at least 2/3) of the total cost required to get the features and results built out fully.
[2] Machine Learning Training Server

Budget 2
Co PI 2: Dr. Scott Harper
Organization Name: Washington State University
Contract Administrator: Stacy Mondy
Telephone: +1 (509) 335-2885
Contract administrator email address: arcgrants@wsu.edu

Item	2025	2026
Salaries	$5,416.00	$5,632.67
Benefits	$1,905.00	$1,981.33
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies	$7,000.00	$7,700.00
Travel		
Plot Fees		
Miscellaneous		
Total	$14,321.00	$15,314.00

Footnotes: Postdoctoral associate at 0.083 FTE

OBJECTIVES

While research is underway for long-term solutions to Little Cherry Disease (LCD), growers are eager for near-term solutions. This project evaluates vision systems to improve our toolbox. The intended result is a tool growers can use to more quickly and reliably capture cherry size and color distribution within the tree. This would reduce time by focusing trained scouts and sampling where it's most needed and aid growers in seamlessly developing reliable maps without human error in either symptom identification or documentation of the correct tree. In evaluating the spread of disease by visualizing trees with symptoms and accounting for removed trees, growers would gain confidence in determining the best management plan for tree removal and replant strategies.

2025

1. Develop and train computer vision and machine learning models capable of:
    a. Accurately sizing and color grading cherries on varying cherry orchard configurations.
    b. Identifying specific trees showing symptoms of LCD
    (Considers Technology Project Priorities 2, 3,5 & 8)

2. Determine how many days before harvest LCD symptoms can be detected by the Orchard Vision System.

3. Manually scout and compare to model results to validate vision system outputs and collect training data for improving the LCD detection statistical machine learning model.

2026

4. Develop automatic map creation methods to quickly enable actions such as:
    a. Infer which trees are candidates for removal vs those that need more investigation.
    b. Determine count of missing trees due to previous tree removal
    c. How many trees are non-bearing (e.g. replant trees)
    d. How many trees are physiologically weak from other pathogens (not LCD)

5. Continue training the machine learning model against confounding factors common in cherry orchards, resulting in similar symptoms such as June drop, tree age, variations in soil and topography, excessive crop load, and other cherry diseases

Spring 2026	Summer 2026	Fall 2026	Winter 2027
Block Selection	LCD Scanning	Entering of Visual Ground truth Data	Machine Learning
Test Scans	Ground Truthing	Cherry Scans Uploaded and Reviewed	2027 Project Planning
	Virus Sample Collection	Machine Learning	
	Postharvest Scanning		

2027 No Cost Extension

6. Improve robustness of machine learning models and demonstrate effectiveness of scanning before visual ground truthing data.

7. Participate in grower educational events or conferences to demonstrate camera use, user interface, and mapping features.

SIGNIFICANT FINDINGS

- Orchard Robotics achieved up to 91% accuracy in determining the relative severity of Little Cherry Disease in evaluated test blocks using the standard statistical AUC metric. This represents an accuracy comparable to a trained professional human scout, while operating at over 20x the efficiency.
- Machine Learning Model:
    - The embedding model separated visibly worse from milder trees at both Zillah–Chelan and Sunnyside–Coral Champagne, and its scores correlated with pathogen load in sampled trees. (AUC 0.91 at Zillah–Chelan and 0.84 at Sunnyside–Coral Champagne).
- Ground Truthing Data and Lab qPCR Results:
    - The Ground Truthing Data is matching the Lab qPCR results very well with notable decreases in Ct values (corresponding with high concentrations of LCD pathogens) as visual severity grading increased, especially between slight (2-4 single symptomatic spurs) and low (<20% symptomatic) severity grades.
- Time efficiency:
    - Using a vision system to detect LCD could decrease scouting time by 95+%. This means detailed scouting of 10 acres would only take about 2 hours with one person compared to two people for 33-63 hours depending on LCD incidence and tree planting densities.

METHODS

Site Selection

We identified five different cherry orchards and scanned 3-10 acres in each block. The strategy for site selection allowed for detailed ground truthing and thorough machine learning model training. We strategized to select blocks with varying degrees of LCD severity including Free Standing, Y-Trellis, V-Trellis, and UFO cherry training systems so the robustness of the model can accommodate a variety of cherry orchard configurations throughout the Pacific Northwest. The varieties in the selected blocks were Chelan, Coral Champagne, Lapin, Skeena, and Sweetheart (Table 1).

Table 1: Parameters of selected orchard and block configuration

Orchard ID	Variety	Configuration	Row Spacing	Tree Spacing	Acres	Pollenizer
Zillah-CH	Chelan	Free Standing	16’	10’	5.3	Lapin
Sunnyside	Coral Champagne	Y-Trellis	13’	7’	5.6	Bing
Zillah-LA	Lapin	UFO	10’	9’	3.2	n/a
West Valley	Skeena	Free Standing	16’	10’	9.6	n/a
Naches	Organic Sweetheart	V-Trellis	13’	6’	10.1	n/a

Camera Set up and Scanning

Understanding the growers' need for early LCD detection, we targeted three timeframes before expected harvest to evaluate the vision system's capacity for earlier LCD detection:

1. 7-10 days before harvest (DBH)
2. 4-6 days before harvest (DBH)
3. 1-3 days before harvest (DBH)

Actual scanning, sample collection and harvest dates are outlined in Table 2.

Table 2: Actual scanning, sample collection and harvest dates by orchard in 2026

Orchard ID	7-10 DBH Scan	4-6 DBH Scan	1-3 DBH Scan	Sample Collections	Actual Harvest	Postharvest Scan
Zillah-*Chelan*		May 29	June 1	June 1	June 1-3	June 5
Sunnyside-*Coral Champagne*	May 28	June 1	June 5	June 7-9	June 8-13	June 13
Sunnyside-*Bing*	June 5	*	June 13	June 15	June 16	June 22
Zillah-*Lapin*		June 18	June 22	June 22-24	June 24-25	June 27
West Valley		June 18	June 22	July 1-2	June 24-25	June 27
Naches	July 1	**	July 6	July 7-8	July 9,12-16	July 23

*No Scan due to harvest of main commercial variety of Coral Champagne
** No Scan due to harvest date being moved up

Ground Truthing & Validation

The fundamental way to "teach" LCD detection statistical machine learning models is to train the model predictions against real life incidences for both infected and non-infected trees. This practice of ground truthing was conducted on 6 sections in each of the orchard sites chosen for this study (Figure 1). Within each section, 50-100 trees were visually evaluated for LCD incidence for a total of 323-554 trees per orchard site (Table 3). LCD scouting for incidence and severity occurred 1-3 days before harvest for the early district blocks and 2-8 days at late district blocks according to the severity scales described in Table 4. The Sunnyside block's main commercial variety was Coral Champagne with Bing pollenizers planted as every other tree, every fourth row. Due to the differences in harvest timings, additional scans and ground truthing occurred to accommodate later ripening fruit.

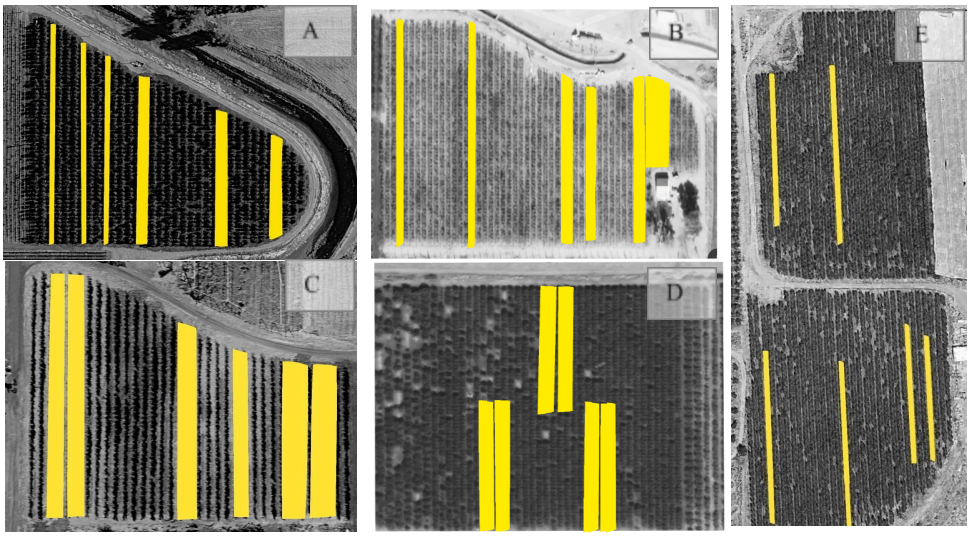


Figure 1: Overview of ground truthing zones within each orchard; A) Zillah-Chelan, B) Sunnyside-Coral Champagne & Bing, C) Zillah-Lapin, D) West Valley – Skeena, E) Naches-Organic Sweetheart

Table 3: Total number of trees with human visual ground truthing for each orchard

Orchard ID	Ground Truth Sections	Avg. Trees per section	Total Trees
Zillah-*Chelan*	6	63	338
Sunnyside	6	78	471
Coral Champagne	6	57	347
Bing	6	21	124
Zillah-*Lapin*	6	92	554
West Valley	6	70	420
Naches	6	54	323

After the 1-3 DBH scan and ground truthing, trees were chosen for qPCR/RT-qPCR confirmation on LCD disease severity. Samples were collected and sent to the Harper Lab at WSU-IAREC for qPCR confirmation of positive and negative trees by using current, validated methodology. The samples were tested for the X-disease phytoplasma ('*Candidatus* Phytoplasma pruni'), little cherry virus 1 (LChV-1) and little cherry virus-2 (LChV-2). The samples were also tested for prune dwarf virus (PDV) and prunus necrotic ringspot virus (PNRSV) as these cherry viruses can impact fruit size and color as well. We collected samples from 4 trees in each visual LCD severity level grouping for a combined total of 24 sampled trees per orchard site. We found that in sites with higher incidence it was difficult to find trees completely free of symptoms. This led us to collect more samples in Grade 0.5 (*Questionable*) to substitute for Grade 0 (*Good*).

Table 4: Severity scale for visually grading LCD symptom expression

Description	Annotations	Numerical Value	Lab Sample Count per Site
No Visual LCD Symptoms	*Good (G)*	0	4
Possible beginning of LCD Symptoms	*Questionable (?)*	0.5	4
Much smaller and lighter fruit on 1-2 spurs	*Very Slight (VS)*	1	4
True Visual LCD Symptoms on 2-4 spurs/limbs (less than 5% of tree)	*Slight (S)*	2	4
True Visual LCD Symptoms on 5-20% of tree	*Low (L)*	3	4
True Visual LCD Symptoms on 20-40% of tree	*Medium (M)*	4	4
True Visual LCD Symptoms on 40+% of tree	*High (H)*	5	
			Total 24

Table 5: Examples of observation notations used during ground truthing

Observation Descriptions	Annotations
Sick tree; maybe other pathogens invloved or other cause	Weak Tree (WT)
Removed Tree; Open Space; No Tree	Removed (R)
Replant Tree; non bearing	Replant Tree (RT)
Young Replant Tree; early fruit bearing years	Young Replant Tree (YRT)

After harvest, an additional postharvest scan was completed to provide another way to evaluate LCD incidence. We believe if growers are still experiencing time constraints just before harvest and miss preharvest scans, scanning just after harvest to detect how many trees had fruit that was left due to poor size and color, could provide another opportunity to quickly map the extreme cases of LCD incidence in their orchard.

Tree-Level LCD Scores from Fruit Images

In 2025, camera scans mapped fruit count, size, and color by tree, and scout grades tracked pathogen load measured by qPCR. In 2026, we used those grades to train models that score each tree for LCD-like fruit symptoms from its fruit images, with lab results and fruit left after harvest as independent checks (Figure 2). We developed and tested them in the Zillah–Chelan and Sunnyside–Coral Champagne blocks.

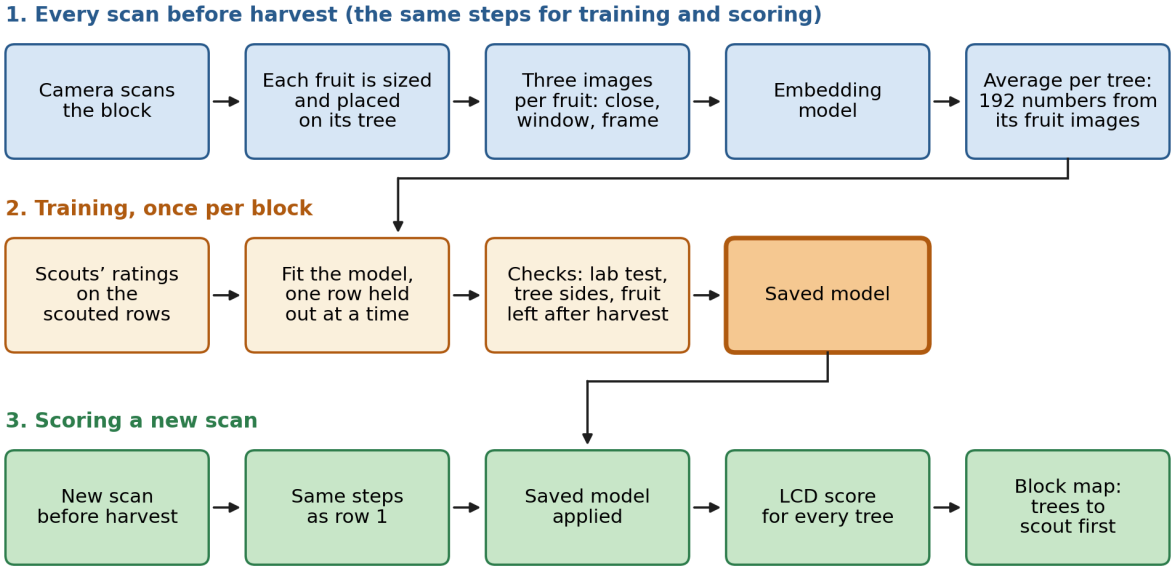


Figure 2: Overview of the fruit-image scoring workflow. Fruit images are cropped, embedded, and summarized by tree (row 1). For validation, the model is refit with each scouted row held out in turn, then checked against lab tests, tree-side ratings, and fruit left after harvest (row 2). A final fit on all scouted rows scores eligible trees in an uploaded scan and produces a map of scouting priorities (row 3). In this study, scoring ran after upload, not on the camera.

Trees were scored from scans taken before harvest: June 1 at Zillah-Chelan, and June 1 and June 5 at Sunnyside-Coral Champagne (Table 2). Postharvest scans served only as a check, on the expectation that pickers leave small, poorly colored fruit on LCD trees.

From each scan we took every camera detection sized at 8 to 40 mm (0.3 to 1.6 in.) on a mapped tree (38,909 fruit on 1,239 trees at Zillah-Chelan) and cut it from the full-resolution image in three views illustrated in Figure 3: b) close crop, c) fixed-size window that keeps the fruit's size relative to the canopy, and d) the whole frame. A general-purpose pretrained image embedding model (not retrained on cherries), turned each view into 1,152 numbers describing its appearance. Principal component analysis, fit on all fruit in the block without the scouts' ratings, reduced each view to 64 numbers: each fruit carried 64 for its close crop and 64 for its window, and each camera frame 64 for the whole frame. Fitting the components without the grades keeps grade information out of the features, and keeping 64 per view retains the main ways fruit images differ while discarding low-variance noise. Averaging each view over a tree's fruit and frames and joining the three averages gave 192 numbers per tree.

We trained a ridge regression to predict each tree's scout grade from these 192 numbers. Ridge regression suits features that are many and strongly correlated when only about 300 trees per block were graded: it keeps every coefficient small instead of selecting a few, which keeps the fit stable

across held-out rows. To test it, we held out one scouted row at a time, chose the ridge penalty on the remaining rows, and scored the held-out row; at Zillah–Chelan, 316 rated trees in nine rows contributed labels. A final model trained on all scouted rows scored the unscouted trees. A higher score means more LCD-like fruit (Figure 3).

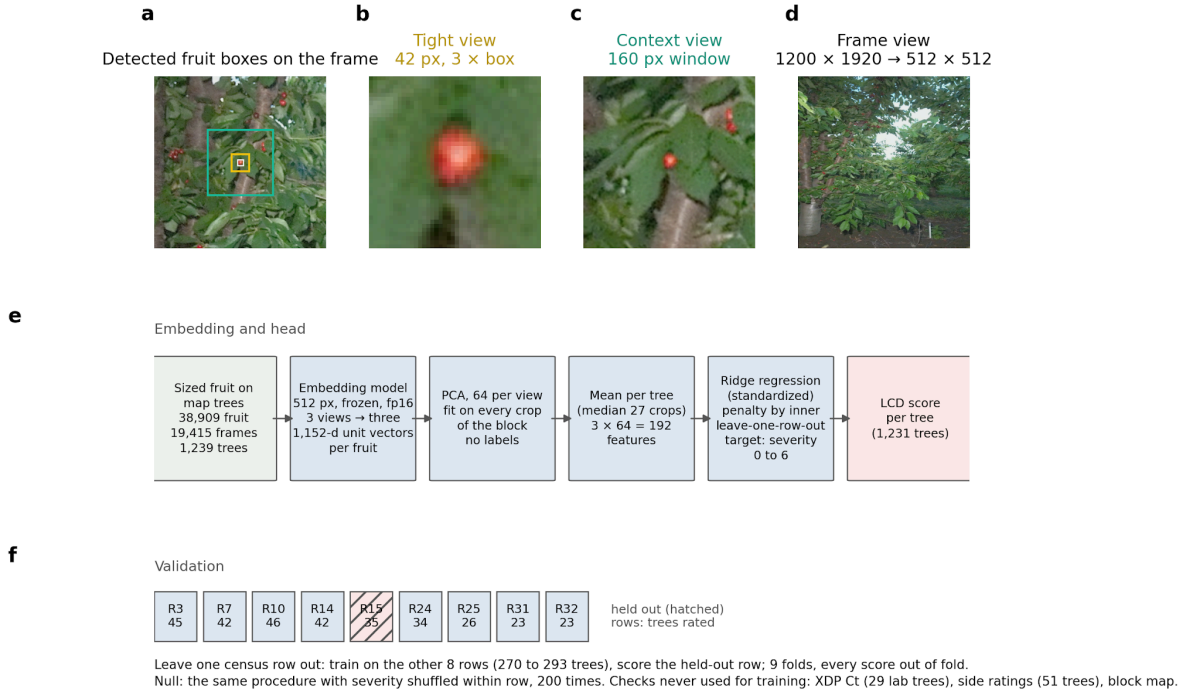


Figure 3: How the embedding model scores a tree, on one Zillah-Chelan camera frame (June 1). (a) Detected fruit boxes. Each fruit is cut three ways: (b) a close crop, (c) a fixed-size window, and (d) the whole frame. (e) Each view is embedded, condensed, and averaged per tree; a ridge regression turns the tree's 192 numbers into an LCD score. (f) Each scouted row is held out in turn, so every validation score comes from a model that never saw that row.

We scored the held-out trees two ways. Rank correlation (Spearman; 1 is the same order, 0 is no relation) measured how closely the score ordered the trees in each row as the scouts did. The area under the curve (AUC; 0.5 is chance, 1 is perfect) measured how well it separated visibly worse from milder trees: *Medium* or worse against *Slight* or better at Zillah–Chelan, and *Low* or worse against *Very Slight* or better at Sunnyside–Coral Champagne, where symptoms were milder overall. AUC is the probability that a randomly chosen visibly worse tree scores higher than a randomly chosen milder tree: an AUC of 0.9 means the worse tree scores higher in 9 of 10 such pairs. Middle grades were left out of the AUC, and both groups are visual-symptom groups, not lab-confirmed infection groups. Statistical significance was assessed with Spearman's rank correlation test and, for AUC, a one-sided Mann–Whitney U test. *P* values below 0.05 are reported as $p < 0.05$.

Two checks used information the model never saw:

1. Lab test (qPCR): on the sampled trees in both blocks with an X-disease phytoplasma (XDP) result, we compared each tree's score with its Ct value.
2. Fruit left after harvest: on the postharvest scans, we measured each tree's remaining fruit relative to its neighbors within 40 ft, for scouted and unscouted trees.

RESULTS AND DISCUSSION

2026 Lab qPCR

In this study we were able to detect presence and absence of each pathogen, and the relative pathogen concentrations because of real-time qPCR methods and the corresponding Ct values. Lower Ct values indicate higher amounts of the targeted pathogen, while higher Ct values indicate lower amount of the targeted pathogen. For example, 20 Ct value is 1,000,000 copies of XDP while 34 Ct value is 100 copies (Figure 4). This is due to Ct values being represented on a log scale. When there is higher initial amounts of targeted pathogen DNA, less cycles (indicated by low Ct values) are required to reach detection thresholds.

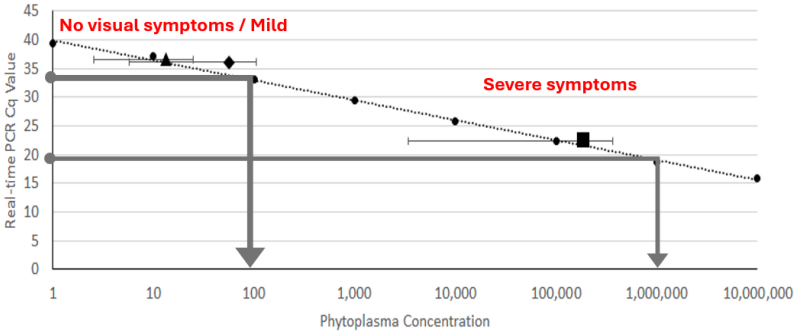


Figure 4: XDP phytoplasma concentrations in relation to Ct values and visual symptom expression. Source: Scott Harper (WSU) and Madalyn Shires (WSU).

Within each block, at least one to seven trees resulted as Non Detect (no LCD pathogens).
XDP only: As depicted in Table 6, across all blocks, samples that tested positive had higher Ct values in *Good* through *Very Slight* grading indicating low infection levels.
Low, *Medium*, and *High* severity grading had progressively lower Ct values, indicating increasing pathogen load.
LChV-2 Only: Was only found in *Good/Questionable* and *Very Slight* severity grades. In trees with
Both XDP and LChV-2: Average Ct values still were higher when visually graded as *Good/Questionable* and lowest in *Medium/High*s severity grades, but we also found at least one of the pathogens at relatively high levels in severity grades between *Very Slight* and *Low.*

Table 6: Lab qPCR results of sample trees by severity based on human visual grading

Description	Severity Scale	XDP Avg Ct	LChV-2 Avg Ct	XDP/LChV-2 Avg Ct
No Visual LCD Symptoms	*Good (0)*	35	34	32/32
Possible Beginning of Symptoms	*Questionable (0.5)*			
Smaller and Lighter Fruit on 1-2 Spurs	*Very Slight (1)*	34	31	22/19
Symptoms on 2-4 Spurs/Limb	*Slight (2)*	29	n/a	33/29
Symptoms on 5-20% of tree	*Low (3)*	25	n/a	33/26
Symptoms on 20-40% of tree	*Medium (4)*	22	n/a	26/25
Symptoms on 40+% of tree	*High (5)*			

Lower Ct values indicate higher amounts of the targeted pathogen, while higher Ct values indicate lower amount of the targeted pathogen.

2026 Model Analyses

Human scouting and lab records were linked to verified FruitScope tree locations, allowing their grades and test results to be compared with camera data. Before building the embedding model, we checked whether simple tree-level measurements separated the scouts' grades.

Fruit Size: At Zillah–Chelan on June 1, trees graded *Medium* or worse carried smaller fruit than trees graded *Slight* or better (tree median 18.9 mm against 20.2 mm; a worse-graded tree had the smaller median with probability 0.76; Figure 5a).

Fruit color: Hue was nearly the same across LCD severity grades (probability 0.42, p = 0.94; Figure 5b), at Zillah-Chelan nor did color show LCD signal in the Sunnyside–Coral Champagne trees. Contrary to our hypothesis, higher infected trees were slightly redder, which is opposite of the pale fruit typical of LCD. A likely reason is that a tree's average color blends hundreds of cherries that differ in ripeness, lighting, and position in the canopy, so a single number cannot show how much of the crop is affected. This motivated the embedding mode. Rather than one or two measurements per tree, a feature embedding can capture more measurements and visual features to train a model.

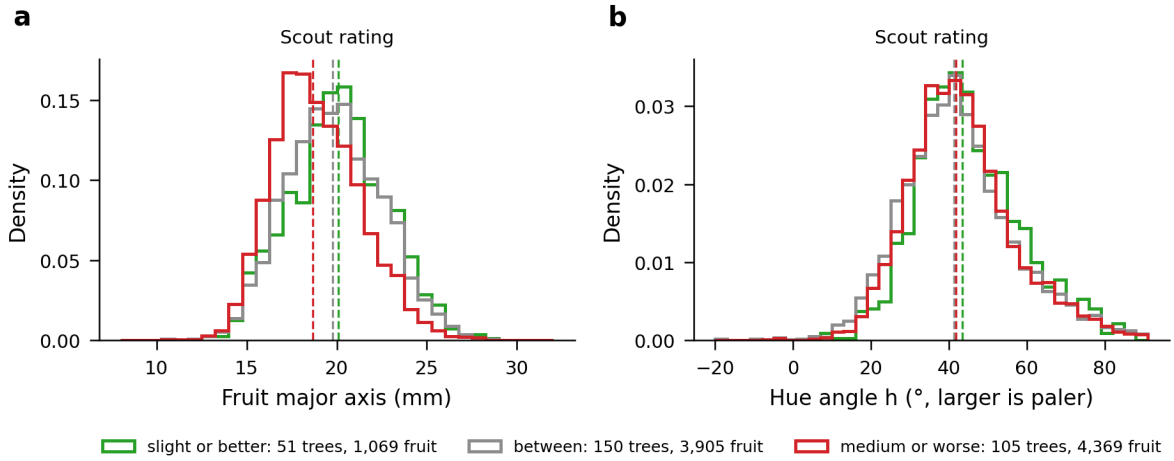


Figure 5: Fruit size and color by the scouts' grade at Zillah–Chelan (June 1 scan). (a) Fruit length; (b) hue angle, where a larger angle means paler fruit. Each line shows how the fruit of one grade group are spread: Slight or better (51 trees), Between (150 trees), and Medium or Worse (105 trees). Dashed lines mark each group's median.

At Zillah–Chelan, the embedding model ranked trees within rows by the scouts' severity grades at a rank correlation of 0.57 ($p < 0.05$; Figure 6a), against 0.40 for fruit size alone ($p < 0.05$; Figure 5a). It separated trees graded *Medium* or worse from those graded *Slight* or better at AUC 0.91 ($p < 0.05$; Figure 6a), against 0.76 for fruit size ($p < 0.05$). The median embedding score increased overall from *Good* to *High* LCD grades, although trees graded *Very Slight* and *Slight* scored about the same. Every tree was scored by a model that had not seen its row, so the score ranks trees within a row and should not be considered a diagnosis.

At Sunnyside–Coral Champagne on June 5, the last scan before the Coral harvest, the score ranked trees within rows at 0.33 ($p < 0.05$) and separated trees rated *Low* or worse from those rated very slight-plus or better at AUC 0.85 ($p < 0.05$; Figure 6b). The ranking was weaker than at Zillah–Chelan because most Coral trees were rated *Very Slight* and only 22 were *Low* or worse; the median score still rose from good and *Very Slight* to *High*.

On scouted rows excluded from training, the embedding model separated the selected visibly worse and milder trees at AUC 0.91 at Zillah–Chelan ($p < 0.05$) and 0.85 at Sunnyside–Coral Champagne ($p < 0.05$). Only 22 Coral trees in this comparison were rated *Low* or worse, so that estimate needs confirmation in more blocks and seasons. AUC measures separation between selected visual-symptom groups; it is not the percentage of infected trees correctly diagnosed. In selected lab samples, higher embedding model scores also accompanied greater XDP load at both blocks (rank correlation 0.43 on 29 Zillah–Chelan trees, $p < 0.05$, and 0.61 on 37 Sunnyside–Coral Champagne trees, $p < 0.05$). On June 5, the Coral score was also associated with XDP load in sampled trees (0.38 on 36 trees, $p < 0.05$).

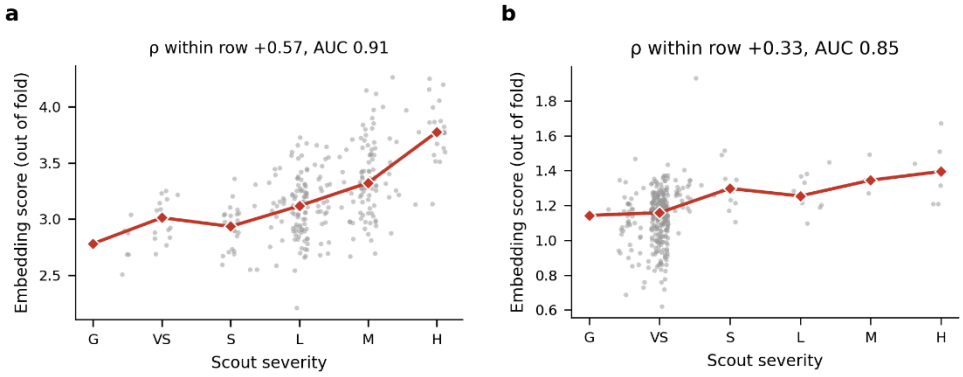


Figure 6: Embedding model score for each scouted tree against the scouts' severity grade, from Good (G) to High (H). (a) 294 Zillah–Chelan trees, June 1 scan. (b) 342 Sunnyside–Coral Champagne trees, June 5, the last scan before the Coral harvest. Each tree was scored by a model that never saw its row. Red diamonds mark the median score for each grade.



Figure 7. FruitScope map of Zillah–Chelan, 1 June. Colored dots show model LCD scores (0–6); rings mark scouted trees and their severity and diamonds mark lab samples. The screenshot was cropped and its satellite imagery adjusted for contrast; prediction markers remain in their original positions. Scores guide scouting, not diagnosis.



Figure 8. FruitScope website screenshot of Sunnyside–Coral Champagne, 5 June (October model fit). Colored dots show LCD prediction scores for Coral Champagne trees; rings mark scouted trees and diamonds mark lab samples. The main comparisons above used the separate June 1 analysis.

Significance to the Industry:
These results show that camera scans taken before harvest can rank trees within each row by visible LCD severity. The embedding model separated worse from milder trees at both Zillah–Chelan and Sunnyside–Coral Champagne, and its scores rose with pathogen load in sampled trees. For growers, the value lies in where scouts and lab samples are prioritized. Block maps listing the highest-scoring trees first lets a crew check the likeliest LCD trees before the rest and aim lab sampling at trees most likely to test positive. Walking and grading every tree manually, or testing every tree by qPCR, doesn't scale well to whole blocks each season, while the scans come from routine camera passes, which facilitate finding affected trees earlier. Fewer scouting and lab hours could lower the cost of LCD surveys and speed the removal of infected trees that serve as sources for further spread. The scores are a scouting aid, not a confirmation of infection as other factors such as other pathogens and crop load, may influence visual symptoms, and visually mild trees sometimes tested positive.

Continued Efforts in 2027:

- Continue building on embedding model to evaluate other orchard scans (Winter 2026/2027)
- Determine if the same model can work across all varieties and training systems or if separate models need to be established. (Winter 2026/2027)
- Test robustness of machine learning models and by scanning *before* visual ground truthing data is collected (Summer 2027)

Proposal Title:
Development of a UV-C Applicator Prototype for Powdery Mildew and Fire Blight Management

Report Type: Continuing Project Report

Primary PI: Gwen Hoheisel
WSU Extension
509-788-5459
ghoheisel@wsu.edu
602 Market St
Prosser, WA 99350

Co-PI 2: Michelle Moyer
WSU Prosser IAREC
509-786-9234
michelle.moyer@wsu.edu
24106 N Bunn Road
Prosser, WA 99350

Co-PI 3: Jason DuBose
Puren Solutions
925-917-0881
jdubose@purensolutions.com
33911 SE Eastgate Circle
Corvallis, OR 97333

Project Duration: 1-Year, NCE

Total Project Request for Year 1 Funding: $88,101

Other related/associated funding sources: Awarded
Funding Duration: 2026 - 2027
Amount: $38,750
Agency Name: Puren Solutions
Notes: This is cost share from Puren Solutions and includes $ 32,000 in labor and $ 6,750 in supplies for total machine development that is not included in this proposal.

Budget 1
Primary PI: Gwen Hoheisel
Organization Name: WSU
Contract Administrator: Lesa Neuman
Telephone: 509-335-8467
Contract administrator email address: lneumann@wsu.edu
Station Manager/Supervisor: Vicki McCracken
Station manager/supervisor email address: mccracke@wsu.edu

Item	2026
Salaries	$9,156.00
Benefits	$2,335.00
Wages	
Benefits	
RCA Room Rental	
Shipping	
Supplies	
Travel	$1,610.00
Plot Fees	
Miscellaneous	
Total	$13,101.00

Footnotes:
Budget is split between Hoheisel ($7041) and Moyer ($6060) to cover salary and travel to sites for field assistance and data collection. All supplies are already owned from other projects.

Budget 2
Co-PI: Jason DuBose
Organization Name: Puren Solutions
Contract Administrator: Jason DuBose
Telephone: 925-917-0881
Contract administrator email address: jdubose@purensolutions.com

Item	2026
Salaries	
Benefits	
Wages	$14,400.00
Benefits	
RCA Room Rental	
Shipping	$2,500.00
Supplies	$57,420.00
Travel	$680.00
Plot Fees	
Miscellaneous	
Total	$75,000.00

Objectives

(i) Quantify dose–response of a UV-C test system in different tree fruit canopy architectures, with and without fan-assisted leaf agitation

(ii) Optimize modular components for height and lateral reach for common training systems

(iii) Meet worker-safety standards for UV-C which can include integrating shields, interlocks, kill-switches, light curtains and/or signage

(iv) Validate tower-sprayer compatibility (hitch, hydraulics, power) and modularity so the kit scales from narrow to wide row spacings and can be serviced with common parts

Significant Findings

- Spring tours conducted with Puren in multiple apple and cherry blocks. Measurements for canopy architecture taken and confirmed with consultants in different regions of E WA.
- Prototype testing completed with an array panel. Determined fans did not increase UV-C dosage.
- Built UV-C field-ready machine with 5x10-foot light array with articulating arms. Generator for UV-C lights operated with pto on a 3-point hitch.
- Machine has articulating arms ranging from 6.5-12 feet wide. Fit well, but tight, in a 10-foot fruiting wall apple orchard. To account for more canopy variations, the chassis should be at least a foot more narrow with arms able to articulate out. Also, robustness of aluminum welds and placement for a few wires should be changed to better allow movement with a forklift.
- Articulating arms for v-trellis have a wide range of angles but are too wide at the base for many 10-foot row v-trellis orchards. A new design may be needed to account for the height of the array and ‘V’ articulation.
- Safety protocols are critically important. New UV-C face shields showed no UV-C exposure under the shield with dosimeters and masks within 2 inches of the light array. However, exposed skin was sensitive to sunburn with minimal time (< 10 minutes, intermittently)
- Kill switches installed on the cab controller and rear of the machine. Additional power switch inside the main control box.
- UV-C light arrays are encapsulated in a protective sheath. They were robust and did not break even when hit with branches. Unfortunately, software updates for light ballasts have to be done ‘in-person’ as opposed to remote, but there are no ballasts that allow for remote upgrades. As technology progresses this would be a good addition.
- In the commercial machine with studies conducted indoors minimizing UV-A and UV-B light, irradiance (power of the lights) decays 15-17% for every foot of distance from the machine.
- In the field using a dosimeter for UV-C light only, we measured dosages appropriate for control getting to the interior of the fruiting wall canopy. Driving at 3 mph is possible, however, 1 to 2 mph would be more appropriate if attempting powdery mildew and potential fireblight control.

Methods

Objective 1: Quantify dose–response of a UV-C test system in different tree fruit canopy architectures, with and without fan-assisted leaf agitation

We characterized canopy architecture by visiting cherry and apple blocks spanning common training systems (e.g., V-trellis, spindle, bi-axis) and row spacings. We took measurements of canopy size and density to inform machine design

Initial work used a very simple test light array and fan to ruffle leaves in each of the canopies. We quantified dose variance from design and leaf movement to determine if fans were needed.

With the full-scale prototype, we measured dosage with a dosimeter (UV-Cense) measuring UV-C (254nm) only at 3 speeds in fruiting wall apples. Average dose was calculated and compared to treatment thresholds in the literature for powdery mildew and fire blight. Additionally, in CPAAS we tested UV irradiance with a spectroradiaometer (Gigahertz-Optik #BTS2048-UV-S) at three distances from the UV-C array. This UV spectroradiometer has been the "gold standard" monitoring unit used for calibration of previously cited field UV-C applicators across the USA and in Norway. It does measure 00-400 nm covering the array of UV-A, UV-B, and UV-C, but we tried to minimize direct UV-A and -B by conducting the light decay measurements indoors.

Objective 2: Optimize modular components for height and lateral reach for common training systems

Using our canopy measurements, initial UV-C measurements, and grower feedback, Puren team built a prototype of a UV-C applicator system that can easily attach to a tractor 3-point hitch and be operated safely from the tractor cab. Due to the varying nature of the different fields with V-trellis or vertical walls and row spacing, the intent was to find a common platform that can allow easy manual adjustments to system widths (+2-3 feet) and pitches of 0-30°. Over the row systems were less desirable, so a single side 'wall' of UVC lamps was built to hopefully provide a uniform dosage of UVC light up to 10 to 12 feet and around 4,200 watts. To test the time needed to change configurations between distinctly different canopy architectures, we tested and refined the set-up and switch for each training system—aiming for <10 minutes from one set-up to the next—and validated that adjustments and maintenance items are manageable in the dark with gloves.

Objective 3: Meet worker-safety standards for UV-C which can include integrating shields, interlocks, kill-switches, light curtains and/or signage

We will modify our current worker safety protocols for PPE and exposure with the latest recommendations from the World Health Organization, International Commission on Non-Ionizing Radiation Protection, and UW Occupational Health and Safety. In general, use of long sleeves, gloves and face shield are recommended. We tested dosage of UV-C exposure through face fields within the highest exposure (< 2 inches from lights).

In tractors, the plexiglass and glass in enclosed cab blocks most if not all UV-C. We will also explore a window tinting film on a window and test UV-C penetration while still being visible. Workers with open cabs will still be protected with the recommended PPE.

For machine design, a kill switch in the cab and rear of the machine has been installed. Additionally, lamps are in a shatterproof coating so there is not a risk of glass in the field or worker safety from changing a bulb.

Objective 4: Validate tower sprayer compatibility and modularity so the kit scales from narrow to wide row spacings and can be serviced with common parts

The field ready machine arrived to WSU-IAREC in October. At the WSU Roza farm, we tested the UV-C applicator in the WA-38 fruiting wall. We attempted to test the applicator in UFO cherries, but had structural issues that needed to be fixed. Once those are complete, with a NCE we will continue to field test the fit, robustness, and dosage in different canopy systems as listed below.

With grower cooperators, we will demonstrate and run the field-ready machine through one orchard of each target canopy. We will assess the systems limitations and successes of operation

across row spacings, heights and trellis systems. Additionally, during the field trials, we will work with our grower cooperators to identify pinch points in serviceability and work to address them.

Results and Discussion

Objective 1: Quantify dose–response of a UV-C test system in different tree fruit canopy architectures, with and without fan-assisted leaf agitation

We measured both irradiance and dose to learn how the test and field-ready UV-C applicator performed.

IRRADIANCE is the power of the light bulbs over a given area. Irradiance stays fixed with time, but reduces with distance. Meaning a light can only shine a certain distance.

DOSE is the accumulated irradiance over time. The longer something is exposed to light, the higher the dose and the more damage is accumulated. The slower a tractor drives, the more time at each tree and therefore a higher dose.

TREATMENT DOSE is the amount of joules per meter^2 effective for treating a pathogen. Because pathogens have the ability to repair themselves in the daytime, a higher UV-C dose is required in the day. However, those repair mechanisms are not active at night so a lower dose (J/m^2) is needed at night. ***Effective nighttime dose for powdery mildew is 50-200 J/m^2 and nighttime dose for fire blight is 200 J/m^2***.



Figure 1:Test array for initial measurements of dose

A document with canopy characteristics was validated in farm visits. Trials in May with a sample light array allowed for preliminary testing of dose and affect of fan (Fig. 1). With the smaller light array dosage on the exterior canopy was within nighttime treatment range (50-200 J/m^2) for powdery mildew, but the light was not penetrating the inner canopy well enough (Table 1). Adding in fans did not add any benefits to the middle of the canopy and in some cases decreased dose.

Table 1: Using the test array (Fig 1) this is a dose response for sensors on the exterior and interior of the canopy in four different systems. Targeting at least 100 J/m2 for nighttime powdery mildew. These results indicate that either more lights or time (slower speed) would be needed.

		Exterior Sensor		Interior Sensor	
Trellis	**Speed (mph)**	**Sensor Distance from Array (in)**	**Ave Dose (J/m2)**	**Sensor Distance from Array (in)**	**Ave Dose (J/m2)**
4D Apple	1	44	144	100	12.5
Fruit Wall Apple	1	27	160	32	10
V-Trellis Apple	1	27	155	33	110
UFO Cherry	1	27	155	33	20
4D Apple	2	44	120	100	0
Fruit Wall Apple	2	27	75	32	5
V-Trellis Apple	2	27	95	33	60
UFO Cherry	2	27	90	33	10

A prototype of the UV-C applicator with a full light array arrived at WSU-CPAAS in October (Fig 2). By measuring irradiance indoors, we can calculate the decay of light as distance from the light

increases. With the full array there was a 15-17% decrease for every foot from the light array (Fig. 3) which was a significant improvement over the test array. These measurements were used to estimate a dosage at different speeds to estimate if we could potentially test up to 3mph. In the field, dosimeters located at the tree trunk and halfway between the trunk and exterior canopy (Fig 4).



Figure 2: Prototype of UV-C applicator with full light array in WA-38 apples at WSU Roza

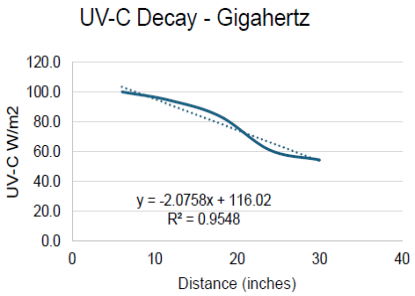


Figure 3: Irradiance curve to show the decrease in light as distance from them also increases.



Figure 4: Dosimeters measuring UV-C only were placed at the tree trunk and midway to the edge of canopy.

The UV-C applicator was positioned close to the canopy and with the full light array the dosage was impressively high (Table 2). Driving at 2 mph showed adequate dosage levels for powdery mildew when treated at night. The critical aspect of this technology is how to manipulate dose. A longer light array can be manufactured to increase time of light exposure and thus speed could increase. Alternatively, a shorter array can be maintained, and autonomous tractors could pull move slowly throw the orchard at night. Daytime treatments could be possible if you significantly increase dose but that is more challenging.

Table 2 Dose response in fruiting wall apple driving at 3 speeds.

	Dose (J/m²)		
Distance from Array (in)	**1.1 mph**	**1.9 mph**	**2.8 mph**
10.1	337.5	215	160
19.3	192.5	120	82.5

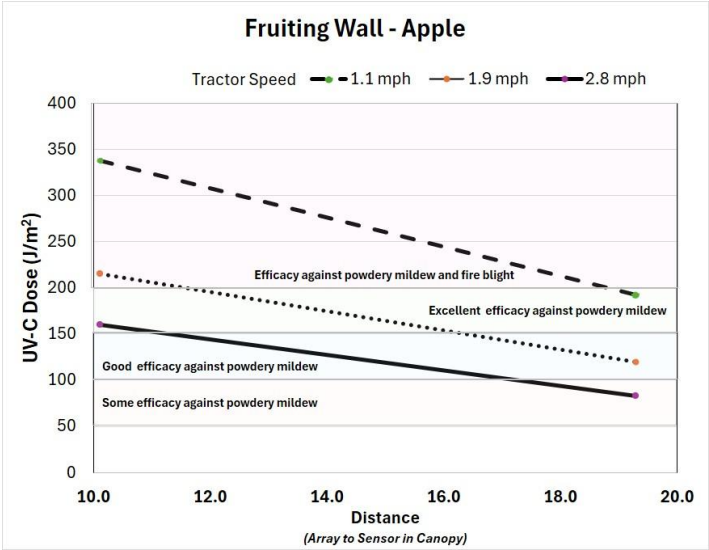


Figure 5: Dose response as distance from light and target increase at three different speeds.

Objective 2: Optimize modular components for height and lateral reach for common training systems

Concerns needing to maximize light and adjust for multiple angles drove the design of the prototype UV-C applicator (Fig. 6). The most sensitive component of a UVC applicator system like this is the light sources, however, those have already been designed and have gone through several years of field testing to endure harsh environments and are impact- and water-resistant, contain a shatterproof coating and are naturally anti-static to minimize dust buildup. Indeed, when driven in the orchard, we hit several larger branches from pollinizers and did not damage the bulbs.

The width of the machine was 6.5 feet wide which should have fit most orchards. However, it was a tight fit in the trellised apples and we are suggesting a 5.5 foot wide platform. Articulating arms can move the array out for a wider row or at an angle to accommodate v-trellis (Fig 7). Unfortunately, the width at the base when angled in this manner is too wide (between 9-12 feet), so modifications to the design may be needed to fit in V-trellis orchards.

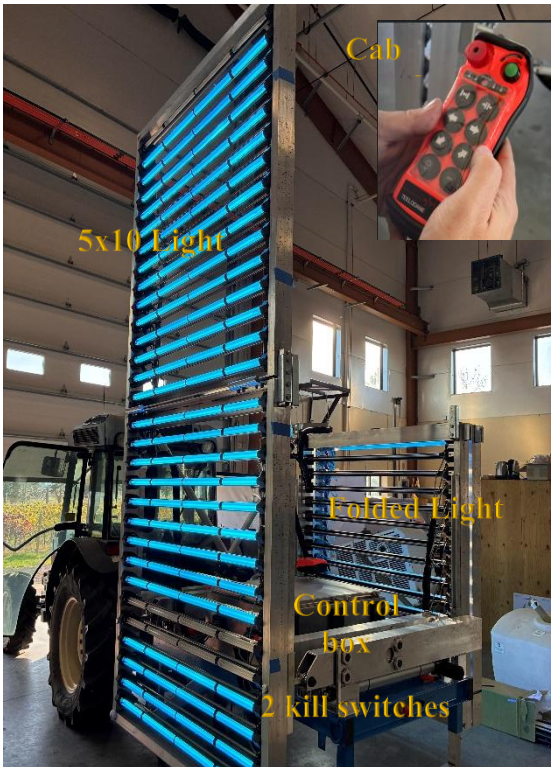


Figure 6: Prototype UV-C applicator with 5x10 light array that folds for transport, kill switches in the rear and on the controller in the cab. Large control box is centered in the middle above a generator powered by the tractor PTO..



Figure 7: Light array can be moved in/out horizontally or at an angle. The width of the angle to fit within the row still needs more work.

Objective 3: Meet worker-safety standards for UV-C which can include integrating shields, interlocks, kill-switches, light curtains and/or signage

The carcinogenic effects of UV exposure are well documented, but they come from UV-A and UV-B exposure. UV-C is a superficial skin exposure would have to be on the order of 1-2 magnitudes higher than UV-B exposure to cause long term dermal illness and eye damage (Sliney and Stuck, 2021). Nonetheless, with these many lights, close exposure does lead to sunburn. The current recommendations is to eliminate exposed skin and wear a face shield to protect the face and eyes, being the most sensitive to damage and light. The dose of UV-C under the face mask within 2 inches of the light was 0. We will continue testing light exposure in the cab and with alternative disposable light weight covers to help when treating in the heat. The system does have light kill switches on the rear of the machine and on the controller that is with the operator.



Figure 8: UV-C can cause surface burns that are painful. No exposed skin (red X) should be used while operating the lights. Workers can be protected (green checks) with a full-face mask that goes over the forehead, long-sleeve clothes and nitrile gloves.

Objective 4: Validate tower compatibility and modularity so the kit scales from narrow to wide row spacings and can be serviced with common parts

This work will be done after modifications and with the NCE.

Literature Review

Finding an alternative to standard fungicide control for is critically important for the longer-term sustainability of perennial crop production. Studies show that cherry powdery mildew (*Podosphaera cerasi*) has evolved resistance to key fungicide classes used in the Pacific Northwest. As early as the mid-1990s, demethylation inhibitor (DMI; FRAC 3) resistance was documented in Washington orchards (Grove, 2000). There are other efficacy trials reporting the emergence of resistant populations to commonly used single-site fungicides and variable performance of several standards (e.g., myclobutanil, triflumizole, quinoxyfen; FRAC 3 and 13) (Moparthi and Bradshaw, 2020). However, most important within Washington are reports and articles from Grove et al. (2020) indicating widespread resistance in all tested regions to FRAC 3 and 11 fungicides. This is in line with what has been seen in other perennial cropping systems dealing with powdery mildew – it's only a matter of time before resistant populations show up (Sharma et al., *in-press*).

UV-C has no residual effect so it could be a significant change in operation to maintain continual use. Therefore, it is critical to understand the epidemiology of infection and target UV-C appropriately. In Washington, the first UV-C trials were conducted on grapevines (*Vitis vinifera*) which exhibit pronounced ontogenic resistance to Erysiphe necator (grape powdery mildew) infection. This means that high susceptibility of fruit or foliage is confined to a brief window, that spans from rachis elongation, to four weeks post 100% bloom (Gadoury et al., 2003). After this stage, fruit rapidly acquire resistance. Foliar infections are similarly limited to young tissue (Merry et al., 2013). However, cluster rachis, and tissue that was infected prior to the onset of ontogenic resistance, remains susceptible to new infections for the remaining of the growing season. In apple, Similarly in apple, overwintering spores are in dormant apple buds (flag shoots). Given that healthy buds emerge prior to infected buds, once infected buds are out, there is sufficient tissue to continue the disease cycle. Infection of flowers parts happens bloom and primary infection of the fruit is more rare (Strickland et al. 2021). Apple powdery mildew management starts prebloom to target early foliar infections through vegetative spur growth; meaning there is an early season infection period that may

lead to higher control of fruit infection if UV-C timing is optimized. In contrast, the management period for cherry powdery mildew is longer, but still can be targeted. In sweet cherry, like apple powdery mildew, the emergence of infected flag shoots after the emergence of early foliage growth means powdery mildew infects and builds on leaves before fruit, with foliar infections typically preceding fruit infections by about six weeks (Probst et al., 2021). Fruit susceptibility increases later in development, approximately 66 days after full bloom. Earlier in the season, fruit are much less susceptible and require higher inoculum loads to become infected, highlighting the importance of monitoring disease progress and maintaining low inoculum levels during the early season for less infection on fruit, which can be difficult in the presence of early-season flag shoots. This longer window of disease management is one of the reasons why fungicide resistance is becoming more common – the longer the management window, the more fungicide applications that are needed, which means more potential selection events. While this longer management window will not be shortened using UV-C, the number of fungicide-resistance selection events can be reduced (if adoption includes a hybrid UV-C / fungicide program), or eliminated (if adoption transitions to a full UV-C program).

There are other commercial UV-C applicators. Octiva (https://octiva.tech/) is a robotic platform with multiple attachments. One of which is for UV-C applications in strawberries, cucumbers, and tomatoes. This is a smaller canopy and often in controlled arenas like hoop and green houses. Thorvald from SagaRobotics (https://sagarobotics.com/) is a robotic platform that specializes in canopies that allow 'over-the-row' applications like grapes and strawberries. AgriAutomation also has partnered with Burrows robotic platforms to drive a small UV-C platform called UVEX. It is single sided but meant for much smaller canopies than tree fruit. While nighttime robotic platforms are undoubtedly a plausible strategy that would enable nearly constant operation and potential user exposure to UV-C, the lamp array and design must be perfected first. The application system can be designed on a 3-point hitch or similar for more immediate use. Then it can be subsequently converted to robotic platforms.

Bibliography:

Gadoury, D. M., Seem, R. C., Ficke, A., & Wilcox, W. F. (2003). Ontogenic resistance to powdery mildew in grape berries. Phytopathology, 93(5), 547–555. DOI: 10.1094/PHYTO.2003.93.5.547

Grove, G. G., Boal, R. J., & Bennett, L. H. (2000). Managing powdery mildew of cherry in Washington orchards and nurseries with spray oils. Plant Health Progress. DOI: 10.1094/PHP-2000-0728-01-RS

Grove, G. G., Swamy, P., Guerra, N. (2020). Current Status of the Powdery Mildew Fungicide Toolbox in Cherries. https://treefruit.wsu.edu/article/current-status-of-the-powdery-mildew-fungicide-toolbox-in-cherries/

Merry, A.M., Evans, K.J., Corkrey, R., & Wilson, S.J. 2013. Coincidence of maximum severity of powdery mildew on grape leaves and the carbohydrate sink-to-source transition. Plant Pathology 62: 842-850. DOI: 10.1111/j.1365-3059.2012.02691.x

Moparthi, S., & Bradshaw, M. (2020). Fungicide efficacy trials for the control of powdery mildew (*Podosphaera cerasi*) on sweet cherry trees (*Prunus avium*). Biocontrol Science and Technology 30, 659-670. DOI: 10.1080/09583157.2020.1755616

Probst, C., Pandey, B., Swamy, P., & Grove, G. G. (2021). Factors affecting the infection of sweet cherry (*Prunus avium*) fruit by *Podosphaera cerasi*. Plant Disease 105(7), 1915–1922. DOI: 10.1094/PDIS-02-21-0229-RE

Sharma, N., Moyer, M.M, & Miles, T. (*in press).* Evolution of Fungicide Resistant Pathogens in Grapes: *Erysiphe necator, Plasmopara viticola* and *Botrytis cinerea.* American Journal of Enology and Viticulture.

Strickland, D. A., Hodge, K. T., & Cox, K. D. (2021). An examination of apple powdery mildew and the biology of *Podosphaera leucotricha* from past to present. Plant Health Progress 22(4), 421-432.

Proposal Title: Online Irrigation University for Washington Tree Fruit Growers
Report Type: Continuing Report

Primary PI: R. Troy Peters, P.E., Ph.D.
Organization: Washington State University
Telephone: 509-786-9247
Email: troy_peters@wsu.edu
Address: 24106 N. Bunn Rd.
City/State/Zip: Prosser, WA 99350

Co-PI 2: Srikanth Gorthi
Organization: Washington State University
Telephone: 509-778-1648
Email: Srikanth.gorthi@wsu.edu
Address: 24106 N. Bunn Rd.
City/State/Zip: Prosser, WA 99350

CO-PI 3: Dattatray Bhalekar
Organization: Washington State University
Telephone: 509786-2226
Email: dattatray.bhalekar@wsu.edu
Address: 24106 N. Bunn Rd.
City/State/Zip: Prosser, WA 99350

Co-PI 4: Bernardita Sallato
Organization: Washington State University
Telephone: 509-439-8542
Email: b.sallato@wsu.edu
Address: 24106 N. Bunn Rd.
City/State/Zip: Prosser, WA 99350

Cooperators: Just the Co-PIs

Project Duration: 1-Year

Total Project Request for Year 1 Funding: $ 49,206

Other related/associated funding sources: Cost share for salaries from Washington State University
Funding Duration: 1 year during the execution of this project.
Amount: Estimated to be about $62,000. Approximately 15% of Dr. Peters, and Dr. Bhalekar's salaries and 5% of Bernardita Sallato's salary.
Agency Name: Washington State University

WTFRC Collaborative Costs: None

Budget:
Primary PI: R. Troy Peters, P.E., Ph.D.
Organization Name: Washington State University
Contract Administrator: Jamie Meek
Telephone: 509-786-9370
Contract administrator email address: Jamie.meek@wsu.edu
Station Manager/Supervisor: Naidu Rayapati
Station manager/supervisor email address: Naidu.rayapati@wsu.edu

Item	2026
Salaries	$34,002
Benefits	$6,800
Wages	$6,400
Benefits	$186
RCA Room Rental	$0
Shipping	$0
Supplies	$1,500
Travel	$168
Plot Fees	$0
Miscellaneous	$150
Total	**$49,206**

Footnotes: Salary is ½ time for Srikanth Gorthi, a post-doctoral research scientist to do the web development. Wages will be for Diana Velasco to do the Spanish translation. Supplies are for a laptop computer. Minimal travel is for field days and presentations. $150 for miscellaneous office supplies

Justification:
Irrigation management is a cornerstone of profitable and sustainable tree fruit production in Washington State. The industry faces mounting challenges, including water scarcity, climate uncertainties, and higher labor and input costs. Precision irrigation tools, such as soil moisture probes, plant sensors, and weather-based decision-support systems, offer solutions, but adoption remains inconsistent. Many growers cite barriers such as limited training, complexity in interpreting data, lack of bilingual resources, and uncertainty about the return on investment (ROI) of adopting new technologies.

Growers increasingly require flexible, on-demand, easily accessible, and interactive educational platforms. An "Online Irrigation University" will address this need by providing a bilingual, multi-format hub that integrates practical training, research-based resources, and interactive engagement opportunities. This will do so while limiting the need for travel costs and registration fees. The program will feature YouTube videos, Fruit Matters and Good Fruit Grower articles, an interactive website with structured training modules, and online Q&A/discussion forums.

A distinctive feature of this initiative will be the development of ROI calculators for irrigation technologies. These grower-friendly tools will allow users to input their own orchard parameters (e.g., acreage, crop type, Irrigation type, water costs, labor costs) and receive clear, customized estimates of financial and water-use benefits from adopting different irrigation sensors and strategies. By linking technology training with economic decision-support, the Online Irrigation University will directly address one of the biggest barriers to adoption: the uncertainty of cost-effectiveness.

The bilingual delivery ensures equitable access, particularly for Spanish-speaking orchard managers and field crew, who play crucial roles in daily decision-making. By combining practical sensor training

with clear economic evaluation tools, this project will help growers adopt precision irrigation tools, conserve water, improve fruit quality, and sustain long-term profitability across Washington's tree fruit industry.

Objectives:

1. Produce and disseminate a minimum of 4 freely available instructional YouTube videos and 4 extension articles (Fruit Matters and Good Fruit Grower) within a year on irrigation management in tree fruit. Topics Include:
    a. Irrigation management of tree fruit using free weather-based tools (Troy)
    b. Sensors and their data for irrigation management in tree fruit. (Troy)
    c. Automation and precision irrigation technologies for irrigation in tree fruit. (Datta) (Article too).
    d. Variable rate irrigation opportunities and options in tree fruit. (Troy)
2. Develop free, grower-friendly, web-based ROI calculators for different precision irrigation technologies. Include default cost estimates for the various technologies but allow growers to modify these for their operations. These will be available from just a web browser. (Srikanth to meld the Datta version and the Troy version)
3. Facilitate interactive grower engagement by establishing an online discussion forum (Srikanth) and hosting at least 2 virtual workshops annually. (Datta advertise, Troy Datta Srikanth deliver. Both the same. Nov 5 @ 10:00, Dec 2 @ 10:00)
4. Ensure that all of these are available in both English and Spanish.

Significant Findings:

This project is a work in progress still. A no-cost extension to the end of April was approved. However, thus far the following progress has been made towards the objectives.

1. We have outlines and material for the instructional videos. They are planned to be recorded in the following weeks.
2. The web-based ROI calculators are functional and available online at https://test.awn.cahnrs.wsu.edu/irrigation-test/calculators/other/cost-benefit. They are under a tab for "tree fruit crops". We are doing some final testing. We used as much information as possible to get reasonable default cost estimates, but allow growers to overwrite the entered assumptions with more accurate information that is specific to their orchards, suppliers, or specific costs. We have defaults set up for the following technologies:
    a. Irrigation Automation
    b. Weather (ET) - Based Irrigation Scheduling
    c. Improved Irrigation System Maintenance
    d. Using Soil Moisture Sensors for Irrigation Scheduling (Own the Hardware)
    e. Using Soil Moisture Sensors for Irrigation Scheduling (Rent the Hardware/Hire Service)
    f. Deficit Irrigation
    g. Stemwater Potential Sensors
    h. Stemwater Potential Sensors Subscription
    i. Dendrometers
    j. Fruit Size Sensing
    k. Sap Flow Sensors
    l. Direct ET Sensors
    m. Irrigation System Remote Monitoring and Control

   n. LoRaWAN for Communication Only
   o. Paid Consulting Service
3. We will use Google Groups for the online discussion forum. This should be available by the end of November.
4. We waited until after harvest to do the workshops. The first one is on Thursday, Nov. 5. For the other one we wanted to schedule for January or February.
5. We have English and Spanish language versions of the online tools available. The Spanish language version is under review by a native Spanish speaker.

Methods:

- The ROI calculators will be located at https://irrigation.wsu.edu/. We will use Google groups for the online discussion forum.
- Instructional videos will be filmed with smart phones or existing video cameras available at CPAAS. Free video editing software will be used. The videos will be posted to the website as well as freely available on YouTube.
- Cost data for the ROI calculators was collected from irrigation technology company providers, from growers, and from online resources.
- The ROI tool is self-explanatory and explains all assumptions and methods. References for assumptions (expected water and labor savings for example) will be readily available on the website.
- An evaluation of some conclusions that can be drawn from the ROI tool and other relevant/applicable findings will be shared at field days, the annual WSTFA meeting and NW Hort Expo and other venues as requested.

Results and Discussion:

We are making good progress towards to completion of the project objectives. An evaluation of some conclusions that can be drawn from the ROI tool and other relevant/applicable findings will be shared at field days, the annual WSTFA meeting and NW Hort Expo and other venues as requested.

Literature Review:

Munoz-Carpena, R., & Dukes, M. D. (2005). Automatic irrigation based on soil moisture for vegetable crops. Retrieved from University of Florida IFAS Extension. AE354.

Osroosh, Y., Peters, R., Campbell, C., & Zhang, Q. (2016). Comparison of irrigation automation algorithms for drip-irrigated apple trees. Computers and Electronics in Agriculture, 128, 87-99. doi:10.1016/j.compag.2016.08.013

Stubbs, M. (2016). Irrigation in U.S. Agriculture: On-farm technologies and best management practices. Congressional Research Service. https://fas.org/sgp/crs/misc/R44158.pdf

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

Report Type: Final Project Report

Primary PI: Joseph Davidson
Organization: Oregon State University
Telephone: 541-737-9193
Email: joseph.davidson@oregonstate.edu
Address: 236 Rogers Hall
Address 2: 2000 SW Monroe Ave
City/State/Zip: Corvallis, OR 97331

Co-PI 2: Cindy Grimm
Organization: Oregon State University
Telephone: 541-737-2600
Email: cindy.grimm@oregonstate.edu
Address: 236 Rogers Hall
Address 2: 2000 SW Monroe Ave
City/State/Zip: Corvallis, OR 97331

CO-PI 3: Jochen Hemming
Organization: Stichting Wageningen Research
Telephone: +31 317 486710
Email: jochen.hemming@wur.nl
Address: Droevendaalsesteeg 1
Address 2:
City/State/Zip: 6708 PB Wageningen, the Netherlands

Cooperators: Munckhof Fruit Tech Innovators, Allan Bros. Fruit, Inc.

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

Item	2023	2024	2025
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:
[1]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.
[2]Supplies include consumables such as fittings, raw stock, and off-the-shelf sensors.
[3]Travel budget is requested to support mileage and lodging for data collection and field experiments.

Budget 2
Co PI 2: Jochen Hemming
Organization Name: Stichting Wageningen Research
Contract Administrator: Tom Molthof (Finance & Control)
Telephone: +31634510679
Contract administrator email address: tom.molthof@wur.nl

Item	2023	2024	2025
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).

Introduction

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, sensorized end-effector embodied with a human-like sense of touch. To accomplish our goal, we defined the following three research objectives for this multi-year project:

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

This Final Report summarizes research results from 2023-2026 (note, 2026 was a no cost extension year). Over the duration of the project, we made substantial progress across all research objectives, including new developments in sensor fusion, intelligent control, and hardware integration. In the remainder of this report we summarize our significant findings, methods, and next steps.

Significant Findings

- Visual servoing corrects for initial errors in fruit coordinates obtained with canopy imaging and deep learning-based computer vision
- Feedback control leveraging multi-modal sensing (i.e. depth, strain, and pressure) improves gripper positioning and grasp quality
- Force-based picking controllers reduce spur breaks compared to pull/pull-twist picking motions
- Volumetric air flow rates may be more important than absolute pressure when picking fruit with suction devices; determining whether to use vacuum ejectors or vacuum pumps to generate suction is a critical design decision

Objective 1: Develop prototype end-effector (OSU lead, WUR participant): Our first objective was to fabricate a prototype apple harvesting end-effector with multi-modal actuation and in-hand sensing. For this effort we designed two unique prototypes, each of which uses suction. The reason for developing two end-effectors was to identify the respective advantages and disadvantages of each design. Both end-effectors were extensively evaluated with lab and field-based studies.

'Single-mode' gripper: OSU and Wageningen University jointly developed a sensorized single suction cup gripper, shown in Figure 1. The system features one large silicone suction cup fitted with four flexible "whiskers" (bend sensors) used to correct the gripper's position with respect to the fruit, a Time-of-Flight (ToF) sensor for depth measurement to the target fruit, and in-line pressure sensors integrated into the vacuum line to continuously monitor suction levels. The suction cup and pressure housing containing the sensors are custom designs. Objective 2 provides additional details about how the sensor signals are used during closed loop fruit picking.

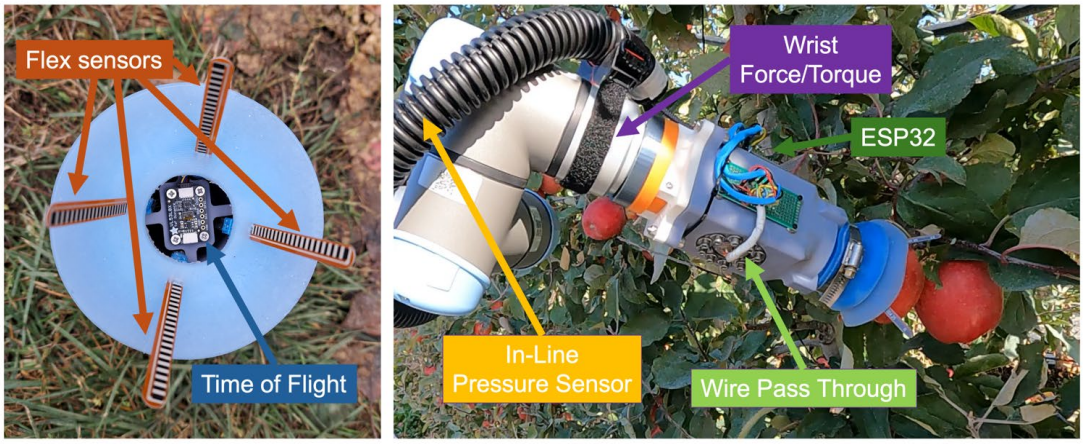


Figure 1. Compliant suction-based gripper with integrated sensing. *Left*: Top-down view of the gripper showing the suction cup and embedded sensors, including vacuum pressure, flex, and time-of-flight (ToF) sensors. *Right*: Gripper during an apple picking operation, illustrating compliant contact and suction engagement during stem abscission.

'Dual-mode' gripper: The second gripper, shown in Fig. 2, is an OSU design that combines small suction cups and three compliant, 'fin-ray' style fingers that conform to the surface of the fruit. The compliant suction cups enable the gripper to attain an initial grasp and then align the gripper for deployment of the fingers (Objective 2). Three suction cups are mounted symmetrically about the center of the gripper with in-line air pressure sensors monitoring the pressure to determine engagement at each cup. The cam-driven finger actuation creates a motion profile that first sweeps away foliage before securing the fruit within the fingers' grasp. The gripper features three fingers evenly spaced about the center-driven, central lead screw. The motor actuating the lead screw is a Cube Mars R60 motor controlled by an ODrive Micro, which enables precision position and torque control. An in-hand RGB camera and ToF sensor are also installed between the suction cups for visual servoing and to provide a depth estimate to the target fruit during the approach, respectively. The ToF sensor is additionally used to determine when to turn on the vacuum to the suction cups. Furthermore, a Realsense D435 RGB-D camera mounted at the base of the gripper can be used for initial fruit detection and localization.

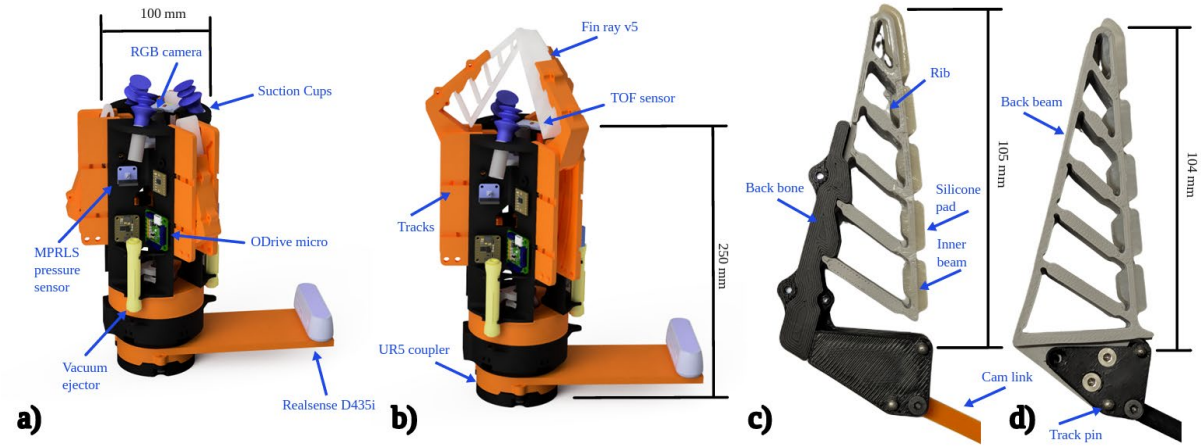


Figure 2. CAD model rendering of the gripper in the open finger configuration (a) and in the closed configuration (b). A physical image of the fin-ray effect fingers with a rigid backbone V5 fin-ray (c) and V4 fin-ray, shown without a laminar jamming layer (d).

<u>Objective 2: Design sensor fusion and control algorithms (OSU lead, WUR participant)</u>: While Objective 1 focused on hardware design, in Objective 2 we developed algorithms to fuse multiple sensor streams to align the gripper, evaluate grasp quality, and determine an optimal pick direction. We subdivided Objective 2 into three tasks.

Task 1 – Precision alignment using visual plus depth feedback: With the *single-mode gripper*, we perform fine alignment of the end effector by combining camera-based fruit localization with depth sensing from the in-line ToF sensor. The ToF sensor provides accurate distance measurements along the z-axis, while the flexible "whisker" bend sensors give feedback for centering in the x- and y-directions. The approach begins with coarse alignment from the vision system, which is then refined using feedback from the gripper's sensors. As the gripper nears the fruit, the ToF readings stabilize (indicating proximity to the suction point), and the whisker sensors confirm lateral centering. Finally, the gripper performs a small varying lateral and angular motion for fine-tune positioning when initiating suction (see Task 2). Similar to the single-mode gripper, the *dual-mode gripper* uses visual feedback from its in-hand camera to adjust its position in the x-y plane and the ToF measurement to update the depth estimate to the target along the z-axis. This depth measurement is also used to turn on suction when the gripper is close to the target fruit (~5cm away).

Task 2 – Measuring grip/grasp quality and stem orientation: To assess grasp quality with the *single-mode gripper*, we use an in-line pressure sensor to monitor the vacuum level in real time. Based on data from lab studies, we established a pressure threshold corresponding to a reliable seal and successful grasp. When the measured vacuum reaches or exceeds this threshold, the system confirms a valid grip and proceeds to the picking phase. If the pressure remains below the threshold, the gripper performs small lateral and angular adjustments to search for a better seal before retrying. This process also provides indirect information about stem orientation and contact stability.

To assist the *dual-mode gripper* in attaining a quality grasp of the fruit a pressure servoing operation is performed once a single suction cup engages with the fruit (see Fig. 3). This happens during the approach phase of the pick and is the last alignment operation before the grasp. The servoing operation uses the known geometric spacing of the suction cups with the pressure sensor readings to determine a center of rotation to traverse around to engage all suction cups. Once all suction cups are engaged, the fingers are then actuated to create a strong grasp. The operation ensures that the fruit is centered and at the correct height in the gripper and thus in the optimal position for the fingers.

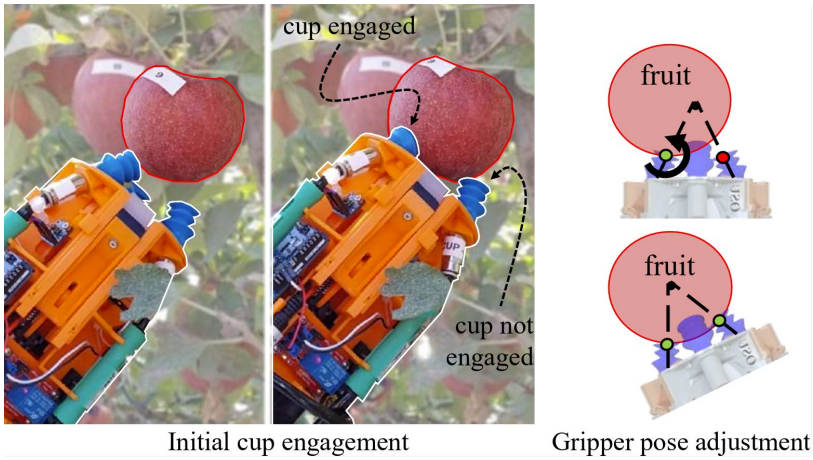


Figure 3. *Left*: Approaching an apple with our multi-cup suction gripper. Notice that one suction cup fails to engage. *Right*: Rotating the gripper with respect to the engaged suction cups until the remaining cups engage.

Task 3 – Intelligent pick directions: We developed two controllers for closed-loop picking motion generation. Both controllers use a non-linear admittance function to transform a measured force at the robot's wrist into a commanded end-effector velocity. This commanded velocity is then passed to a low-level velocity controller for control of the robot arm. We benchmarked these controllers against a naive open-loop linear pull, in which the robot arbitrarily pulls back along the plane normal of the palm of the end-effector. Our goal was to understand the difference in picking controller performance across a wide range of possible scenarios. To conduct a large number of experiments, and in order to separate the effects of controller type, plant stiffness, and plant geometry, we performed 396 trials using our indoor proxy orchard testbed. We found that plant geometry had a significant effect on simulated plant damage rate, with more orthogonal geometry being more favorable (less damage). Moreover, while the linear pull resulted in an overall spur break rate of 45%, the two closed-loop controllers achieved reduced rates of 39% and 12%, respectively.

Objective 3: Integrated field trials (OSU lead, WUR participant): The project team performed field experiments each project year (2023-2026). Test locations included Randwijk (The Netherlands), Hood River (Oregon), Prosser (Washington), and Pasco (Washington). Lessons learned from each harvest season were addressed during the following year. Here we summarize results from the 2026 harvest season with the *dual-mode gripper*. Note, we also conducted studies with the *single-mode gripper* in 2026, but data analysis was not yet complete at the time of report submission.

In 2026 the dual-mode gripper was evaluated on Red Anjou pears, Green Anjou pears, Bosc pears, Envy apples, and Cosmic Crisp apples. We included pears in the 2026 testing to evaluate whether the gripper could pick other types of tree fruit without modification. We completed two experimental protocols. For the first, we manually placed the gripper in front of the fruit (also known as free-driving the arm) and then executed a robotic pick; this step was taken to isolate end-effector performance from the computer vision system, which was not the focus of the project. For the second protocol, we completed 100 completely autonomous picks, split between Envy and Cosmic Crisp, that integrated all subsystems required for automated harvesting (i.e. fruit detection and localization, motion planning, and closed loop picks). Figure 4 shows the setup used for these studies.



Figure 4. Free drive experiment with Green Anjou pears (*left*) and autonomous harvesting of Cosmic Crisp apples (*right*).

Table 1 summarizes the results from the free-drive experiments for all fruit varieties. The dual-mode gripper successfully picked 92% of the fruit, which was a significant improvement from previous years. The gripper's suction cups and fin-ray fingers were able to pick fruit of varying size and geometry – the Anjou pears were small while the Bosc pears were large and asymmetrical. The gripper was able to complete most picks even when only one suction cup engaged due to the compliance and strength of

the fingers. Most failed picks were due to incorrect depth estimates from the ToF sensor pinging foliage such as a leaf or limb. The rate of spur breaks with the force-based stiffness seeking controller was significantly reduced compared to the naive pull and twist picking motion. Of the 101 autonomous picks, the robot successfully picked 89 apples. The 12 missed fruit were due to failed grasps where the error in the initial fruit localization from the computer vision system was so large that the gripper's in-hand sensors could not compensate.

Table 1. Summary of results from 2026 free drive studies.

Variety	Attempts	Successful grasps	Successful picks
Red Anjou	67	65	62
Green Anjou	49	42	40
Bosc	28	28	25
Envy	80	78	76
Cosmic Crisp	40	37	37
Total	**264**	**250**	**240**

The results from field experiments clearly demonstrated the potential for in-hand sensing to improve harvesting performance. While they are promising, they should still be considered preliminary. Our datasets are small and our research prototypes are not robust for long-term use in the orchard environment. Moving forward, OSU and Wageningen are collaborating with companies working on automated harvesting to translate research outcomes into commercial impact.

Project dissemination and stakeholder involvement: The team discussed the research project at multiple public events over the duration of the project, including the following:

- In the Netherlands, WUR presented the sensorized gripper design on different occasions to interested machine manufacturers. The Dutch companies Munckhof and RIWO, which are involved in an ongoing robotic apple harvesting project (UC5 Apple Picking Robot - NXTGEN Hightech), have confirmed that the integration of close-range sensors next to camera sensors is very important to increase the current picking success rate of the robot. Inspired by our project, Munckhof has started to integrate such sensors into their suction cup. The first prototypes have already been built and tested.
- OSU hosted members from the WTFRC Board and Technology Committee for an 'Innovation Exchange' in Corvallis, OR (March 2025).
- OSU discussed the harvesting project and demonstrated the robotic system for a visiting group of national journalists in September 2025
- Results from the project were presented at FIRA in 2023, 2024, and 2026
- The project team presented five research papers at the 2025 IFAC Conference on Sensing, Control, and Automation Technologies for Agriculture (Davis, CA)
    - J. Hemming, N. van Damme, M. Sytsma, R. van de Ven, G. Kootstra, and J.R. Davidson, "Multi-sensor vacuum gripper for closed-loop grasp in robotic apple harvesting," *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.
    - M. Cravetz and J.R. Davidson, "Abscission joint localization during robotic fruit harvesting using force sensing," *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.

- M. Rosette, K. Nave, E. Yong, C.M. Grimm, and J.R. Davidson, “Increasing fruit reachability in semi-structured orchards with tree templates,” *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.
- A. Velasquez, O. Gehrke, C. Grimm, and J.R. Davidson, “Air-pressure-guided servoing for robotic grasping with multi-cup suction grippers,” *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.
- E. Krueger, O. Gehrke, M. Cravetz, M. Sytsma, J. Hemming, and J.R. Davidson, “Detecting apple abscission during robotic harvesting with force and pressure sensing,” *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.

Executive Summary

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

Key words: Robotic harvesting; end-effector; sensor fusion; suction gripper; fin-ray fingers; visual servoing; force-based control; admittance control; time-of-flight sensing

Abstract: Harvesting is the most labor-intensive step in fresh-market tree fruit production, yet no commercial robotic harvester exists after nearly four decades of research. Much of the prior work on automated harvesting has relied on vision alone and ignored the sense of touch humans use during a pick. Documented performance metrics such as pick success rates, spur breaks, and fruit bruising remain inadequate for commercial adoption. This project (2023–2026), led by Oregon State University with Wageningen University & Research, aimed to increase fruit detachment rates, reduce spur breaks, and minimize fruit damage with a sensorized end-effector. The team built two suction-based prototypes: a single-mode gripper with one large suction cup, bend-sensor "whiskers", a time-of-flight (ToF) depth sensor, and in-line pressure sensing, and a dual-mode gripper combining three suction cups with three compliant fin-ray fingers, an in-hand camera, ToF, and pressure sensing. We also developed algorithms that fuse these sensor streams for visual servoing, grasp-quality assessment, and force-based admittance picking controllers. Visual servoing corrected initial fruit localization errors, and multi-modal sensing improved gripper positioning and grasp quality. In 396 indoor testbed trials, a naive linear pull broke spurs 45% of the time, versus 39% and 12% for the two force-based controllers. Suction results also suggest that airflow rate may matter more than absolute pressure, which makes the choice between vacuum ejectors and pumps a critical design decision. In 2026 free-drive field trials on five pear and apple varieties, the dual-mode gripper picked 240 of 264 fruit (91%), with most failures caused by ToF readings that hit foliage. In fully autonomous trials on Envy and Cosmic Crisp apples, it picked 89 of 100 fruit, and all misses came from localization errors too large for the in-hand sensors to correct. Dutch industry partners Munckhof and RIWO confirmed the value of close-range sensing. The work was shared with industry boards, at FIRA, and in five papers at AgriControl 2025. The results remain preliminary because datasets are small and the prototypes are not yet durable enough for long-term orchard use, so OSU and Wageningen are now working with harvesting companies to translate the findings into commercial systems.

Project Title: KISS Automated Robotic "Direct-Tree-to-bin" Apple Harvester

Report Type: Final Project Report

Primary PI: Randy Allard
Organization: ABC Med Tech
Telephone: 206.550.7675
Email: randy@abcmedtech.com
Address: 1935 Zinnia St
City/State/Zip: Golden CO 80401

Cooperators: Jeff Cleveringa – wooden apple bin, loan of bin trailer to attach robot arm, section of orchard to practice, search for elephant-ears/motor, direction by his Grower experience, statistics, orchard architecture and labor habits. Also Jeff would be orchard/harvest host during in-field trial

Project Duration: 1-Year

Total Project Request for Year 1 Funding: $ 68,384.98

WTFRC Collaborative Costs: NONE

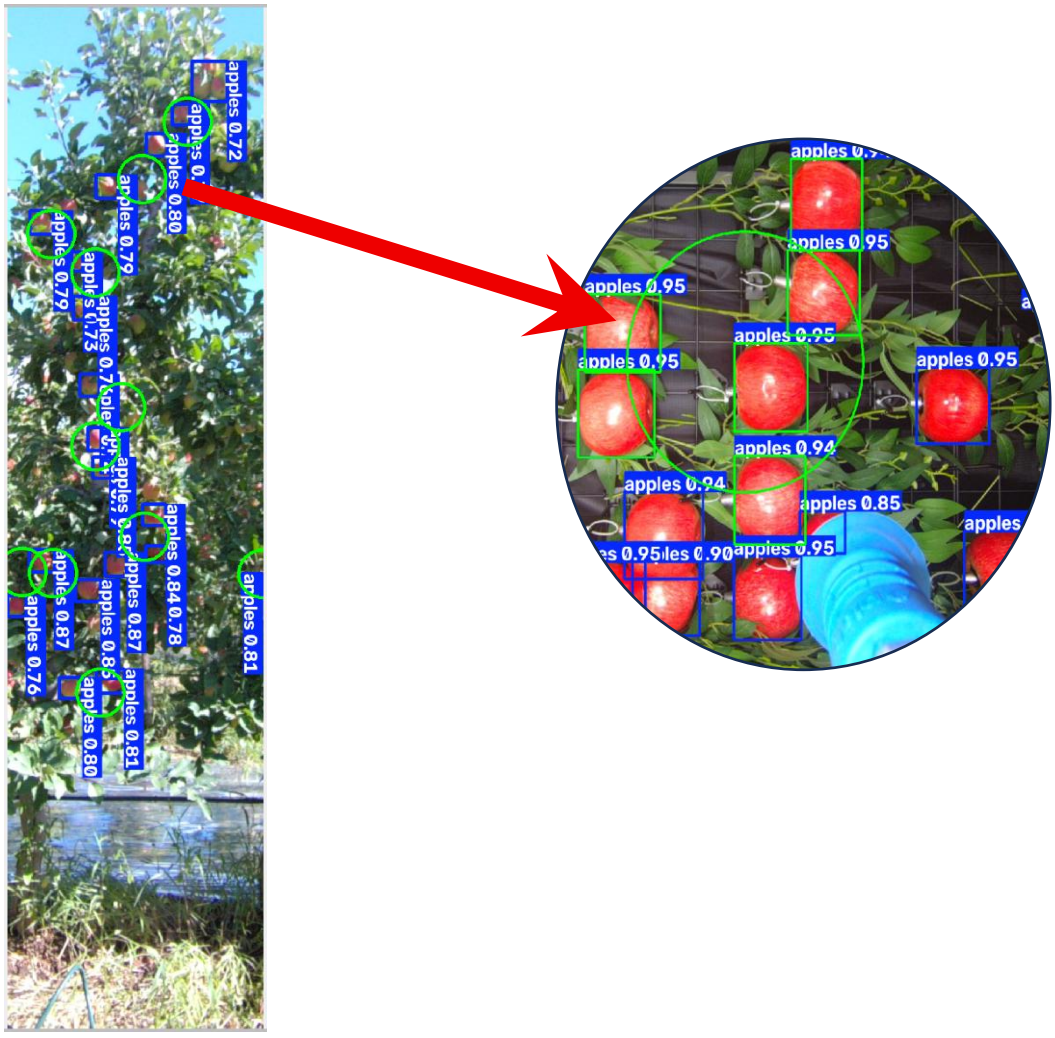
Budget 1
Primary PI: Randy Allard
Organization Name: ABC Med Tech
Contract Administrator: Randy Allard
Telephone: 206.550.7675
Contract administrator email address: randy@abcmedtech.com

Salaries -Software Eng Vision/Robotics	$25,000.00
Benefits	$0.00
Wages - Project Manager/CTO	$10,000.00
Benefits	$0.00
RCA Room Rental	$0.00
Shipping - COBOT Arms	$7,384.98
Supplies - Fabrication, hardware, pneumatic switch, cuction cup	$2,000.00
Travel	$2,500.00
Plot Fees	$0.00
2X RGB-IR Depth Cameras	$1,398.00
One 6 ft COBOT Industrial Arm	$14,600.00
Bin Air Bag Components	$1,000.00
Vision Capable Laptop Computer	$2,800.00
Miscellaneous - fake apples and rack	$1,702.00
Total	$68,384.98

Recap of Original Objectives

1. **Path Optimization & Picking Efficiency:** A ‘pre-scan’ scout camera ahead of the robotic picking arm in the orchard canopy evaluated the location or loci for groups of apples to ‘tell’ the COBOT where the apples are. The RGB-D camera ‘pre-scan’ scout camera has color RGB lenses to qualitatively (percent of redness) locate the apple then an overlay of infrared “D” which precisely locates the apple within millimeters. This ‘pre-scan’ location of loci-groups of apples improves the movement of the COBOT robotic picking arm and the picking efficiency (time) by NOT wasting unnecessary picking motions.

   Accomplishment: The scout camera successfully detected apples within a 2-foot section of the orchard canopy and identified groups of approximately six apples, providing their precise locations to the COBOT robotic picking arm. The COBOT acquired each apple within these groups in just a few seconds. The camera’s infrared capability, represented by the “D” in its designation, enabled depth perception, allowing the COBOT to prioritize and pick apples closest to the camera first.



2. **Develop for Cost Containment:** Utilizing proven components such as a waterproof industrial COBOT, waterproof RGB-D cameras, and a PIAB suction cub designed for apples provides assurance and simplicity for performance and to lessen breakdowns. Based on a per apple-cost of four cents, the ROI can occur at around 3 years for the KISS automated robotic harvesting system whereby its inherent increased picking efficiency goal 2X, longer hour picking cycles, and the deferment of human associated labor costs can further decrease this ROI time to about 1.5 years.

   ROI: If the KISS system has:

   - 2X picking efficiency goal over a human
   - Can pick for 10 hrs/day instead of 7 hrs = 1.4X
   - Extra administrative costs (H2A) per picker per day $26.50 (subtract off harvester cost over 3 years)

   The long-term thinking would be this harvester would be a labor supplement. This harvester would gradually supplement labor that is not available, capable, or becomes too expensive. Because the KISS system is small and scalable, systems could be deployed as needed/proven as the Grower adapts to the technology and could be upgraded to existing Automated Ag platforms with bin fillers.

   Accomplishment: The COBOT demonstrated the ability to traverse its picking path in just a few seconds when operating at full speed. However, several software limitations prevented the system from achieving smooth, continuous picking operations. The current robotic arm software driver did not support smooth starts and stops or continuous motion, resulting in segmented movements. In addition, a camera timestamp synchronization issue prevented the cameras from scanning while the COBOT was in motion. These limitations are correctable but had not yet been resolved during this proof-of-concept demonstration. Consequently, a full day of continuous operation and a comprehensive evaluation of sustained picking efficiency could not be established at this stage.

3. **Develop for Simple Maintenance:** Complex systems are more prone to breakdowns and incur higher repair costs. By eventually using two to four industrial-grade waterproof robotic arms, the KISS system is simpler and designed for durability and longevity and requires no maintenance for conveyance mechanisms, transition damage between mechanisms, elevating conveyors for rotary bin filling, or the monitoring of jams associated with high apple production rates. These long-reach 6-foot robotic arms, plug-play waterproof RGB-D cameras, and the PIAB ‘designed for apples’ end-effector suction cups will provide the simplicity needed for harsh agricultural environments.

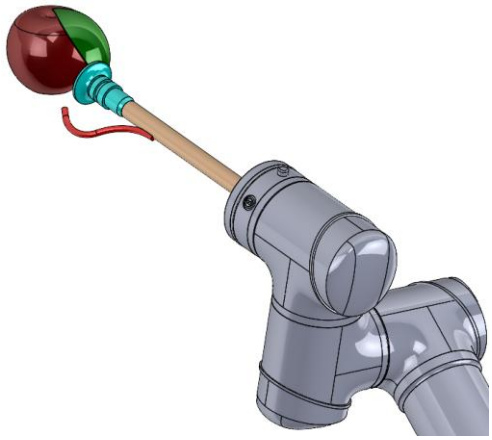
   Accomplishment: The KISS system’s design, consisting of just three primary components, supports simplified maintenance, component replacement, and reduced downtime. The system integrates an industrial COBOT with an anticipated service life of 10–15 years, self-contained waterproof RGB-D cameras designed for bolt-on, plug-and-play replacement, and a PIAB suction cup specifically designed for apple picking. The suction cup can be manually replaced if it becomes torn or worn during orchard operations. This modular, straightforward design supports practical field maintenance and helps minimize interruptions to harvesting operations, especially during a ‘Saturday service event’.

Significant Findings

1. Pre-Scan Scout Camera: Path Optimization and Picking Efficiency

The project evaluated a pre-scan scout camera system designed to identify apple locations within a two-foot section of the orchard canopy and provide precise positional information to the collaborative robotic arm (COBOT).

- Image Processing Speed: A high-performance laptop was initially used to capture and process the pre-scan image of the two-foot orchard section. However, processing overhead associated with the Microsoft Windows operating system and background applications resulted in image-processing times that exceeded the time required for the COBOT to pick the identified apples. Future development will utilize an NVIDIA Jetson computing platform running Linux and leveraging multiple GPU (Graphics Processing Unit) cores to accelerate image processing and achieve the scan speeds necessary for efficient robotic harvesting.
- Scout Camera Positioning and Fruit Visibility: The initial camera position, providing a relatively horizontal view into the orchard canopy, did not consistently capture the complete edges and boundaries of apples because leaves and branches obscured portions of the fruit. Future development will position the scout camera approximately three feet lower to provide an upward view of the canopy. This perspective is expected to reveal more of each apple's surface and boundaries, improving fruit identification and positional accuracy.
- Six-Degree-of-Freedom Robotic Arm Flexibility: The improved upward camera view is expected to enable the six-degree-of-freedom (6-DOF) COBOT to approach apples from more favorable angles, including slight downward approaches and lateral movements from the left or right. This flexibility allows the robotic arm to maneuver around leaves and branches in a manner more closely resembling human hand-eye coordination. In contrast, most other robotic systems are limited to telescoping movements or three-degrees-of-freedom (3-DOF) and have fewer options for adjusting their approach to individual apples.
- Air-Jet Leaf Management: An air jet was tested to displace leaves immediately before the suction cup engaged the apple. The initial configuration directed air straight toward the apple at a slightly upward angle. Testing indicated that this arrangement could cause leaves to remain against the apple's surface, potentially influenced by the Coanda effect, rather than moving away as intended. Future development will incorporate a rotatable air jet that directs airflow from the left or right to improve leaf displacement and provide clearer access for the suction cup.



Significance to the Industry and Potential Economic Benefits

The pre-scan scout camera is a key component of the KISS automated harvesting concept. By identifying apple locations with millimeter-level positional precision, the system is intended to guide the COBOT along optimized picking paths, reduce unnecessary arm movements, and increase the number of apples harvested per unit of time. The project's target is to achieve twice the picking efficiency of a human worker; however, this performance level remains a goal requiring validation through continuous field testing.

Combining precise fruit localization with the maneuverability of a 6-DOF robotic arm could provide a significant advantage in complex orchard environments, where leaves, branches, and varying fruit orientations frequently obstruct access. The ability to adjust the approach angle for each apple may reduce unsuccessful picking attempts, minimize wasted motion, and support gentle fruit handling.

If these anticipated improvements are achieved, the technology could increase harvesting productivity, reduce labor requirements per unit of fruit harvested, and improve the economic feasibility of robotic harvesting. Further development and field trials are necessary to quantify improvements in picking speed, successful-pick rates, fruit quality, and overall system efficiency.

2. Cost Containment and Potential Return on Investment (ROI)

Feedback received from the apple-growing community during project demonstrations highlighted several opportunities for robotic harvesting to reduce labor costs and improve orchard productivity.

- **Reduced Costs for Upper-Canopy Harvesting:** Growers indicated that harvesting apples at heights of approximately 6–12 feet can cost up to 20% more than harvesting lower fruit. These additional costs are associated with repositioning ladders, moving between trees and bins, and the time required to access upper-canopy fruit. A robotic harvesting system could reduce these inefficiencies while eliminating the need for workers to climb ladders, thereby reducing exposure to ladder-related fall hazards.
- **Improved Harvesting Economics:** The estimated cost of harvesting an apple has increased to approximately $0.05 per fruit, according to project assumptions and industry feedback. Increased regulatory requirements, higher consumer quality standards, and the need to clip stems on many apple varieties contribute to increased harvesting costs. These rising expenses strengthen the potential economic case for robotic harvesting by increasing the value of improvements in picking productivity and labor utilization. However, the actual return on investment will depend on demonstrated harvesting rates, system utilization, capital costs, and operating expenses.

Significance to the Industry and Potential Economic Benefits

The compact size and maneuverability of the KISS collaborative robot (COBOT) offer potential advantages in modern orchards, particularly V-trellis systems. Its small footprint may improve platform space utilization, reduce strenuous worker movements, and allow integration with existing picking platforms without replacing entire harvesting systems. The COBOT may also extend operating hours beyond a conventional 45-hour workweek and function in cool or damp conditions. Its soft, apple-specific suction cup and controlled movements are designed to minimize bruising and fruit damage, with performance requiring verification through field trials.

Additional economic potential comes from adapting the robotic platform for other orchard tasks, including pruning and fruit thinning, through interchangeable tools and task-specific software. This multifunctional approach could improve equipment utilization, reduce labor costs, and provide a scalable pathway to orchard automation. However, these benefits remain prospective and require further technical development, field testing, and economic evaluation to establish commercial viability.

3. Design for Simple Maintenance and Long-Term Reliability

A fundamental design objective of the KISS Automated Robotic "Direct-Tree-to-Bin" Apple Harvester is to minimize mechanical complexity, simplify maintenance, and reduce equipment downtime in demanding orchard environments. The project demonstrated several practical advantages of the system's modular, three-component design:

- **Rapid Robotic Arm Installation:** Mounting the collaborative robotic arm (COBOT) to the test bed/trailer required approximately 10 minutes, demonstrating the potential for straightforward installation and removal.
- **Modular Camera Replacement:** The waterproof RGB-D cameras are self-contained, bolt-on components designed to facilitate quick replacement without requiring extensive disassembly of the robotic system.
- **Quick-Change Picking End-Effector:** The soft PIAB suction cup, specifically designed for apple picking, can be replaced by hand in approximately one minute. This feature allows worn or damaged suction cups to be replaced quickly, minimizing interruptions during harvesting operations.
- **Durable, Replaceable Air Jet:** Because the air jet must navigate through and around branches within the orchard canopy, it will be designed to be flexible, durable, and easily replaceable. This approach is intended to reduce Apple damage during operation and simplify repairs when necessary.

Significance to the Industry and Potential Economic Benefits

The KISS system's simplified, three-component design addresses the apple industry's "Saturday service issue," when equipment failures during critical harvest periods can cause costly downtime due to limited access to technicians and replacement parts. Its modular components—the industrial COBOT, self-contained RGB-D cameras, and apple-specific suction cup end-effector—are designed for straightforward maintenance and rapid replacement, minimizing complex mechanisms and potential failure points. By eliminating extensive conveyors and transfer systems, the direct-tree-to-bin approach may reduce maintenance needs and improve reliability. Its compact design also offers the potential to retrofit existing orchard platforms, lowering adoption costs and enabling incremental automation. Long-term reliability, maintenance requirements, and economic benefits must be validated through extended field trials.

Results

The one-year project demonstrated the preliminary feasibility of the KISS "direct-tree-to-bin" apple-harvesting concept using a collaborative robot (COBOT), RGB-D cameras, and an apple-specific PIAB suction cup. The orchard proof of concept demonstrated fruit detection and robotic picking but did not establish full-day harvesting performance or economic return.

Vision and Picking: The scout camera identified apples within an approximately 2-foot canopy section and provided groups of about six fruit locations to the COBOT. Individual apples were acquired within seconds, with infrared depth data helping prioritize nearer fruit. However, slow image processing, leaf-obstructed fruit boundaries, and camera timestamp limitations restricted scanning during robot movement.

Robotic Motion and Fruit Access: The COBOT traversed its picking path quickly at full speed, but software driver limitations caused segmented movements and prevented smooth, continuous operation. Initial air-jet testing also showed that airflow could press leaves against apples rather than clear them, requiring further design refinement.

Assembly and Maintainability: The modular design supported rapid assembly and component replacement. The COBOT was mounted in approximately 10 minutes, while the suction cup could be replaced by hand in about one minute. The separate, bolt-on cameras and a proposed flexible, replaceable air jet further support simplified maintenance and orchard serviceability.

Discussion

Pre-scanning provided useful fruit-location data, but overall harvesting efficiency remains unverified because continuous operation was not achieved. The proposed twofold efficiency improvement and full-day comparison with human pickers remain unconfirmed.

Key improvements needed include faster image processing using NVIDIA Jetson computer (without Microsoft), synchronized timestamp cameras and smoother COBOT arm motion, improved camera positioning with dual-view lower vision trajectories, and adjustable airflow for leaf displacement.

The modular design demonstrated easy maintenance, with COBOT installation taking approximately 10 minutes and suction-cup replacement about one minute. Long-term durability and the projected 10–15-year COBOT service life remains unverified.

Potential benefits include reduced labor, compatibility with existing orchard platforms, and improved upper-canopy access. However, efficiency gains and ROI remain estimates pending measurements of picking rates, fruit damage, downtime, and operating costs. Future trials should measure picking rates, scan-to-pick time, fruit quality, uptime, and maintenance under orchard conditions to establish commercial viability and payback.

Literature Review

1. Oregon State University; Joseph Davidson PhD; GitHub access “Apple 3D Localization” 2024
2. B Yan; X Li; “RDG-D Camera and Fractal Geometry Based Maximum Diameter Estimation of Apples for Robot Intelligent Selective Graded Harvesting”; MDPI Fractal Fract 8, 649 https://doi.org/10.3390/fractalfract8110649; https://www.mdpi.com/journal/fractalfract
3. W Hua et al: “Vacuum Suction End-Effector Development for Robotic Harvesters of Fresh Market Apples”; Biosystems Engineering; Vol 249, Jan 2025, Pages 28-40
4. Patents and Intellectual Property: US11425852 Autonomous Detection and Control of Vegetation: US12004451 Autonomous Crop Harvester; US12137681 Detection and Precision Application of Treatment to Target Objects: US2024/0343500 Item De-Binning Systems and Methods; WO2023/154267 End Effector for Picking of Items; WO2024/215617 Container Filling Systems and Methods

Executive Summary

The KISS (Keep It Simple, Stupid) Automated Robotic "Direct-Tree-to-Bin" Apple Harvester project evaluated a cost-effective approach to apple harvesting using a collaborative robotic arm (COBOT), waterproof RGB-D cameras, and an apple-specific PIAB suction cup. Objectives included demonstrating robotic picking, improving efficiency, reducing seasonal labor dependence, controlling costs, and simplifying maintenance through modular design compatible with existing orchard platforms.

Vision Technology and Robotic Picking: The project demonstrated pre-scanning a two-foot canopy section to identify apple locations and communicate groups of approximately six apples to the COBOT. Individual apples were acquired within seconds, while infrared depth information helped prioritize nearer fruit. However, processing delays, camera synchronization issues, and robotic motion limitations prevented continuous operation. Faster computing, improved synchronization, refined leaf management and revised camera positioning are recommended.

Cost Containment and Economic Potential: The KISS design uses three components: an industrial COBOT, self-contained RGB-D cameras, and an apple-specific suction end-effector. Its simplified architecture aims to reduce mechanical complexity, minimize fruit handling, and integrate with existing picking platforms. Robotic harvesting could reduce upper-canopy labor and ladder-related risks. Preliminary projections suggest a three-year payback, potentially decreasing to 1.5 years if productivity targets are achieved. These estimates remain unverified because sustained picking rates and operating costs were not established.

Maintenance and Durability: The modular design demonstrated practical serviceability. The COBOT was mounted in approximately 10 minutes, and the suction cup replaced by hand in about one minute. Separate cameras allow straightforward replacement. Eliminating extensive conveyors and bin-transfer mechanisms may reduce maintenance and failure points. The COBOT's anticipated 10–15-year service life requires orchard validation.

Future Potential and Next Steps: The platform could support pruning and fruit thinning through interchangeable tools and task-specific software. The one-year project established a proof of concept for robotic apple detection, picking, and modular construction. However, full-day operation and the targeted twofold productivity improvement remain unverified. Future trials should measure picking rates, fruit damage, uptime, maintenance, labor savings, and operating costs to establish commercial viability and validate return on investment.

Overall, the KISS approach offers potential to improve efficiency, address labor constraints, simplify maintenance, and support incremental adoption of robotic automation in commercial apple orchards.

KISS Automated Robotic "Direct-Tree-to-Bin" Apple Harvester

Key words: robotic, automation, apple, camera, labor

Abstract: Developed by ABC Med Tech aka Pluck Robotics, the KISS (Keep It Simple, Stupid) Automated Robotic "Direct-Tree-to-Bin" Apple Harvester explores an affordable, maintainable approach to robotic apple harvesting that addresses rising labor costs and seasonal worker shortages. The system integrates three components: an industrial collaborative robotic arm (COBOT), waterproof RGB-D cameras, and an apple-specific PIAB suction cup. The one-year project demonstrated pre-scanning a two-foot canopy section, identifying groups of approximately six apples, and guiding the robot to acquire individual fruit within seconds. Its modular design also supports straightforward installation and component replacement. Image-processing delays, camera synchronization issues, and robotic motion limitations prevented continuous operation. Therefore, full-day productivity and the targeted twofold improvement over human picking remain unverified. Future development will focus on faster processing, improved coordination, and smoother robotic movement. Preliminary projections suggest a potential 1.5- to 3-year payback, subject to achieving productivity and cost-saving targets. Further field testing will establish commercial viability and the system's value to apple growers.

Budget: $68,384.98

Project Title: Dutch & American Tech in Action: Sensor-Driven Precision Spray

Report Type: Final Project Report

Primary PI: Steve Mantle
Organization: innov8.ag
Telephone: 509-795-1395
Email: steve@innovate.ag
Address: 103 E Main St Ste 301
Address 2:
City/State/Zip: Walla Walla, WA 99362

Co-PI 2: Joost Hazelhoff
Organization: Aurea Imaging
Telephone: +31-626-640-659
Email: joost@aureaimaging.com
Address: Nijverheidsweg 16A
Address 2:
City/State/Zip: 3534 AM Utrecht, Netherlands

CO-PI 3: Gwen Hoheisel
Organization: Washington State University (WSU) Extension
Telephone: 509-788-5459
Email: ghoheisel@wsu.edu
Address: 620 Market St.
Address 2:
City/State/Zip: Prosser, WA 99350

Co-PI 4: Lav Khot
Organization: Washington State University (WSU)
Telephone: 509-786-9302
Email: lav.khot@wsu.edu
Address: 24106 N Bunn Road
Address 2:
City/State/Zip: Prosser, WA 99350

Cooperators: Daniel Rowley (Cherry Hill Farms); NWFM LLC (Keith Veselka; Carmelo Garcia, area manager), operator of Smart Orchard Zillah (2025) and Smart Orchard Moxee (2026), WA; Outfield Technologies (Jim McDougall); Tyton Aviation (Aaron Tyler); Red Ant Agri (James Reid); Burrows Tractor (TJ Lange, Tom Riel); Washington Fruit Growers (Paul Cathcart); Slimline/Turbomist; Agromanager; WSU Smart Apple Orchard team.

Project Duration: 2-Year

Total Project Request for Year 1 Funding: $74,565
Total Project Request for Year 2 Funding: $75,284

Other related/associated funding sources: Awarded
Funding Duration: 4 years
Amount: €2.481 million
Agency Name: Dutch Ministry of Agriculture, Nature and Food Quality

Notes: Total program size is €4.962 million over 4 years; the other half (€2.481 million) is financed by Dutch growers and companies (in cash and in kind) and the Washington Tree Fruit Research Commission.

WTFRC Collaborative Costs: None

Budget 1
Primary PI: Steve Mantle
Organization Name: innov8.ag
Contract Administrator: Susan Colter
Telephone: 509-473-0252
Contract administrator email address: susan@innovate.ag

Item	**2025**	**2026**
Salaries		
Benefits		
Wages	$8,250.00	$8,662.50
Benefits	$1,650.00	$1,732.50
RCA Room Rental		
Shipping		
Supplies	$11,000.00	$2,500.00
Travel	$1,305.60	$1,370.88
Plot Fees		
Miscellaneous		
Total	$22,205.60	$14,265.88

Footnotes: Wages calculated at a blended $50/hr and benefits at 20%, estimating ~160 hours of labor each year to support equipment integration and coordination across co-PIs and collaborators to meet objectives. Travel to/from sites and collaborators estimated at $0.67/mi in 2025 with a 5% increase in 2026. Supplies support equipment install and integration.

Budget 2
Co PI 2: Joost Hazelhoff
Organization Name: Aurea Imaging
Contract Administrator: Stefan Kueken
Telephone: +31 611 279 512
Contract administrator email address: stefan@aureaimaging.com

Item	**2025**	**2026**
Salaries	$24,000.00	$24,000.00
Benefits		
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies		
Travel	$10,000.00	$10,000.00
Plot Fees		
Miscellaneous	$9,500.00	$9,500.00
Total	$43,500.00	$43,500.00

Footnotes: Miscellaneous = data processing and cloud compute/software services. Travel includes flights and accommodation between the Netherlands and Washington to support equipment install and operation. Grower participation is expected to include allocating a budget for data collection equipment rental.

Budget 3
Co-PI 3: Gwen-Alyn Hoheisel
Organization Name: Washington State University
Contract Administrator: Lesa Neumann
Telephone: 509-335-8467
Contract administrator email address: lneumann@wsu.edu
Station Manager/Supervisor: Naidu Rayapati/Karen Lewis

Item	**2025**	**2026**
Salaries	$2,203.00	$2,291.00
Benefits	$566.00	$589.00
Wages		$3,197.00
Benefits		$591.00
RCA Room Rental		
Shipping		
Supplies		$4,500.00
Travel	$453.00	$453.00
Plot Fees		
Miscellaneous		
Total	$3,222.00	$11,621.00

Footnotes:

Budget 4
Co-PI 4: Lav Khot
Organization Name: Washington State University
Contract Administrator: Lesa Neumann
Telephone: 509-335-8467
Contract administrator email address: lneumann@wsu.edu
Station Manager/Supervisor: Naidu Rayapati/Manuel Garcia-Perez

Item	**2025**	**2026**
Salaries	$4,100.00	$4,305.00
Benefits	$1,086.50	$1,140.83
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies		
Travel	$452.00	$452.00
Plot Fees		
Miscellaneous		
Total	$5,638.50	$5,897.83

Footnotes: Budgets 1–4 are shown as approved in the 2025 Continuing Project Report.

Recap Original Objectives

1. Validate precision-spray workflows linking TreeScout sensing with variable-rate sprayers.
2. Compare OEM-integrated versus retrofit configurations for cost, reliability and scalability.
3. Demonstrate complete data flow, from canopy mapping through spray execution and as-applied tracking.
4. Engage growers, equipment dealers and research partners in real-world validation and education.

Status by objective. Objective 1, met: maps from TreeScout, Aurea Imaging's tractor-mounted camera that scans each tree and counts its blossoms, drove chemical variable-rate thinning on the grower's own controller at Cherry Hill (Section 2), and drone maps drove chemical thinning on the retrofit at Moxee (Section 3); the TreeScout-to-retrofit link itself ran water only (2025). Objective 2, partly met: costs and reliability are reported (Section 1, Table 1), but the factory-integrated (OEM) path was not run in 2026; the 2025 report had set the retrofit as the 2026 focus. Objective 3, met: maps went from canopy mapping into the sprayer controllers, and as-applied records were logged in Red Ant's portal and reviewed (Section 4). Objective 4, met (Section 8).

Significant Findings

- **Ground and drone bloom maps both drove thinning sprays (2026).** At Cherry Hill Farms, grower Daniel Rowley has logged 57 Aurea Imaging TreeScout scans across his 22 fields and thinned about 20 acres from a TreeScout prescription map on his own John Deere GPS and CapstanAG system. At Smart Orchard Moxee (WSU testbed; Block 11, organic Honeycrisp), Outfield drone blossom maps drove variable-rate lime sulfur thinning sprays through the Red Ant retrofit on April 23 (from an April 21 map) and April 24 (from the April 23 map). On April 24 the map skipped 251 of 2,184 map cells (about 1 in 9) in the variable-rate rows, planning 8% less spray than a flat rate; Red Ant's portal logged both runs (Section 4).
- **TreeScout blossom counts tracked hand counts.** On Cherry Hill block A81B, TreeScout counts tracked the grower's hand counts ($R^2 = 0.73$, where 1.0 would be a perfect match), so on that block one calibration converts scans into a blossom-load estimate (Section 2).
- **Early signs of benefit from tree-by-tree thinning.** At Cherry Hill, Rowley observed that bloom was quite uniform in 2026 and attributes it to the tree-specific thinning done in 2025 from Aurea blossom maps (Courtney 2026; a grower observation, not a measured result). In Cornell AgriTech's 2026 New York trials (preliminary; not conducted by this project), high-bloom trees were thinned to almost exactly the target at two of three farms, and at one Aurea-mapped farm low-bloom trees had 23% single-fruit clusters against 46% conventional (Jiang et al. 2026; Section 6).
- **Three ways to control a sprayer from a map.** In 2025 Aurea TreeScout, Green Atlas and Outfield maps ran, water only, with left/right control on a factory-integrated New Holland system (≈$20K or more per sprayer; closed-cab tractor required) and on a Red Ant Agri retrofit on existing tractors (about $3K in parts in 2025; about $4,800 dealer-installed, Red Ant's preliminary 2026 estimate). In 2026 the grower-built system at Cherry Hill added a third path.
- **At Moxee, no measurable thinning effect from the spray could be shown, with variable rate on only part of the program.** Of three lime sulfur passes, the first (April 21) was uniform across the block and only the last followed the analysed map. Before hand thinning, light trees the map skipped did not carry more fruit than sprayed light trees in a control strip in most comparisons; Outfield's bloom-timing-adjusted estimate of 6–9% more fruit on skipped light trees at harvest appeared only after hand-thinning crews removed more fruit from the sprayed light trees, and most ranges of uncertainty included no difference (one block, one season).
- **Spray drift limits map resolution.** In one WSU water-sensitive-paper test, valves switched at the mapped points (judged by eye), but spray drifted at least 4 ft down the row past the shut-off point (the cards ended at 4 ft), about one tree at this block's spacing. WSU notes this would

indicate the fan is oversized for the canopy; the drift is one reason the team used 16-ft cells. RTK corrections also dropped out at times during both thinning sprays.

- **Late trees can look like light trees.** The Moxee map was made before peak bloom, while the north end of the block was still opening. Mapping bloom on two or more dates before the spray should help separate late trees from light ones.
- **Extension.** At the Smart Orchard Field Day at FIRA USA (October 22, 2026; more than 250 attendees), innov8.ag joined the crop load track and the Red Ant retrofit was shown, with Red Ant Agri's James Reid on hand; WSU Extension also presented the retrofit at the Codling Moth IPM Field Day (July 31).

Methods

Sites

- **Smart Orchard Moxee (WSU Smart Apple Orchard testbed), Moxee, WA.** For 2026 the testbed moved from Smart Orchard Zillah (2025), which was sold, to an organic Honeycrisp block (Block 11; 11.5 ac, planted 2011, single leader, 4 × 10 ft spacing). NWFM LLC operated both. Co-PI Khot's team moved the testbed here and organized the field day; co-PI Hoheisel's team ran the spray placement test.
- **Cherry Hill Farms (Daniel Rowley), Caldwell, Idaho.** Grower cooperator since Year 1 (Mantle et al. 2025), with 22 fields on Aurea's TreeScout platform.

Terms used in this report

- **Spray map** (also called a prescription or task map): a map that tells the sprayer where to spray and where to shut off.
- **Map cell:** one grid unit along a row in Outfield's maps, about 1 to 4 trees. At Moxee, "variable rate" meant on or off by cell.
- **Blossom index:** Outfield's relative bloom-density score from drone imagery. It is not a count, surveys are not on a common scale, and it was not calibrated to hand counts at this site.
- **Light cell:** a cell below the spray cut-off on the April 23 blossom map; heavy cells were above it.

Sensing

- **Aerial (Moxee).** Tyton Aviation and Outfield Technologies used DJI Dock 2 and Dock 3 drone-and-dock systems, which fly scheduled missions from a base station within a 2 to 3 mile radius. The dock was about 2 miles from Block 11; each survey took about 14 minutes and was flown autonomously to Outfield flight plans, monitored by Tyton Aviation. Thirteen blossom surveys were flown from April 19 to May 11, near-daily through bloom, and 10 more followed from 18-mm fruitlets (May 24), including fruit-loading and canopy-closure maps. Fruit counts for the September 2 flight were calibrated to hand counts. Tyton Aviation reports more than 60 survey flights in 2026, with data delivered within 4 hours of tasking in all but a few (A. Tyler, Tyton Aviation, pers. comm., September 2026). About a dozen panels in the northwest corner could not be surveyed because of power lines; missing cells were filled in from neighbouring cells.
- **Ground (Cherry Hill).** Tractor-mounted TreeScout. Blossom mapping ran April 7–10, 2026 (22 blossom drives). The grower hand-counted 20 to 30 trees per field and sent the counts to Aurea for calibration. His own system, John Deere GPS with a CapstanAG controller, executed Aurea prescription maps. In 2026 Aurea's TreeScout work centred on Cherry Hill; Aurea did not scan the Moxee block, which was mapped by drone.

Moxee thinning trial

A water test on February 24 at Smart Orchard Zillah checked map loading, RTK GPS and valve switching; setup and water tests on Block 11 followed on April 9–10. The bloom thinner was lime sulfur at 8% (32 gal in a 400-gal tank; K. Veselka, NWFM, pers. comm., November 2026) applied at 80 gal/ac, the rate set in the Red Ant jobs, or about 6.4 gal/ac of lime sulfur. A first variable-rate

attempt on April 21 failed when the valves on the sprayer then fitted would not close reliably (Section 7), and the grower sprayed the whole block uniformly that day ahead of a storm. The system was moved to a second Turbomist with one valve per side, which made variable-rate applications on April 23, from a map built on April 21 (Red Ant configuration “Moxee11 20260421”), and on April 24, from the April 23 map described here. The Red Ant portal shows no further runs from April 25 through May 15.

The April 24 map applied a single blossom-index cut-off (4.89) to the April 23 survey, set with the orchard management team, in 16-ft sections (four trees). Treatment was assigned by row group, not at random: in rows 1–30, light cells were skipped; the control strip (rows 31–42) was sprayed in full, including 188 light cells. At its nominal 80 gal/ac, Red Ant's plan for the job was 837 gal instead of 912 gal at a flat rate (8% less). The field team reported any offset between the map and the sprayer GPS so Outfield could move the map. Red Ant's plan for the April 21 map was 720 gal instead of 912 gal (21% less), so it skipped more of the block than the April 24 map. Crews hand thinned the block to a per-tree target around May 29. The April 21 map's cut-off and the hand-thinning target are not documented in the records available for this report (Red Ant Agri 2026; project team communications 2026).

Retrofit sprayer control (Red Ant Agri)

Red Ant Agri (Ceres, South Africa) supplied the retrofit controller. In the 2025 configuration it drove two solenoid valves for independent left/right control and was run from a rugged Android phone whose Red Ant app handles job selection, map loading and as-applied mapping; position came from the phone's built-in GPS receiver, with no external receiver. The controller accepts GeoJSON or shapefile maps. Red Ant reports that the controller needs internet only at log-in, to receive its configuration; in the field the phone stores as-applied data and sends it to Red Ant's online portal when a connection returns. RTK (centimeter-level) corrections, however, need a data link in the field; at Moxee in 2026, where there is no cellular coverage, an NTRIP correction feed reached the phone over a tractor-mounted Starlink terminal, and the portal logged speed, reported accuracy and correction status. Red Ant's James Reid supported setup and troubleshooting remotely at Moxee and Washington Fruit Growers (WashFruit) in 2026.

Spray placement test (WSU)

On April 10, 2026 (Block 11, row 6), WSU Extension placed water-sensitive paper in a grid at 1-ft increments through sprayed, transition and unsprayed areas while a Red Ant–controlled Turbomist applied water, comparing high and low air. The test map had 16-ft sections (Outfield, April 8); WSU's later summary describes 8-ft sections. On this four-zone sprayer only the lower nozzles were switched, and the thinning sprays used a different Turbomist with one valve per side, so the test characterizes the method rather than the thinning sprayer. Efficacy was not tested.

Thinning outcome analysis (Outfield)

Outfield analysed the trial; this project did not re-run the analysis. It compared how fruit changed on skipped light cells in rows 1–30 with sprayed light cells in the control strip. Heavy cells were sprayed in both zones, so comparing the light-minus-heavy difference between zones cancels out zone differences unrelated to the spray (a difference-in-differences design, using count models with errors clustered by row). Models were adjusted for pre-spray bloom timing (how fast each cell was still opening between April 19 and 23) and position along the row, and a threshold check compared cells just either side of the cut-off. Fruit was measured as counts from drone surveys on May 24 (before hand thinning) and June 30, and from the calibrated count on September 2; fruit size and packout were not measured. WSU hand counts at 8 sites (5 trees each) recorded bloom clusters (April 9), fruiting clusters (May 26, before hand thinning), fruit set (July 7) and fruit a week before harvest.

Results and Discussion

Year 1 to Year 2. In 2025 both control paths executed TreeScout, Green Atlas and Outfield maps with water at Smart Orchard Zillah (Mantle et al. 2025); the 2025 report set the retrofit as the 2026

focus and listed seven next steps (Table 3). The 2025 report called the retrofit a viable path at about $3K in parts; 2026 showed that it runs, at about $4,800 dealer-installed (Red Ant's preliminary 2026 estimate), and that it needs setup help (Table 1, Section 7). In 2026 the testbed moved from Smart Orchard Zillah to Smart Orchard Moxee, where the spray maps came from Outfield drone surveys rather than TreeScout (Aurea's 2026 field work under this project was at Cherry Hill), and the sprays carried chemical. Section headings carry objective tags; Section 5 reports the thinning outcome, which was exploratory (efficacy was not a project aim); Section 6 summarizes related New York work this project did not conduct; Section 7 collects what did not work; Sections 9 and 10 answer the 2025 commitments and the Committee's comments.

1. Control paths: factory-integrated, retrofit and grower-assembled (Objective 2)

In 2025 both project control paths (Scenario 1, factory-integrated, and Scenario 2, retrofit, in the 2025 report) ran TreeScout prescriptions from vigor (March 21 and July 30), blossom (April 15–17) and fruit-density (September 29–30) scans with independent left/right control. Both also ran Green Atlas and Outfield/Tyton Aviation maps as delivered. All 2025 runs used water (Section 7). The factory-integrated (OEM) path depended on New Holland firmware updates; the retrofit installed on existing open-cab New Holland tractors and ran from a phone app. In 2026 a grower-assembled path emerged at Cherry Hill (Section 2). Both the Red Ant and the grower's CapstanAG setups switch the left and right sides independently: Red Ant on or off, CapstanAG off, low or high. Both could control finer sections, but that would need additional valves and controls. Burrows Tractor (Ag Technology Manager TJ Lange) and innov8.ag installed and tested the project's Red Ant controller on a WashFruit Rears sprayer on June 10, 2026, for an on/off foliar nitrogen application from an Orchard Robotics task map. It ran on standard GPS without RTK corrections, which Red Ant judges sufficient for foliar and growth-regulator sprays but not for bloom thinning. WashFruit's Paul Cathcart has said that handing variable-rate thinning to a new technology carries a lot of risk, and that growers should start with zonal applications such as fertilizer, where a miss costs little (Courtney 2026); the WashFruit trial follows that order. On the control side, Red Ant Agri reported more than 120 Smart Node implements deployed worldwide, including spray applications, and is expanding into U.S. tree fruit (Mantle et al. 2025); Burrows Tractor is its prospective Washington dealer, no Washington sales were reported in 2026, and scaling through Burrows and WSU Extension is in progress (Table 3). On the sensing side, Aurea's TreeScout is in commercial use: Aurea had five units on U.S. commercial orchards as of September 2026 (B. Rijk, Aurea Imaging, pers. comm., September 1, 2026), in addition to 45 deployments in Europe and South Africa reported in 2025 (Mantle et al. 2025).

Table 1. Three paths from a spray map to a variable-rate sprayer. Costs come from different sources and cover different components; they exclude sensing and map services and are not a cost-of-ownership comparison.

	Factory-integrated (OEM, 2025)	**Retrofit (2025–26)**	**Grower-assembled (2026)**
Controller	New Holland RCM + Raven RS1 RTK GPS + Viper display	Red Ant controller driving 2 solenoid valves (on/off, left and right sides); Android app for job, map loading and as-applied mapping	CapstanAG nozzle controllers + John Deere GPS via a grower-built switch-and-relay interface (off/low/high, left and right sides)
Map sources run	TreeScout, Green Atlas, Outfield	TreeScout, Green Atlas (2025), Outfield; Orchard Robotics (WashFruit, 2026)	TreeScout
Equipment cost (source)	≈$20K or more per sprayer (2025 report)	≈$3K, controller and two valves (2025 report); ≈$4,800 dealer-installed, Red Ant's preliminary 2026 estimate (J. Reid, pers. comm., June 2026)	≈$15K for the John Deere GPS (Courtney 2026)
Tractor	Closed-cab New Holland T4.100 only (≈$85K or more)	Existing open-cab New Holland tractors	Closed-cab John Deere

	Factory-integrated (OEM, 2025)	Retrofit (2025–26)	Grower-assembled (2026)
Where used	Smart Orchard Zillah 2025 (water)	Smart Orchard Zillah 2025 (water); Smart Orchard Moxee 2026 (thinning sprays, April 23–24); WashFruit 2026	Cherry Hill 2026 (~20 ac thinned)
Reliability issues observed	Depended on New Holland firmware updates	Moxee: valves stuck open (April 21); row-end faults (April 23); RTK dropouts, one stall (April 23–24); map offset; valves judged prone to blocking with lime sulfur. WashFruit: phone disconnections (June 23). Section 7	Not monitored by this project

2. Cherry Hill Farms: Aurea TreeScout at grower scale (Objectives 1 and 2)

Before bloom, Aurea ran pre-season checks with grower Daniel Rowley, including test scans and test task maps, and confirmed that TreeScout, GPS and sprayer worked together. Rowley then thinned about 20 acres from a TreeScout prescription map. On his remaining acres he did not use prescription maps because rapidly changing weather made that unsuitable, and he wants maps again for the fruitlet thinning round. He wanted spraying to switch automatically, tree by tree, so he wired a switch-and-relay interface that drives CapstanAG nozzle controllers on his Turbomist sprayer from the map through John Deere GPS, choosing off, a low rate or a high rate (for example 100 or 200 gal/ac) on each side, tree by tree; the CapstanAG controllers split that rate between upper and lower nozzles. He bought the John Deere GPS for about $15,000 after a beta test, and he uses the same maps for Apogee, ethephon, gibberellins and other crop load products (Courtney 2026). Before bloom he mapped tree positions in several fields, the first step before any map-based application; he has logged 57 scans across his 22 fields on Aurea's platform, including blossom, vigor and apple-count maps.

Aurea reported one validation block, A81B: TreeScout counts tracked Rowley's hand counts with R^2 = 0.73 across roughly 230 to 740 blossoms per tree, so on this block a single calibration gives a blossom-load estimate. The number of trees compared was not reported. Rowley observed that bloom was quite uniform this season and attributes it to the tree-specific thinning done in 2025 from Aurea blossom maps; that is a grower observation, not a measured result. No post-thinning fruit counts or yield were reported for the map-thinned acres.

3. Moxee: a drone blossom map as the spray map (Objectives 1 and 3)

Near-daily flights through bloom let the team follow bloom emergence across the block, then turn the April 23 blossom map into the Red Ant spray map for the April 24 application, shown from the drone in Figure 1. In the variable-rate rows, 251 of 2,184 cells (11.5%) fell below the cut-off and were skipped, mostly at the north end of rows 1–12 with scattered pockets elsewhere (Figure 2).

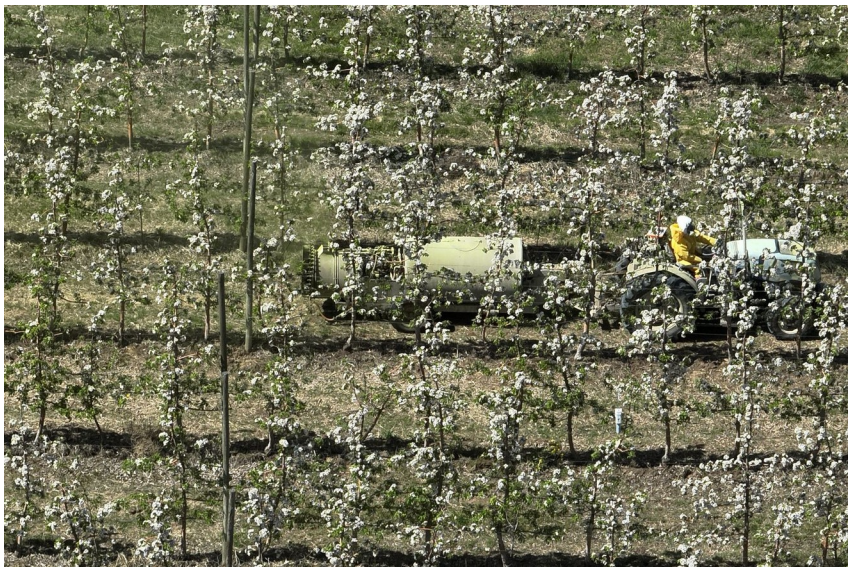


Figure 1. Drone view of the Red Ant–controlled sprayer in Block 11 at bloom, April 24, 2026, the variable-rate application from the April 23 map. Source: Outfield Technologies / Tyton Aviation.

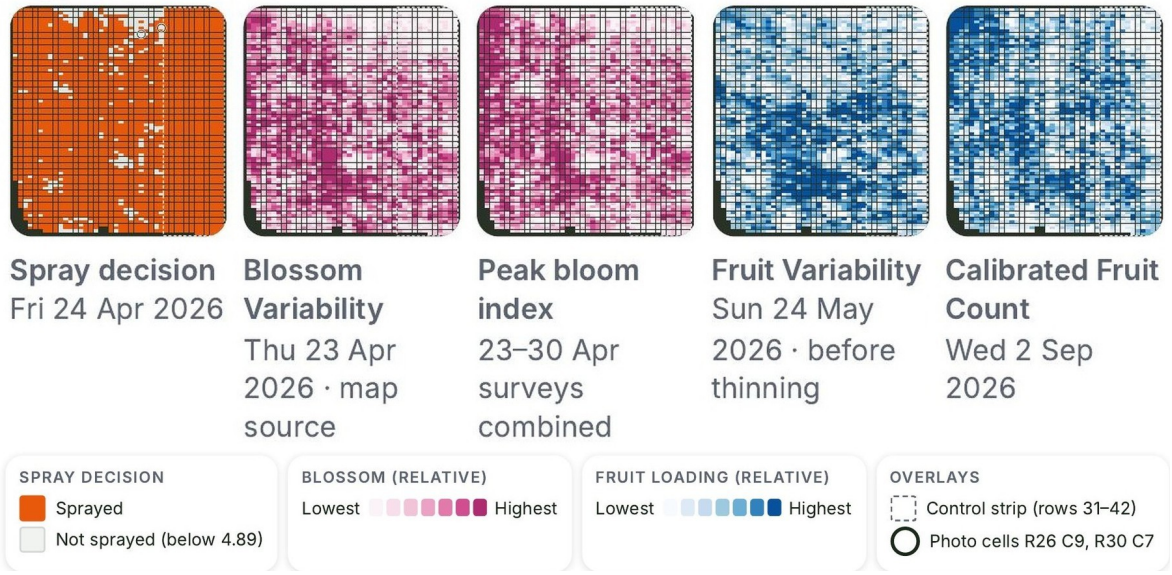


Figure 2. Block 11 maps, north up (row 1 is the west edge; the dashed control strip is rows 31–42). From left: spray decision for the April 24 application (orange sprayed, white skipped); blossom index, April 23 (map source); peak-bloom index, April 23–30; fruit loading, May 24 (before hand thinning); calibrated fruit count, September 2. Colours rank cells within each map (each shade is one-seventh of the cells), so shades cannot be compared between maps. Source: Outfield Technologies, Block 11 Thinning Review (2026).

4. Moxee: as-applied record and where the spray landed (Objective 3)

Red Ant's portal logged the April 24 application from 11:28 a.m. to 2:33 p.m. in four sessions (Figure 3). At the logged points checked in the block, the sprayer travelled 3.1–3.3 mph (setting 3.0 mph) with reported position accuracy of ±0.5–0.9 ft; the run paused three times, the longest for about half an hour. The April 23 application (April 21 map), logged from 11:19 a.m. to 2:09 p.m., showed similar speeds and accuracies. On both days RTK corrections dropped out for periods, even over Starlink, so parts of each run were positioned without fresh corrections; reliable RTK is a prerequisite for tree-level maps. RTK generally holds lock more easily early in the season, with less foliage and RF interference, and gets harder as the canopy grows, so later-season sprays will be more demanding.

On April 21 the portal logged only setup runs and one test pass along a single row. Positions logged without fresh corrections may be less accurate than reported. The as-applied record was not compared cell by cell with the plan or used in the outcome analysis.

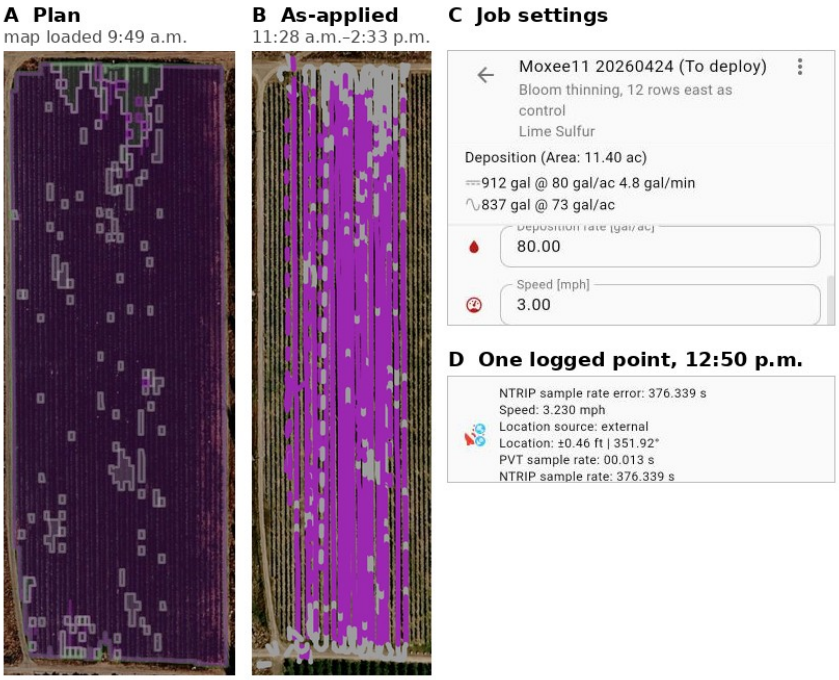


Figure 3. Red Ant record of the April 24 variable-rate spray, Block 11, north up. A: spray map as loaded (purple sprayed, grey-outlined cells skipped). B: logged as-applied points (colours as in A; the portal shows no legend). C: job settings (nominal planning rate). D: one logged point (speed, position accuracy and correction status). Source: Red Ant Agri portal (A shared by Outfield, April 24; B–D captured November 2026).

In the April 10 water test the valves turned the nozzles on and off at the mapped points, judged by eye against the phone map; no surveyed check was made. Even so, WSU recorded decaying drift down the row for at least 4 ft after shut-off (the cards ended at 4 ft; Figure 4), roughly one tree at this block's 4-ft spacing, which WSU notes would indicate the fan is oversized for this canopy. The fan can be modified. Three limits set how fine a spray map can usefully be. The first is how far spray carries past the shut-off point, at least 4 ft here. The second is how repeatably the sprayer can be positioned: Red Ant's and Outfield's rule of thumb is about a third of the cell length, which the logged ±0.5–0.9 ft meets only while RTK corrections hold. The third is switching time: at the 3 mph logged here, a 4-ft tree passes the nozzles in under a second. The weakest of the three sets the cell, and Outfield knows of no grower who yet sprays reliably by the single tree. Between-row drift was not measured. In response, WSU and innov8.ag proposed 16-ft cells with a 4-ft buffer at each end, judging results only in the middle 8 ft; Outfield favoured including the buffers, and its analysis (Section 5) does not apply one. Being one water test on a different sprayer (Methods), it does not show how much spray reached skipped cells on April 23–24; Outfield's analysis does not address drift.

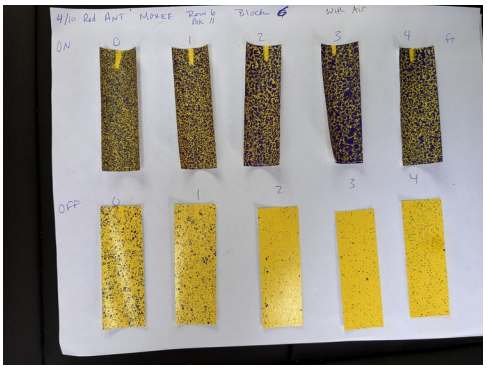


Figure 4. Water-sensitive paper at 1-ft steps from the shut-off point (Block 11, row 6, April 10, 2026, air on). Top ("On"): deposition while spraying water. Bottom ("Off"): blue deposits show drift down the row after shut-off. Source: G. Hoheisel, WSU Extension.

5. Moxee: thinning outcome (exploratory; efficacy was not a project aim)

In plain terms: this block did not show a measurable thinning effect from the variable-rate spray. Before hand thinning, skipped light cells mostly did not carry more fruit than sprayed ones; a difference appeared at harvest only after hand crews thinned the sprayed light cells harder. In part this is because variable rate could not be applied across the thinning program: of three lime sulfur passes, the first was uniform and only the last followed the analysed map.

Outfield compared skipped light cells (rows 1–30) with sprayed light cells in the control strip (Table 2). After hand thinning, the timing-adjusted comparisons put skipped light cells 6–9% higher on September 2, but only the closest-matched comparison (rows 19–42) cleared zero, and only on June 30; the peak-bloom version also clears zero but uses surveys flown after spraying began, so it is an upper limit. Without the bloom-timing adjustment the difference is +1% on September 2, because the control strip's light cells were more often late-blooming north-end trees. Cells just above and just below the cut-off within rows 1–30 showed no jump in fruit on May 24 or June 30, and +8% (−3 to +17) on September 2.

Table 2. Fruit on skipped light cells compared with sprayed light cells, with 95% range. Positive means the skipped cells carried more fruit. Signs are reversed from Outfield's table, which reports the change from spraying. Outfield reported no ranges for May 24, the least reliable fruit map. "North end" is cells 1–14 of each row. Source: Outfield Technologies, Block 11 Thinning Review (2026).

Comparison	May 24 (before hand thin)	June 30	Sept 2 (calibrated)
Timing and row position adjusted, rows 19–42 (variable-rate and control rows side by side)	−8%	+8% (+1 to +15)	+7% (0 to +14)
Timing and row position adjusted, whole block	−6%	+5% (−6 to +15)	+6% (−1 to +12)
North end only (cells 1–14)	+8%	+13% (−6 to +28)	+9% (−3 to +20)
Adjusted on peak bloom (uses post-spray surveys; upper limit)	−2%	+9% (+2 to +15)	+8% (+2 to +14)
No timing adjustment	−8%	+2% (−6 to +9)	+1% (−6 to +8)

Five reasons the harvest difference cannot be credited to the spray. First, and most important, comparing drone surveys flown on May 24 and May 30, either side of the hand thin, crews removed about 15% more fruit from sprayed light cells than from skipped ones ($p = 0.03$), so the harvest difference may come from hand thinning rather than the spray; this season's data cannot separate the two. Second, the spray contrast was smaller than the map implies: WSU reported that the farm sprayed the whole block uniformly on April 21 (the morning plan had held the northeast corner back for a later spray); the April 23 spray ran the April 21 map, which skipped more of the block (Methods); and only the April 24 spray used the map analysed here, although Outfield's analysis

assumed both variable-rate sprays did. Skipped light cells were therefore thinned less, not left unthinned. Third, before hand thinning (May 24) most adjusted estimates point the other way, although that is the least reliable fruit map (drone versus May 26 hand counts, r ≈ 0.6, a loose match); the difference appears only after hand thinning (around May 29) and June drop, when the drone tracked hand counts closely (June 30 survey versus July 7 counts, r = 0.81). Fourth, the groups were unbalanced: 65% of the control strip's light cells sat at the late-blooming north end, against 45% in rows 1–30. Fifth, only one of the eight hand-count sites was unsprayed, so the hand counts cannot test the spray on their own.

Two observations may be useful beyond this block. First, the crop evened out: bloom differed 3.3× between the lightest and heaviest fifth of the block, but fruit only 1.8–2.1×. At the hand-count sites, heavy-bloom trees (230–250 clusters) set fruit on 22–31% of clusters, while light-bloom trees (45–75 clusters) set fruit on 67–75%. Outfield notes this evening-out was already present before the hand thin; because heavy cells were sprayed in both zones, it reflects chemical thinning as well as natural set. Second, a cell can read light because it is light or because it has not finished opening, and this map was built before peak bloom. Outfield recommends treating the late-blooming north end as its own zone and flying two or more blossom surveys before the spray to separate late cells (still rising fast) from light cells (levelled off low).

6. Related work, not conducted by this project: Cornell AgriTech, New York

In three 2026 on-farm Honeycrisp trials in New York (Jiang et al. 2026, poster; preliminary), trees mapped at full bloom with the same systems used here (Aurea Imaging's TreeScout at two farms, Outfield's drone system at one) were classed as high, low or no blossom and given a full or no dose of ATS at full bloom, with a second spray two days later. At two of three sites, high-bloom trees were thinned to almost exactly the target fruit number; at the third, set was slightly above target. Under variable rate, medium- and low-bloom trees carried fewer single-fruit clusters at the two farms reported; at one Aurea-mapped farm, low-bloom trees had 23% singles against 46% conventional, and medium- and low-bloom trees had two to three times as many clusters with three or more fruit. From 2024–25 trials the authors estimate revenue gains of up to $5,000 per acre in Honeycrisp; crop value against a conventional control had not been reported for 2026.

A Washington lens (an illustration, not a result). At WSU's 2024 Honeycrisp budget assumptions (47–58 packed bins/acre, $660 a bin FOB at 72% packout), one percentage point of packout adds roughly $430–$535 per acre at the packinghouse door, and less after packing charges, which average about $22 a packed box in the budget; at those assumptions Honeycrisp returns did not cover total costs (Gallardo et al. 2025). On that arithmetic, if variable rate bought one point of packout, a retrofit at about $4,800 dealer-installed would be repaid on roughly 10 to 20 acres in one season, before map services, which this project did not price. The case for variable-rate thinning in Washington therefore rests on packout, fruit size, hand-thinning time and return bloom, not on the 8% chemical saving (about 0.5 gal/ac of lime sulfur on the April 24 pass), and those are what a Washington trial should measure (Conclusions, item 2).

7. What did not work

- **2025 chemical sprays.** The planned sulfur blossom-thinning applications were delayed past bloom, so all 2025 runs used water.
- **Moxee sprayer hardware.** On April 21 the four valves on the first Turbomist stuck open when switched together. Red Ant attributed the fault most likely to the wire gauge. Ahead of a storm the grower sprayed the block uniformly that day. The system moved to a second Turbomist with one valve per side, rewired with unspliced 16 AWG leads. On April 23 a water check worked, but with chemical the system at first ignored start and stop at row ends; the operator cut the PTO until it was corrected on site. Red Ant later judged the US Solid valves used at Moxee too prone to blocking with lime sulfur and specified Tecomec agricultural valves for later installs. A feed line blew in the February water test; Red Ant recommends a bypass regulator where valves switch often.

- **Sensor software.** Aurea fixed a mid-season TreeScout camera issue with a software update in July.
- **Connectivity.** 4G coverage was patchy in parts of Cherry Hill Farms, so Aurea advised Rowley to upload scans from his office area. On the first mapped application (June 23) the Red Ant phone app repeatedly lost its link to the controller; Red Ant traced this to phone settings and a borrowed Android 11 handheld instead of its rugged phone, and the next run had one disconnection.

8. Extension and outreach (Objective 4)

- **Horticulture for Engineers** (October 19, 2026), led by WSU Extension, including a spray application and pest management session for 35 attendees.
- **2026 Smart Orchard Field Day** (October 22, Gilbert Orchards, Yakima; closing social at Gilbert Cellars), the closing event of FIRA USA, organized by the WSU Smart Orchard team: more than 250 attendees, about 24 demonstrations, three tracks. The Robotics and Autonomous Technologies track, moderated by Hoheisel and Mantle, included the Red Ant sprayer retrofit, with Red Ant Agri's James Reid on hand; the Crop Load and Nutrient Management track included innov8.ag and Tyton Aviation/Outfield.
- **WSU Codling Moth IPM Field Day** (July 31, 2026): Hoheisel presented the Red Ant retrofit in a WSU Extension sprayer calibration session; no live demonstration.
- **2027 class.** WSU Extension has outlined a new class on sprayer calibration, optimization and variable-rate application for Smart Apply, John Deere's precision spray system, to launch in 2027 with Deere staff.

9. Status of 2026 commitments in the 2025 report

Table 3. Status of the 2026 next steps listed in the 2025 Continuing Report.

2026 commitment (2025 report)	Status	Evidence
Spray chemicals to validate workflow reliability	Met (chemicals applied; reliability faults in Section 7)	Moxee: variable-rate lime sulfur bloom-thinning sprays on April 23 and 24, executed by Red Ant from Outfield drone maps, after a failed attempt on April 21. Cherry Hill: ~20 ac thinned by prescription.
Single Red Ant GPS feeding TreeScout and sprayer	Not done	Not tested in 2026.
Scale retrofit kits via Burrows and WSU Extension	In progress	Burrows and innov8.ag installed the project kit at WashFruit (June 10); Burrows is the prospective dealer, no 2026 sales reported; retrofit shown at two WSU events (Section 8).
Bilingual (English/Spanish) operator training	Partly	Operator videos in Spanish and English on sprayer setup and the phone app (F. Valdovinos, innov8.ag, April 21); a farm operator ran the April 23–24 sprays; no formal module delivered.
Vigor maps + soil-health layers for foliar fertility	Data collected	Moxee block scanned with SoilOptix; soil map shared with WSU (B. Sallato); not used for variable-rate application at Moxee. WashFruit foliar-N on/off trial set up from an Orchard Robotics map; results pending.
Continue interoperability testing	Met	Outfield drone map executed by Red Ant at Moxee; Aurea maps executed by the grower's CapstanAG controller at Cherry Hill.
Removable controller security, cloud sync	Partly	Controller security not addressed. As-applied data synced to Red Ant's portal and were reviewed (Section 4).

10. Response to 2025 Technology Committee comments

Table 4. Committee comments from the December 22, 2025 award notice that apply to this project, and how it addressed them.

Comment	Response
"The sprayer technology is exciting, but difficult to use"	Agreed. The retrofit runs from a phone app on existing tractors, but setup needed partner support in the field, the first mapped application at a commercial orchard had phone disconnections, and the sprayer must be matched to the map (Sections 4 and 7). One grower built and ran his own map-driven system (Section 2): within reach of a motivated grower, but not easy. WSU Extension's planned 2027 class (Section 8) addresses this.
"Would be helpful to have unbiased economic analysis for technologies"	Not done by this project; a designed Washington efficacy and economics trial is the main unmet need. The report offers equipment costs (Table 1), Cornell's New York estimates with a Washington packout illustration (Section 6) and what such a trial should measure (Conclusions, item 2); none is Washington trial data.
"Goal should be to produce usable tech, not to accumulate more logos on the banner to show how many companies are participating"	Usability was tested in grower and dealer hands: a cooperating grower ran TreeScout prescription thinning on about 20 acres with his own controller, and Burrows Tractor and innov8.ag installed the Red Ant retrofit at a commercial orchard with Red Ant's remote support (Sections 1, 2 and 7). Both core components are in commercial use (Section 1).
"We still need a data management/decision system that integrates input from various instruments & apps"	Partly addressed. Maps from three providers ran as standard files, an Orchard Robotics task map was prepared for WashFruit, and Red Ant's portal holds the as-applied data (Section 4). The project built no integrated system; outside it, innov8.ag's HarvestReplay brings these layers together on commercial farms (Aurea Imaging, Burro and Agtonomy data with labor, packout and ERP records), and Agromanager offers an Aurea Imaging integration (neither evaluated here).

Conclusions and action for growers

1. **Map bloom more than once, and check the map against your own counts.** At Cherry Hill, Aurea TreeScout counts tracked the grower's hand counts on one block ($R^2 = 0.73$). The Moxee drone index was relative and uncalibrated, and a map made before peak bloom mistook late trees for light ones.
2. **Test sparing light trees before adopting it, and measure where the benefit would show.** At Moxee no thinning effect from skipping light trees could be measured, and once crews thin every tree to a per-tree target, fruit numbers at harvest tend to converge whatever the spray did (Section 5). Any benefit should show elsewhere: in fruit per cluster before hand thinning, in hand-thinning time and fruit removed per tree, in fruit size, singles and packout, and in return bloom the next spring, which is where the cooperating grower sees the value (Courtney 2026). To test it, apply variable rate on every thinning pass; interleave several strips sprayed the usual way through the block rather than one strip at one end; and hand-count trees in both skipped and sprayed light cells.
3. **Consider a retrofit before replacing equipment.** Retrofit parts cost about $3K in 2025 (about $4,800 dealer-installed, Red Ant's preliminary 2026 estimate); the factory path cost $20K or more and needs a closed-cab New Holland (Table 1). Map services are extra, and the retrofit needed field support (item 5). The kit snaps in and out of a sprayer in about 10 minutes (PI's experience), so one kit can move between sprayers and tractors while growers are early in adoption; at Moxee it moved between two Turbomists. Bloom thinning is the hardest variable-rate workload, as bloom is brief and its timing shifts; foliar growth-regulator and micronutrient sprays carry less time pressure, so start there on standard GPS, as at WashFruit, and add RTK for bloom thinning.
4. **Match sprayer air and map resolution.** Run water-sensitive paper past a shut-off point, as WSU did; at Moxee, spray carried at least 4 ft, roughly one tree, past the shut-off.
5. **Use the recommended phone and wiring, keep the GPS on the sprayer, and plan for setup help.** At Moxee, a wiring fault cost the first spray window, the GPS had to move from the tractor to the sprayer, closer to the nozzles, and with no cell coverage the RTK correction feed ran over a

tractor-mounted Starlink, yet RTK corrections lapsed, even at bloom, and holding RTK gets harder as the canopy fills in; patchy coverage slowed scan uploads at Cherry Hill. Run a water test on the block before the spray window.

Looking ahead: converging capabilities. Bloom moves fast, and data moves slowly around a farm. Drone mapping used to need a pilot in the field at the right moment, then a manual data transfer; at both Smart Orchard sites Tyton Aviation flew autonomously from a dock, including 13 blossom surveys in 2026 from a dock 2 miles from Block 11. A survey became an approved spray map by the next morning, or about four hours after the flight on April 23; on April 24 the dock's slow data link meant the spray used the previous day's survey. Approval should stay a human step: the cut-off was set with the orchard management team, and the April 24 rates with Keith Veselka minutes before the map was pushed. The hardest hand-off is to the person spraying, often on an open-station tractor at night or in poor weather, for whom an app is the last thing they need: at Moxee the phone map was hard to read in daylight, and on April 23 the operator had to turn off the PTO and call when the controller ignored row ends. Experienced crews need bilingual training and support (the farm crew had setup videos in Spanish and English and a number to call), a screen they can read, and the standing to stop. Objective 3 set a test from the outset, data flowing in and out: Aurea and Outfield maps went into the Red Ant and CapstanAG controllers in standard formats, and Red Ant's portal logged the 2026 as-applied records (Section 4). The team will keep pressing autonomy providers and equipment makers to take maps in and send as-applied data out. Outlook (not tested here): these pieces are converging. Docked drones and ground sensors such as Aurea's TreeScout can map more acres in near real time; autonomous platforms such as Burro, Agtonomy and Yamaha Agriculture's Prospr bring connectivity, RTK or vision positioning and edge compute that a spray controller can share; digital scouting could drive variable-rate sprays for mildew, blight and pest pressure; and the operator's role shifts from driving one sprayer to supervising several machines from a truck and approving each prescription, so an orchard can plan its labor around what the maps show.

Literature Review

Cornell AgriTech has reported preliminary on-farm variable-rate chemical thinning trials in New York Honeycrisp using the same TreeScout and Outfield blossom maps (Jiang et al. 2026; Section 6). Good Fruit Grower described the grower-built, map-driven sprayer interface at Cherry Hill Farms (Courtney 2026).

Aurea Imaging. 2026. Year 2 progress report to project partners (October 28, 2026).

Courtney, R. 2026. Innovative apple grower achieves DIY spray precision. Good Fruit Grower, October 2026 issue (online October 29, 2026).

Gallardo, R.K., S.P. Galinato and B. Sallato C. 2025. 2024 Cost and Return Estimates of Establishing, Producing, and Packing Honeycrisp Apples in Washington. TB106E. Washington State University Extension.

Jiang, Y., M. Miranda Sazo, M. Curreti, L. Gonzalez and T. Robinson. 2026. Variable Rate Chemical Thinning. Poster, summer 2026. School of Integrative Plant Sciences, Cornell AgriTech, Geneva, NY.

Mantle, S., J. Hazelhoff, G. Hoheisel and L. Khot. 2025. Dutch & American Tech in Action: Sensor-Driven Precision Spray. Continuing Project Report. Washington Tree Fruit Research Commission, Wenatchee, WA.

Outfield Technologies. 2026. Block 11 Thinning Review: variable-rate bloom thinning, 2026 season (Moxee, WA). Report to project partners.

Project team communications. 2026. WhatsApp spray-coordination group (WSU Extension, Outfield Technologies, Tyton Aviation, Red Ant Agri, NWFM LLC and innov8.ag), February 13–August 18, 2026; archived by the PI.

Red Ant Agri. 2026. SmartNode reports and configurations, Moxee Block 11, April 10, 21, 23 and 24, 2026. Red Ant online portal, accessed November 6, 2026.

Executive Summary

Project Title: Dutch & American Tech in Action: Sensor-Driven Precision Spray

Key words: variable-rate thinning, blossom mapping, sprayer retrofit, precision spraying, crop load

Abstract: This two-year project paired TreeScout, Dutch partner Aurea Imaging's tractor-mounted camera that counts blossoms tree by tree, with sprayer retrofits, growers and WSU to test whether tree-level maps can drive variable-rate spraying on equipment growers already own. It can, with setup help: in 2025 TreeScout, Green Atlas and Outfield maps ran on a Red Ant Agri retrofit controller (about $3K in parts; about $4,800 dealer-installed, Red Ant's preliminary 2026 estimate) and a factory-integrated New Holland system (≈$20K or more per sprayer), water only, and in 2026 TreeScout and drone maps drove thinning sprays. At Cherry Hill Farms, TreeScout blossom counts tracked grower Daniel Rowley's hand counts on one block ($R^2 = 0.73$), and he thinned about 20 acres from a TreeScout map on his own system; he credits tree-specific thinning in 2025 for quite uniform bloom in 2026 (a grower observation). In Cornell AgriTech's 2026 New York trials (preliminary; not part of this project), low-bloom trees on an Aurea-mapped farm had 23% single-fruit clusters under variable rate against 46% conventional. At Smart Orchard Moxee, a WSU testbed, drone bloom maps drove variable-rate lime sulfur sprays through the retrofit on April 23 and 24; on April 24 the map skipped 11.5% of cells in the variable-rate rows, and Red Ant's portal logged both runs. At Moxee no measurable thinning effect from the spray could be shown, with variable rate on only part of the program (the whole block was sprayed uniformly on April 21): before hand thinning, skipped light trees mostly did not carry more fruit, and the 6–9% more fruit Outfield estimated at harvest appeared only after hand crews removed more fruit from sprayed light trees (one block, one season). Drift was the other challenge: in a WSU water-sensitive-paper test, spray drifted at least 4 ft past the shut-off point, so sprayer air and map resolution should be matched. The map, made before peak bloom, mistook some late trees for light ones. The work was shown to more than 250 attendees at the 2026 Smart Orchard Field Day; the main remaining need is a designed Washington efficacy and economics trial.

Acknowledgments. We thank the Washington Tree Fruit Research Commission and the Dutch Ministry of Agriculture, Nature and Food Quality for funding. We owe special thanks to Keith Veselka and NWFM LLC, who generously contributed their orchards, the use of their tractors and sprayers, and Keith's and his staff's time; area manager Carmelo Garcia and the farm's spray operators ran Smart Orchard Zillah and Smart Orchard Moxee and applied the sprays. Co-PI Joost Hazelhoff and the Aurea Imaging team, including B. Rijk, provided TreeScout scanning, maps and grower support at Cherry Hill. Co-PI Gwen Hoheisel and WSU Extension ran the spray placement test and the extension program; co-PI Lav Khot and the WSU Smart Apple Orchard team, including Datta Bhalekar, moved the testbed to Moxee and organized the field day. The AgAID Institute funded WSU intern Mitchell Milander's 2025 work on the project; his internship presentation is on the AgAID Institute website. Daniel Rowley (Cherry Hill Farms) hosted field work and shared his hand counts; Paul Cathcart and Washington Fruit Growers hosted the WashFruit trial. Jim McDougall and the Outfield Technologies team built the survey plans and spray maps in both seasons and the 2026 thinning analysis, and Aaron Tyler and the Tyton Aviation team ran the docked drone surveys at both Smart Orchard sites and installed the Moxee dock at short notice. James Reid (Red Ant Agri) gave remote engineering support throughout. TJ Lange of Burrows Tractor supported the project throughout, particularly in Year 1, when Burrows provided equipment and technical support at Smart Orchard Zillah, including the New Holland factory-integrated path; in 2026 he and Tom Riel installed the retrofit at WashFruit. Slimline/Turbomist and Agromanager supported equipment and records. Freddy Valdovinos and Tim Reich (innov8.ag) supported field setup, and Freddy recorded the bilingual operator videos. We also thank Y. Jiang, M. Miranda Sazo, T. Robinson and colleagues at Cornell AgriTech for the New York results summarized in Section 6; Ross Courtney of Good Fruit Grower for documenting Daniel Rowley's work; and Gilbert Orchards for hosting the 2026 Smart Orchard Field Day.