Project Title: Efficient heat stress management for improved apple fruit quality

Report Type: Final Project Report.

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Notes: Funded in 2018 to develop localized orchard climate and crop physiology sensing system for apple fruit surface temperature and heat stress monitoring.

WTFRC Collaborative Costs:

Item	**2021**	**2022**	**2023**
Salaries	40,500	42,120	43,804
Benefits	14,875	15,470	16,089
Wages			
Benefits			
Equipment			
Supplies	10,210	5,510	5,010
Travel	3,132	3,132	3,132
Miscellaneous			
Plot Fees			
Total	68,717	66,232	68,035

Footnotes: Year 1 -- Salaries of $20,000 will support 5-months at 100% FTE of postdoc jointly supervised by Khot & Peters; $14,000 to support 7-months research associate at 50% FTE supervised by PI-Torres and $6,500 to support lab technician for 4-months at 50% FTE supervised by PI-Sallato. Pertinent HR benefits for these three personnel will be $14,875.Supplies include procurement of material to integrate crop physiology sensing nodes (8 nodes, $700/unit), telemetry (Wi-Fi router, cellular subscription, $620), pressure transducers w/ data logging capability ($250 × 4 units), misc. hardware, harness & related costs ($150) and orchard diagnostics/testing supplies for Soil test, Tissue samples, Fruitlets and Fruit ($1,350). Travel include 60 trips (× 90 miles/round × 0.58/mile) for members of team to travel to field sites for research and extension activities. **Year-2 and -3 –** Salaries are inflated by 4% respectively and pertinent benefits. Supplies include $2,670 to upkeep the sensing nodes and $1,350 for orchard diagnostics/testing supplies. Travel costs will remain unchanged from year-1.

Objectives

1. Evaluate the impact of three different heat stress management techniques on fruit quality at harvest and after storage.
2. Assess the effectiveness of sensing technology for automated stress monitoring and management.
3. Estimate the economic cost-benefits of each technology.
4. Deliver new knowledge to the apple industry through extension and outreach.

Key findings

1. Conventional overhead evaporative cooling (hereafter referred as 'conventional'), fogging, and a combination of fogging and netting (fognet), were reliable in regulating air (T_{air}) and fruit surface temperature (FST) below the critical threshold of 113 °F. However, seasonal variability was observed for each of these techniques' efficacy with respect to control (without heat mitigation) and netting.
2. Conventional cooling and fogging can be effective in mitigating heat stress with desired modification. Although effective, the conventional (25 min ON/OFF) cooling cycle can fail to keep FST below the threshold during the late afternoon (15:00 – 17:00 p.m. pacific) periods of hotter days. Thus, it is recommended to use variable cycle frequency tied with changes in either or both T_{air} and FST. Manual cyclic operation often results in considerably higher amount of water use (up to 63%). Automation would help in saving such excess water (/energy) usage and operational labor costs.
3. FST thresholds ranges for automated fogging were identified to be between 86 and 95 °F. Fogging did not cause FST to exceed the threshold during the study, its effectiveness however can be compromised if $T_{air} > 95$ °F for prolonged period. Reducing spacing between foggers, their diagonal placement in adjacent rows, and using high flow rate foggers could be potential solution to remove additional heat load on fruits.
4. For wider adoption of automation using FST thresholds, a feasible technology is needed to estimate FST. CPSS is not readily available or scalable due to commercialization challenges. Hence, the project explored a broadly useable machine learning model to estimate FST using in-orchard — open field weather, fruit size, and ground truth FST. A more comprehensive model is being developed on similar lines, incorporating high temporal FST data collected using CPSS through this project. The developed model is being planned to be ready by 2024.
5. In Honeycrisp, netting (in 2022 and 2023) led to smaller and lighter fruits, with delayed coloration across three seasons. In 2021, fruit size under netting was comparable to other treatments and potentially contributed to increased storage losses to bitterpit and softscald. Compared to netting, conventional, fogging, and fognet treatments with larger fruits, caused more storage losses to bitterpit and softscald. Such variations corresponded to changes in T_{air} and FST. Adoption of these treatments shall be considered in relation to crop load, tree vigor, and fruit size.
6. For WA38, netting delayed fruit coloration. Weight and fruit size was comparable to fogging and control. No soft scald and bitter pit disorders losses were observed in any treatment. Overall, treatment effect on fruit quality in WA38 were minimal compared to Honeycrisp.

Objective 1: Evaluate the impact of three different heat stress management techniques on fruit quality at harvest and after storage.

Experiment design.

The project was conducted at two independent sites: 1. Honeycrisp block (of Farmland Services commercial orchard near Prosser, WA); and 2. WA-38 research block (WSU Roza farm, Prosser, WA). Honeycrisp trees were on M9-339 rootstock planted in 2016 on vertical system with three leaders per trees planted at 10'×4' tree spacing. WA-38 trees were on M9-Nic 29 rootstock planted in

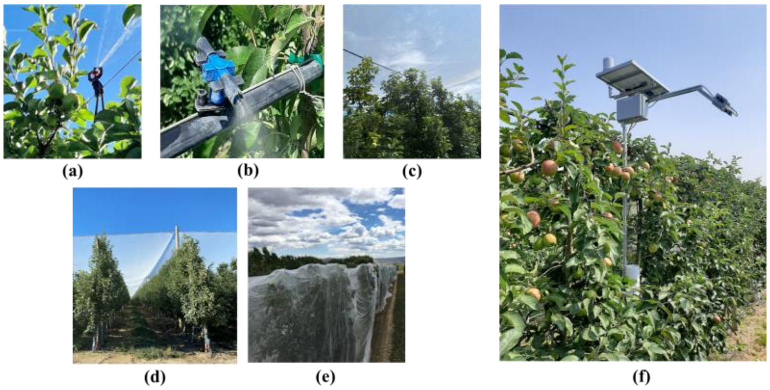

Figure 1. Heat stress mitigation treatments: (a) Conventional, (b) Fogging, (c) Over-the-top netting, (d) Fogging + Over-the-top netting (fognet), (e) Drape net. A (f) crop physiology sensing system (CPSS) was installed to monitor heat stress on fruits.

2013 on a vertical system with a bi-axis training system at 10’× 3’ spacing. Evaporative cooling using conventional overhead sprinklers (hereafter referred as ‘conventional’), fogging, netting, and fognet (foggers installed underneath netting) [Figure 1a, 1b, 1d, and 1c, respectively] were the mitigation techniques under evaluation. Effectiveness of conventional and fognet treatments was studied only in Honeycrisp block. Fogging treatments were established at both sites in similar manner by installing foggers perpendicular (East-West) to the tree row (South-North). However, netting treatment was established using over-the-top type nets in Honeycrisp (Figure 1d) and drape net (Figure 1e) in WA38.

Heat stress monitoring.

Within each heat mitigation treatment, several soil, plant, and weather processes were monitored during the growing season. Heat stress in each treatment was monitored using automated crop physiology sensing system (CPSS). CPSS nodes installed in each treatment utilized thermal-RGB imager (Teledyne FLIR LLC., OR) and an all-in-one weather station (Meters Group, Pullman, WA) to estimate apple FST. Thermal-RGB imagery data help derive the mean measured FST of 20% hottest part of the fruit surface (FST_{20}). The weather data helps derive weather-model-predicted FST (FST_w). Detailed methods on FST_i and FST_w estimation are in Ranjan et al. (2020) and Amogi et al. (2023). The FST_w has been found to be highly sensitive to variables as fruit size, color, and part of fruit exposed to sun. These variables are either difficult to measure or cannot be measured in real time. Hence assumptions are made for real time FST_w estimation, leading to less accurate FST values compared to imagery based FST. Therefore, this study used imagery based FST (FST_{20}) estimates in data comparison stage. In 2023, preliminary studies were also carried out to improve weather data based FST modeling using advanced machine learning algorithms. Developed model has shown some promising results over previously available energy balance-based methods for weather based FST estimation (Goosman et al., 2023) and our team is further refining these models.

Honeycrisp: Investigation into the effects of heat stress on fruits involved assessing the variations in T_{air} and FST across different treatments. This analysis focused specifically on the hottest days of the season. Selected dates for Honeycrisp were 19, 20, 24, 26, and 28 July in 2021; 12, 13, 14, 25, and 29 July in 2022; and 14, 15, 16, 27, and 28 August in 2023. Statistical evaluations of the differences were conducted using appropriate methods, with a significance set at 5% level. The comparisons were based on mean values and standard deviations. Additionally, a time-series analysis was performed on T_{air} and FST data collected in 2022 using CPSS at one-minute and five-minute intervals, respectively.

W38: Similar to Honeycrisp, effectiveness of heat stress mitigation techniques in WA38 were studied for, 25, 28, 30 July and 02, 04 Auguust in 2021; 24, 26, 27 July and 14, 24 August in 2022.

Fruit quality.

At commercial harvest, five to ten trees per replicated sub-block were selected based on uniform trunk cross-sectional area and crop load for at harvest and post harvest fruit quality analysis. In 2021 for both cultivars, trees underwent one time strip harvesting, followed by field assessment of sunburn damage, categorized into four levels: 1) no external symptoms, 2) browning, 3) photooxidative, and 4) necrosis. The 2022 and 2023 seasons, for the Honeycrisp block due to notable color and maturity disparities among treatments, three trees per replicated unit were evaluated at two distinct harvest timings: the first when 60% of the fruits in the most advanced treatment met commercial harvest criteria (over 50% red coloration), and the second coinciding with the least advanced treatment reaching these guidelines.

Moreover, in 2022 and 2023, the Honeycrisp trees were strip harvested by section (top, middle, and bottom) and transported to the WSU IAREC fruit laboratory. There, assessments for sunburn, bitter pit, and other defects, along with fruit color and size distribution, were conducted at harvest. For the WA38 block, one time strip harvest was continued from 2021 through 2023 without sectional distinction due to smaller study area, low crop load, and uniform maturity. From the total harvest, 110 representative fruits from each of the three replicated sub-blocks per treatment were transported to WSU-TFREC Wenatchee (PI-Torres lab) for post harvest quality evaluation over six months. Treatment-specific fruit quality was determined using a commercial sorting line (Aweta Inc., The Netherlands). Additionally, standard lab procedures were employed to measure maturity indexes, including flesh firmness (lb), soluble solids (ºBrix), titratable acidity (% malic acid), and starch index (1-6), using 10 fruits per replicate per treatment. Post harvest storage evaluation for the 2023 dataset is still in progress.

RESULTS (Objective 1)

cv. Honeycrisp

Air temperature. Distinct variations were observed in effectiveness of heat mitigation techniques, over three seasons. In 2021, T_{air} distribution across all treatments were closely aligned, indicating generally consistent effectiveness (Figure 3a). The 2022 data showed contrary trends with varying effects of mitigation techniques impacting T_{air} (Figure 3b). Control treatment recorded a significantly higher mean T_{air} (M [mean] = 89.24 °F, SD [standard deviation] = 5.4 °F). Netting, while better than the control, exhibited relatively more frequent higher temperatures around 95 °F. Fognet treatment showed highly effective cooling, achieving the lowest mean T_{air} (M = 84.2 °F, SD = 3.96 °F). Compared to 2021, T_{air} in 2022 exhibited increased variability and extreme temperature fluctuations. No significant difference was observed between the fogging (M = 85.1 °F, SD = 3.96 °F) and conventional (M = 84.74 °F, SD = 4.14 °F). In 2023, T_{air} in conventional (M = 90.1 °F, SD = 4.68 °F) was significantly lower than all others. There was no difference between control, fogging, fognet, and netting.

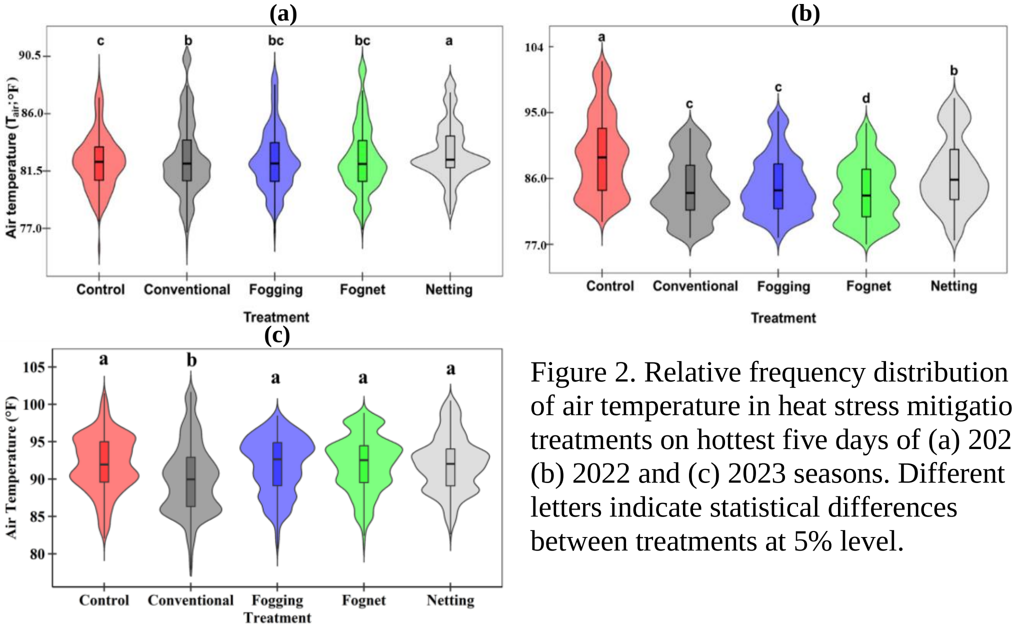

Figure 2. Relative frequency distribution of air temperature in heat stress mitigation treatments on hottest five days of (a) 2021 (b) 2022 and (c) 2023 seasons. Different letters indicate statistical differences between treatments at 5% level.

Comparing the three seasons, while the netting had some effect in regulating T_{air}, its overall impact was relatively modest in 2021 and 2022. There was no difference between conventional, fogging, and fognet in terms average air temperature measured during hottest days of all three seasons.

Fruit surface temperature. Heat stress mitigation treatment effects on FST were highly significant in 2021 and 2022. In 2021, the control treatment had the highest FST (M = 115.88 °F, SD = 5.22 °F), followed by netting (M = 111.92 °F, SD = 3.78 °F), fogging (M = 104.72 °F, SD = 4.14 °F), fognet (M = 100.4 °F, SD = 4.5 °F), and conventional (M = 98.96 °F, SD = 3.24 °F). Similarly, in 2022, the control and netting treatments exhibited significantly higher means (M = 110.66 °F, SD = 7.38 °F; M = 109.94 °F, SD = 7.2 °F, respectively) of FST compared to the conventional, fognet, and fogging treatments (M = 104.36 °F, SD = 6.84 °F; M = 104.18 °F, SD = 5.22 °F; M = 102.38 °F, SD = 7.02 °F, respectively). Latter three treatments were not different from each other. Control and netting had interesting results, where both were significantly different from each other in 2021 but not in 2022. This can be explained from corresponding T_{air} (Figure 2). A more detailed analysis was hence conducted for 2022 using timeseries analysis of T_{air} and FST.

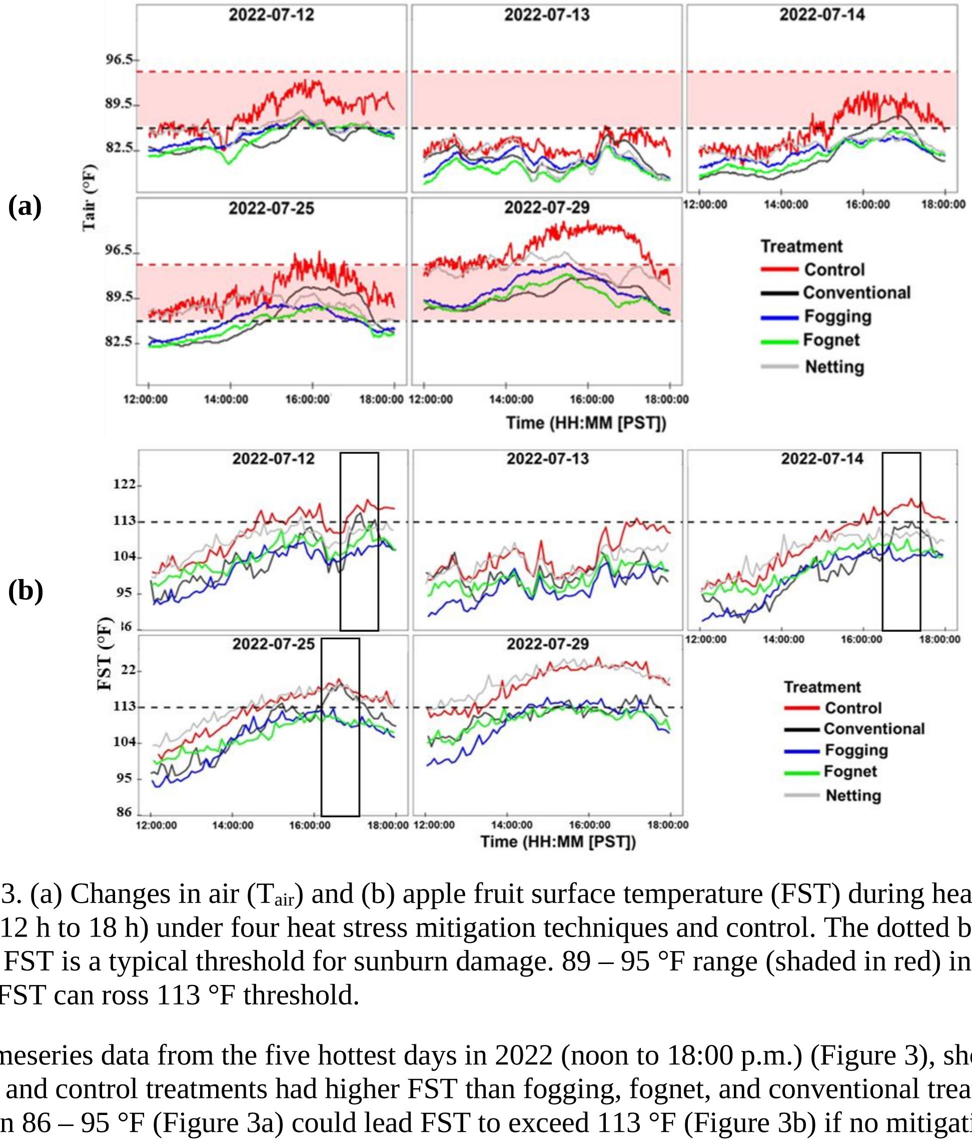

Figure 3. (a) Changes in air (T_{air}) and (b) apple fruit surface temperature (FST) during heat stress hours (12 h to 18 h) under four heat stress mitigation techniques and control. The dotted black line at 113 °F FST is a typical threshold for sunburn damage. 89 – 95 °F range (shaded in red) in T_{air} is where FST can ross 113 °F threshold.

Timeseries data from the five hottest days in 2022 (noon to 18:00 p.m.) (Figure 3), showed that netting and control treatments had higher FST than fogging, fognet, and conventional treatments. T_{air} between 86 – 95 °F (Figure 3a) could lead FST to exceed 113 °F (Figure 3b) if no mitigation measures were in place. For instance, on the 12th, 14th, 25th, and 29th of July 2022, FST in control treatment exceeded 113 °F when T_{air} exceeded 90 °F. However, fogging, fognet, and conventional methods kept FST below the critical threshold even when T_{air} neared 100 °F. On the July 13, 2022, a cloudy day with reduced solar radiation, the FST in the control treatment still reached 113 °F in the afternoon with T_{air} at 86 °F. This scenario provided a crucial insight into how T_{air} alone, even in the absence of intense solar radiation, can significantly influence FST.

Fruits absorb heat from surrounding air (environment). This heat is not instantaneous but rather accumulative. Solar radiation and T_{air} are the key drivers of this rate of change. Direct solar radiation can raise FST almost instantaneously through radiative heating of fruits. Whereas convective heat transfer from surrounding air to the fruit gets compounded over time, increasing the thermal load on fruit. Unlike evaporative cooling under conventional methods of heat mitigation, fogging removes heat from fruits and surrounding environment mainly through convection (thermal energy exchange with surrounding air) and evaporation of small droplets. Hence cooling in fogging is not immediate due to thermal inertia of the fruits, meaning retained heat inside fruits takes time to cool down. Considering this lag time between initiation of fogging and its actual effect on FST, it is crucial to start fogging before fruits reaches the FST threshold. From the time series data, it was interpreted that fogging actuation when FST is in the ranges of 86 (13th July) to 95 °F (29th July), typically earlier in the day, can help regulate FST at or below 113 °F in the late afternoon hours.

Conventional method occasionally failed to keep FST below the threshold, particularly from 15:00 – 16:00 p.m., likely due to inadequate cooling from its 25-minute ON-OFF cycle. Here, water evaporated from the fruit surface and exposed fruits to intense solar radiation and elevated T_{air} until the next cycle. This lead to quick changes in FST on July 12th, 14th, and 25th, corresponding to fluctuations in T_{air}. In contrast, fogging and fognet treatments were consistently effective throughout the day. Data from July 29, 2022, suggests that FST is reflects cumulative heat exposure and doesn't show immediate decline with T_{air} drops, which is critical for understanding the lag in heat dissipation within the fruits. Therefore, adjustments to the conventional method, in response to FST inputs from the CPSS may enhance its performance. Meanwhile, for fogging treatments, optimizing the system by increasing flow rates, adjusting spacing, or rearranging fogger positions could enhance its capacity to mitigate heat effectively.

Fruit size. In 2021, heat mitigation techniques mildly affected fruit diameter. Average fruit diameter of fruits under conventional (82 mm) highest whereas lowest under control (79 mm). In 2022, however, differences in fruit diameter were more pronounced. Average diameter of fruits under fogging, fognet, and conventional differed from control and netting with significantly smaller fruits. A significant decrease in the performance of netting and control treatments from 2021 to 2022 could be attributed to the higher T_{air} and FST, which may have negatively impacted fruit growth under these treatments.

The growth pattern in 2021 was characterized by uniformity and consistency, with fruits developing steadily over the season. In contrast, during the period from the 12th of July to the 9th of August in 2022 — a span marked by episodes of extreme heat stress — the growth of fruits in the control and netting treatments was notably hindered and virtually halted. This stagnation in growth during the peak heat stress weeks highlights the limitation of the no mitigation (control) and netting treatments during extreme heat events. However, further validation is necessary as other factors may also influence these outcomes.

In 2023, unlike previous years, conventional resulted in significantly smaller fruits (M = 53.6 mm, SD = 7.82 mm) compared to other treatment. The observed difference was primarily due to the non-uniform crop load management. Average crop load in control (78 fruits/ tree) was about 30% lower than conventional (113 fruits/tree). Similarly, the crop load in fogging, fognet, and netting was 92, 100, and 126 per tree, respectively.

Sunburn. In the 2021 and 2022 seasons, control treatment fruits experienced the highest sunburn, with 30% losses in 2021 and 8% in 2022, a threefold decrease. Conventional evaporative cooling, netting, and fognet significantly reduced sunburn. In 2021, netting was most effective, reducing sunburn by 81% compared to the control. In 2022, there was less than 2.5% damage across treatments. More direct sunlight exposure led to higher damages on canopy top than in middle and bottom layers. While this pattern was consistent across all treatments, there were slight variations. In 2023, sunburn losses were lowest with no damage under netting and fognet, and only 2-3% in control, conventional, and fogging.

Post harvest fruit quality.

Soft scald. Soft scald incidence in storage in 2021 and 2022, ranged between 0 – 9.4%. There were no differences in soft scald levels among the treatment groups in 2021. In 2022, however, differences were significant after six months of storage. Fruits under conventional treatment had 7.5 % soft scald compared to 0% in the control and netting, with no differences among the other treatments.

Bitter pit. Bitter pit incidence was higher in 2021 ranging between 35.4% and 60.6%, and much lower in 2022, ranging from 1.4% to 9%. In 2021, after three months of storage, the incidence had already reached over 30%. Bitter pit incidence in fogging (M = 51.9%), fognet (M = 60.6%), and netting (M = 53.1%) treatments were significantly higher than in the control (M = 35.4%) and conventional (M = 38.2%). In 2022, the incidence of bitter pit was significantly lower in the control (M =1.8%) and in netting (M = 1.4%) than others. There was no difference between conventional (M =8.7%), fogging (M = 5.6%), and fognet (M = 9%).

Higher bitter pit incidence in 2021 can be attributed to larger fruits where the fruit size was > 80 mm. Previous studies have found that fruits with > 80 mm diameter can cause more than 50% of bitter pit after storage (Reid & Kalcsits, 2020). This exceptional growth in fruit size can be attributed to bienniality with lower crop load (Total fruits/ tree) in 2021. In 2021, netting has the lowest number of fruits whereas, fogging with 73 fruits per tree represented highest crop load. However, in 2022, the crop load varied between 200 (SD = 60) under fognet to 265 (SD = 45) under control. Average fruit count per tree under conventional, fogging, and netting was 254 (SD = 72), 219 (SD = 50), and 235 (SD = 35), respectively. Therefore, chosen mitigation techniques should consider fruit size, crop load, and tree vigor. This might help in avoiding any excessive growth in fruit size and post storage bitter pit losses. Treatments that lead to higher bitter pit losses reportedly decreased soft scald incidences, similar to observation made by Tong et al. (2003). No sufficient reasoning can be made with available data to explain this association between soft scald and bitter pit.

Fruit maturity. Heat stress mitigation treatment effects on quality was analyzed over six months at Initial (after harvest) and 1st and 3rd day after three and six months of storage (five evaluation points). Results for each of the five maturity indices (2023 analysis is ongoing), i.e., color (% Red), weight (g), firmness (N), Chlorophyll degradation (IAD index), and SSC (°Brix) are described below.

Weight (g): Fruit weight in control and netting were lower than other treatments in both seasons. There was no significant difference between fogging, fognet, and conventional treatments in 2021.

Color (% Red): In 2021, at initial evaluation point after harvest, fruit color was also lower under netting. There was no consistent difference between netting and other treatments after three and six months of storage. In 2022, after storage, no consistent difference was observed in fruit color under netting and other treatments. For both years, after storage, fruit color under conventional, fogging, and fognet was advanced than or equal to control and netting.

Firmness (N): In 2021, fruit firmness in netting was about 2 N higher after six months of storage. In 2022, fruit firmness in control followed by netting were higher compared to all other treatments, starting after three month and seven days post-storage.

SSC (°Brix): In 2021 and 2022, treatment significantly affected SSC at most evaluation points, with moderate to high differences, but differences between treatments were inconsistent. Average SSC was highest in control and netting, followed by fogging, conventional, and fognet.

IAD index: In 2021 season data, the only consistent difference over six months of storage was IAD for fruits under netting. It was significantly higher than all other treatments. In 2022, however, IAD in netting (except at initial evaluation after harvest) and control were significantly higher than all other treatments. This again corresponded to T_{air} being significantly higher under netting only in 2021 (Figure 2a), whereas in 2022 (Figure 2b), control and netting both exhibited higher T_{air}. This signified that heat accumulations under netting might have delayed maturity.

Overall, post-storage analysis revealed that fruits under netting were less ripe in 2021; whereas in 2022, both netting and control had less ripened fruits. Such results are most possibly due to higher T_{air} (Figure 2a,b) and FST (Figure 3a,b).

cv. WA38

Air and fruit surface temperature. For 2021, the analysis revealed a significant effect of treatment on T_{air}, with fogging resulting in the highest temperature (M = 91.76 °F, SD = 4.79 °F), followed by control (M = 90.32 °F, SD = 4.37 °F), and netting being the lowest (M = 88.16 °F, SD = 4.00 °F). In 2022, netting recorded the highest temperature (M = 96.8 °F, SD = 8.01 °F), while the control (M = 94.46 °F, SD = 7.65 °F) and fogging (M = 94.46 °F, SD = 7.24 °F) treatments were not different from each other. In terms of FST, results in WA38 were similar to Honeycrisp for both years. In 2021, the control had the highest FST (M = 124 °F, SD = 5.68 °F), followed by netting (M = 120 °F, SD = 5.26 °F), and fogging (M = 114 °F, SD = 5.31 °F). Similar results were observed in 2022. T_{air} and FST analysis for 2023 data is in progress.

Sunburn. External sunburn symptoms in 2021 varied between 5 and 9%, with no difference between treatments. The sunburn was associated mostly to necrosis and cracking (averaging 11%), while browning averaged only 1%. In 2022, sunburn damage was considerably lower in both netting (0.6%) and fogging (1.8%) compared to control (7.6%). Overall, browning was prominent compared to other types of sunburn. Lower sunburn % trend continued in 2023, which varied between 0.8% in fogging and 2.4% under netting. There was no difference between treatments, however, browning was prominent under netting.

Post harvest fruit quality. No significant losses to bitter pit and soft scald were observed.
Weight (g): In 2021, no significant treatment effects were observed at initial evaluation stages under storage. However, after 3 months and 1 day, fruit weight in fogging (M = 229.69 g, SD = 26.54 g) and netting treatments (M = 232.51 g, SD = 29.46 g) were significantly lower than control. In contrast, average fruit weight in 2022 under fogging (M = 262.91 g, SD = 40.14 g) and netting (M = 209.66 g, SD = 38.88 g) were significantly higher when compared to the control (M = 195.59 g, SD = 44.32 g).
Color (% Red): No consistent differences were observed in 2021 as well as in 2022.
Firmness (N): In 2021, the netting had lower firmness (M = 67.33 N, SD = 3.91 N) compared to the control (M = 70.36 N, SD = 4.45 N). However, subsequent evaluations showed no differences. In 2022, inconsistent differences in firmness have been observed in the later stages of storage.
SSC (°Brix): In 2021, at initial and 3 months and 1 day of storage, higher SSC was observed in fruits under the netting (M = 13.19, SD = 0.77) compared fogging (M = 12.45, SD = 0.98). However, no differences were observed at later stages of storage. In contrast, in 2022, SSC in the control remained significantly higher than fogging at all stages of storage.
IAD index: In 2021, the IAD score indicated significant differences, only after six months of storage. After six months of storage, netting had lower IAD score than control and fogging. No differences in IAD score were observed in 2022.

Overall, across both years, treatment effects became more evident with increased storage time, particularly for weight, IAD, and SSC. The weight differences were slightly reversed between the two years, with fogging and netting resulting in lighter fruits in 2021 but heavier fruits under fogging in 2022. The color retention was better under treatments than control in the 2022. Firmness showed the least variation due to treatments, while SSC and IAD indicated some treatment-related effects, suggesting these parameters as sensitive indicators of post harvest changes due to different heat stress mitigation techniques.

Objective 2. Assess the effectiveness of sensing technology for automated stress monitoring and management.

In years 2022 and 2023, automated fogging was tested in WA38 research block. Instead of using FST, T_{air} was used as an input. Figure 4 below represents the schematic workflow of the automation.

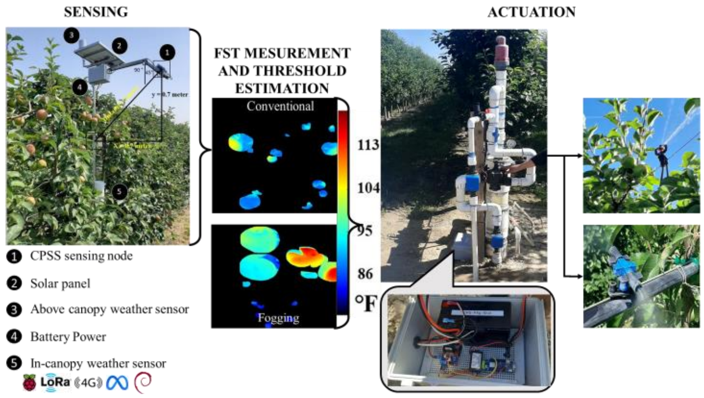

Figure 4. Automation system installed in Honeycrisp block to actuate overhead sprinklers and foggers.

Additional details of the automation and technology know-how are in the PhD dissertation (Amogi, 2023). Ideally, actuation of foggers based on FST would provide a more precise approach to manage heat stress. The current industry practice is to initiate fogging when T_{air} hits 80 ºF, but exact FST thresholds for activation were not well defined. Objective 1 outcomes helped our team to identify a critical FST range (between 86 – 95 ºF) for fogging activation. With this new understanding, one can better assess and optimize the effectiveness of CPSS-driven automated fogging against these established FST thresholds.

In contrast to fogging, conventional cooling treatments involve the direct application of water to the fruit and its surrounding canopy. This method effectively removes heat from the air and the fruit predominantly through evaporation and conduction, leading to an immediate heat stress mitigation and reduction in FST. Therefore, 108 ºF of FST (with buffer from actual 113 ºF threshold) could be an input to actuate overhead sprinklers.

To enable season long automation, significant work was done in 2022 by developing advanced machine learning (Convolutional Neural Network) algorithm to segment canopy from green fruits and reliably estimate FST on CPSS, independent of cultivar and fruit color (Amogi et al., 2023).

Objective 3. Estimate the economic cost – benefits of each technology.

Please note: Cost-benefit analysis has been done with key assumptions listed in following paragraphs. Though the numbers might differ, the relative significance should remain same amongst the different heat stress mitigation techniques.

The study assessed the costs of conventional, fogging, netting, and fognet treatments ‘Honeycrisp’ block. We measured water usage in conventional and fogging methods, excluding energy costs under the assumption of comparable water usage through automation (7% or less; Table 1). Cost comparisons focused on initial and operational expenses. This included hardware purchase, installation, operation, and maintenance of each treatment over a season.

Volume of water used. To estimate the total water usage by conventional and fogging treatments, flow rate per treatment rows was measured using ultrasonic flow sensors (Sonata Ultrasonic Water meter, Master Meter, TX). At the end of the hottest days, water flow (Gallons/day, GPD) was recorded from these flow sensors for 20 days in 2022 and 8 days in 2023 season. This daily water usage was a single digit value in GPD. In 2023, this daily water usage was cross validated by monitoring per minute flow rate (Gallons per minute; GPM) in a continuous manner for multiple times a day. The recorded gallons/day data was used to quantify actual percent difference between volume of water used in fogging and conventional treatment. This data was then scaled for an acre.

Table 1. Estimated water usage per acre in conventional and fogging technique.

Treatment	Nozzle configuration (ft.)	sprinkler or fogger rows/acre	*****Flow rate, GPM/row	Flow rate, GPM/A	Operation time (min)	#Water use (gallons/acre)
Fogging	10 × 10	8	2.12	16.96	360	6108
Conventional	20 × 20	4	9.37	37.48	180	6559

*Each 650-foot row contained 60 sprinklers (conventional) and 30 foggers (fogging), based on the specified nozzle spacing. #The estimations are calculated for 6 hours (12.00 p.m.– 18.00 p.m.) of usage.

Over 28 (20 in 2022 + 8 in 2023) days, maximum T_{air} were compared for conventional and fogging treatments. No significant difference was found in recorded maximum T_{air} between conventional (M = 88.39 °F) and fogging (M = 89.31 °F). However, water usage differed significantly. Daily water use in conventional averaged 10,605 gallons/acre, about 63% higher than fogging (6496 gallons/acre). Actual water use in fogging matched estimates based on average flow rate (GPM) (Table 1). However, actual daily water use in conventional (10,605 gallons/acre) treatment was higher than estimates (6559 gallons/acre). Possibly, conventional might be running more than expected duration leading to overutilization of water (Figure 5). Thus, study emphasize the need of an automated cooling based on T_{air} or FST, as per the availability of technology and resources, which can help save significant volume of water.

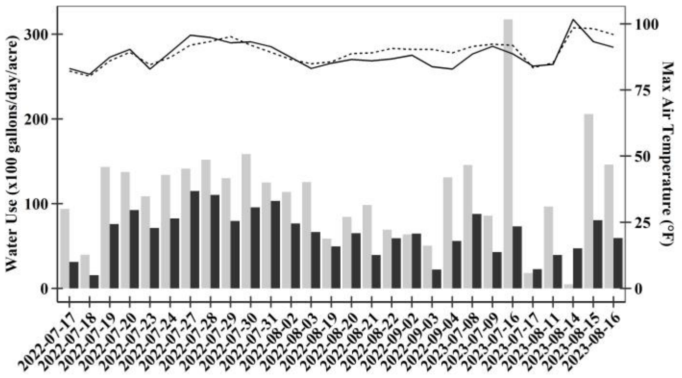

Figure 5. Per acre daily water usage in conventional overhead cooling and fogging for selected hottest days in 2022 and 2023. ‘maxT_Conventional' and ‘maxT_Fogging’ are maximum air temperature recorded for that day.

Fixed and operational costs of mitigation techniques.

Assumptions: Per acre budgeting was based on retail equipment prices, excluding wholesale discounts. Fixed costs, including land and irrigation infrastructure, were considered equal for all treatments. Since all treatments used drip irrigation, their costs weren't compared. Installation labor charges were uniform across treatments, ranging from \$250 to \$300. Operational labor costs differed, with sprinklers costing about \$50/day and fogging, assumed at 50% of sprinkler costs, at \$25/day. These operations often coincided with other farm tasks. Seasonal maintenance, applicable only to sprinklers and foggers, focused on checking for clogs and leaks. The analysis was based on an average usage of 35 days for fogging and overhead evaporative cooling.

Costing: To set up conventional overhead sprinkler and fogging treatments per acre, 120 sprinklers and 480 foggers are needed, with 10 × 10 feet spacing for sprinklers and 20 × 20 feet for foggers. With a 650 ft row, an acre comprises about eight rows. Fogging lines are required for each row, while sprinklers are placed in alternate rows due to the spacing differences.

Table 2. Cost per acre of establishing and operating different heat stress mitigation techniques

Cost (\$/acre)	Cost component	Conventional	Fogging	Netting	Fognet
Fixed	No. of rows/acre*	4	8	8	8
	1” sprinkler poly tube (\$95.26/500 ft. role) / ¼” drip tape for fogger (\$13.28/100 ft.)	476	637		800
	Sprinkler FT2 feed tube assembly with R10 rotator + stake [Total ~\$10.23]	1227			
	Two-way fogger with 2 way cross + raiser (\$2 + \$1.86)		1852		1852

	Over the top shade net (shade cloth + cables + wood posts)			4000	4000
	Initial installation	250	250	250	250
	Total Fixed	1953	2739	4250	6902
Operational					
	General Farm Labor 1. Operating sprinklers in cycles ($50/day) 2. Actuating foggers ($25/day) 3. Netting retraction before harvest + Seasonal maintenance	1750 + 250	875 + 250	250	875 + 250 + 250
	Total (Fixed+ operational)	3953	3864	4500	8277

Labor rate is considered as $17.56/hour (Source: Employment Security Department/DATA; NGTS, UI Wage File).
* Row length was assumed to be 650 ft. Hence in one acre, there will be 8 tree rows.

Comparing the costs, fogging appears to be the most economical option at $3,864 per acre (Table 2), with lower fixed and operational costs. Labor accounts for 44% and 22% of total cost in conventional and fogging methods, respectively. Both can benefit from automation. Netting costs around $4500, 16.5 % more than fogging. While offering comprehensive mitigation, fognet is significantly expensive. Conventional cooling, slightly expensive than fogging, can also be used for supplementary irrigation and frost protection, an advantage not offered by fogging. Fogging may require supplemental irrigation for water deficit on hotter days. Similarly, irrigation scheduling frequency would need to be adjusted on days the conventional overhead sprinklers are operational as it adds considerable surplus moisture to the soil. In summary, automation of both water-based cooling systems and actuation based on air or fruit surface temperature, especially in conventional evaporative cooling, would help realize reliable heat stress mitigation in peak heat hours and help growers in saving considerable amount of water (& energy) usage.

Objective 4. Deliver new knowledge to apple industry through extension and outreach.

Field days. Throughout the project, approximately ten field days were organized, coordinated by Co-PI B. Sallato, PI Lav Khot, Co-PI Carolina Torres, and J. Bolivar. These events consistently attracted 16 to 35 participants each. Industry collaborators like Jain USA, along with other professionals in tree fruit crop production management, actively participated in these field days. In addition to these regular events, the project outcomes were also showcased at Smart Orchard 2022 & 2023 Field Day (Grandview, WA), and Smart Orchard + AgAID Field Day. The latter event was held on September 15, 2023, at Sunrise Orchard in Wenatchee and was well-attended by over 50 attendees, including USDA NIFA and NSF national program leaders.

Presentations, Meeting, Media, and Peer reviewed publications. Study outcomes were showcased at the WTFA annual meetings from 2021–2023, reaching over 200 individuals, including growers, and professionals. Results were also presented at the ASABE meetings, and IEEE conference, reaching out to wider range of academic experts in the US, and Europe. Findings were also discussed with growers at the Columbia Tree Fruit Club meeting, for research feedback. The team authored an article for ‘Irrigation Today’ magazine, distributed to over 12,000 growers. The project gained visibility through coverage in ‘Good Fruit Growers’, ‘Fruit Growers News’, and WSU CAHNRS News. Additionally, five research articles related to the project were submitted for peer review in international journals to get feedback from academic community.