Project Title: Modeling Orchard Effects on Meteorological Measurements

Report Type: Final Project Report

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WTFRC Collaborative Costs:
Budget 1
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Item	**2020**	**2021**	**2022**
Salaries	$13,245.75	$40,693	$42,321
Benefits	$4,517.25	$14,223	$14,792
Equipment	$36,150	$0	$0
Travel	$6,000	$8,000	$8,000
Total	$60,025	$62,916	$65,113

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

[2] Benefit rates are budgeted for 35%.

[3] Equipment includes 8 weather sensors, 8 soil moisture sensors, and 2 instrument towers.

[4] Travel budgeted for travel to field sites, meetings with collaborators and presentation of results at industry winter meetings in Washington State.

Objectives

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

Key findings:

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

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

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

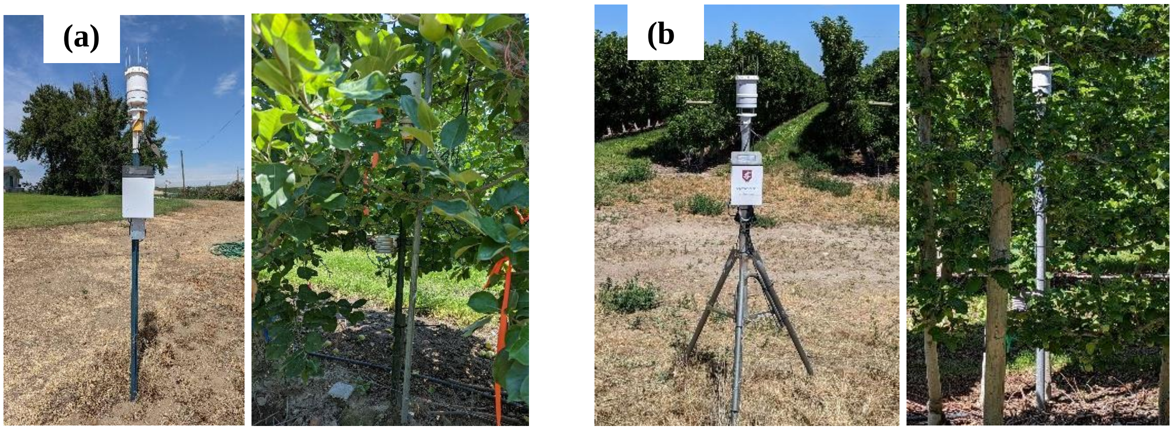

Fig. 1. Example of open-field, and in-orchard weather station installations at (a) site 1b (architecture: solaxe) and (b) site 5 (architecture: V-trellis).

Effects of canopy attributes

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

Effects of overhead evaporative cooling and irrigation

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

Results and Discussion

Open-field seasonal weather patterns

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

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

Daily orchard effects

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

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

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

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

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

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

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

* AT$_o$: Air Temperature Offset; RH$_o$: Relative Humidity Offset; SR$_o$: Solar Radiation Offset; WS$_o$: Wind Speed Offset; **Y: year

Monthly orchard effects

Fig. 2 show the line graphs of the monthly offsets during year-1 and -2, respectively. Offsets of all-weather variables varied monthly depending on the weather conditions and canopy growth stages. All the orchards had similar monthly SR_o, AT_o, $RH_{o,}$ and WS_o patterns through year-1 and -2, even though the magnitude varied between the sites.

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

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

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

Seasonal hourly orchard effects

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

All the sites have higher humidity inside the orchard compared to the open-field during the summer season and were highest at site 1a orchard with voluminous canopies. However, RH_o shows negative and positive values in the other seasons, indicating higher and lower humidity inside the orchard. The seasonal hourly mean RH_o varies from -9.4 to 7.7 %, -28.0 to -0.8 %, -13.8 to 4.4 %, and -5.8 to 8.5 % during the respective seasons. Orchards have drier microclimates during winter and spring when the plants are in dormancy or post-dormancy stages.

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

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

Effects of canopy attributes

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

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

Factors	p-value			
	AT_o	RH_o	SR_o	WS_o
Height	0.11	0.02*	0.09	0.06
Training system	0.01*	0.00*	0.06	0.09
Height x Training system	0.00*	0.00*	0.18	0.18

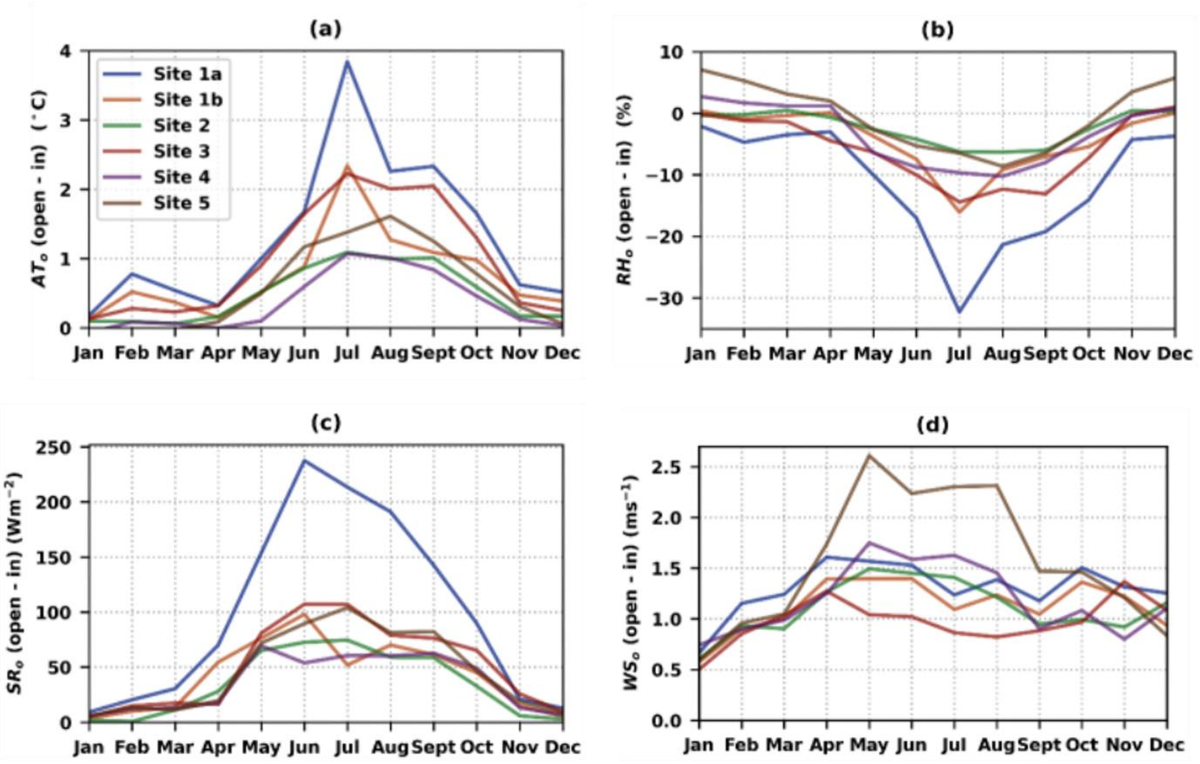

Fig. 2 Mean monthly offsets between open and in-orchard (a) solar radiation (SR_o), (b) air temperature (AT_o), (c) relative humidity (RH_o), and (d) wind speed (WS_o) for orchards for year-1. The different color lines represent different sites.

Effects of irrigation and overhead sprinklers

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

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

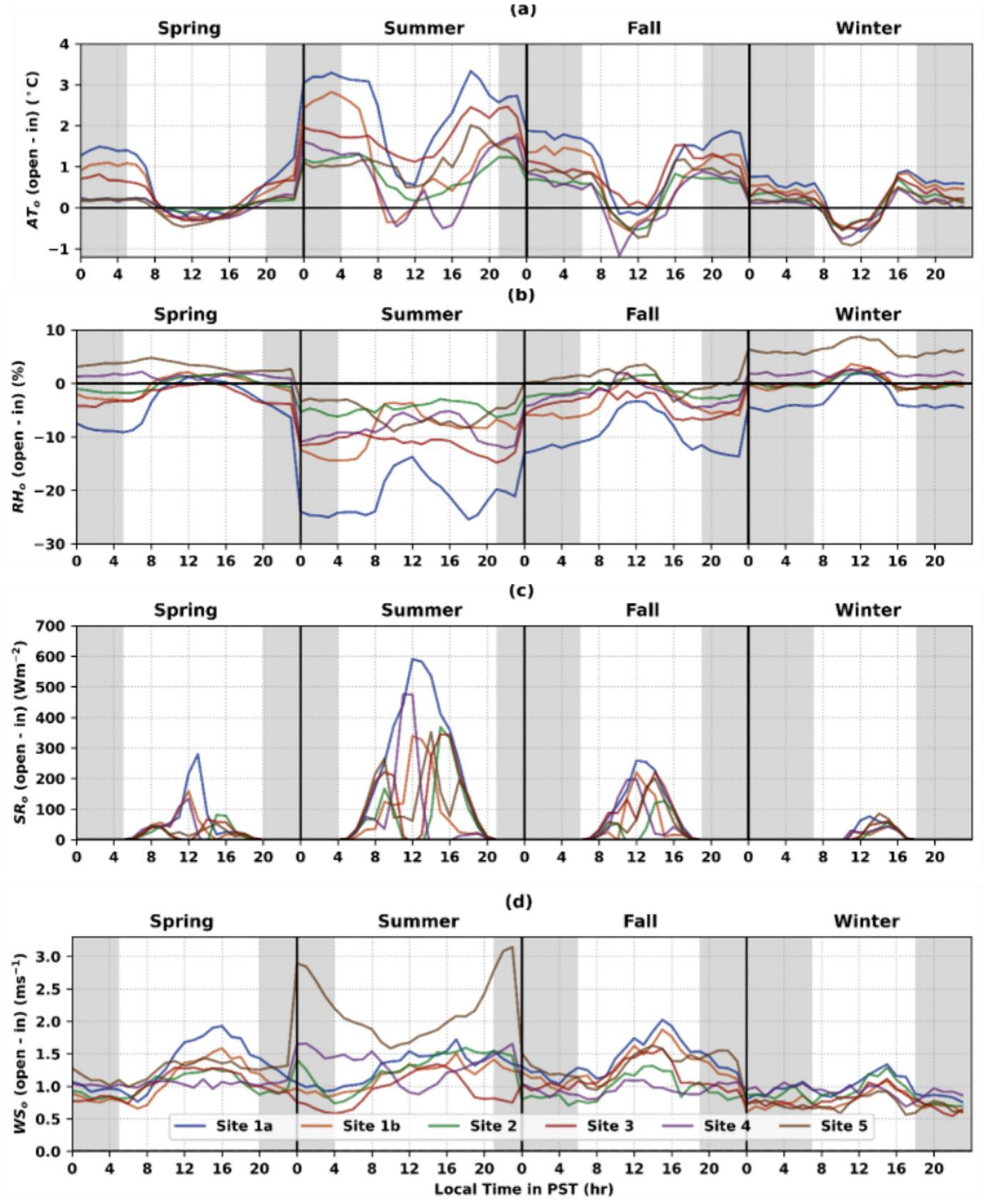

Fig. 3. Mean hourly seasonal offsets between open- and in-orchard (a) air temperature (AT_o), (b) relative humidity (RH_o), (c) solar radiation (SR_o), and (d) wind speed (WS_o) for apple orchards for year-1. The different color lines represent different sites. The shaded gray areas represent night hours.

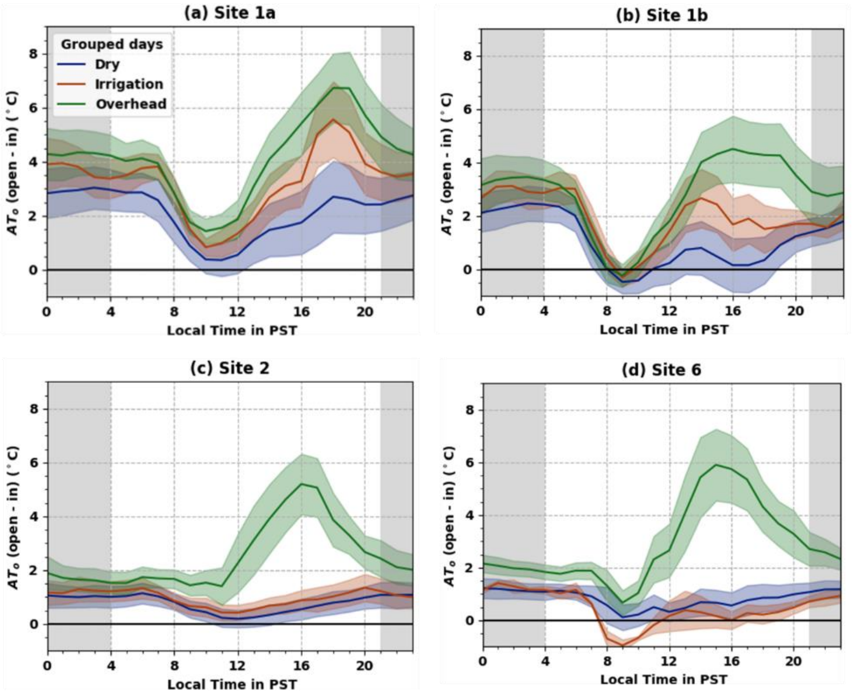

Fig. 4. Site-specific mean hourly AT_o (line) and 0.5 SD (shaded) between paired open- and in-orchard stations for dry, irrigation, and overhead sprinkler days at (a) site 1a, (b) site 1b, (c) site 2, and (d) site 6.

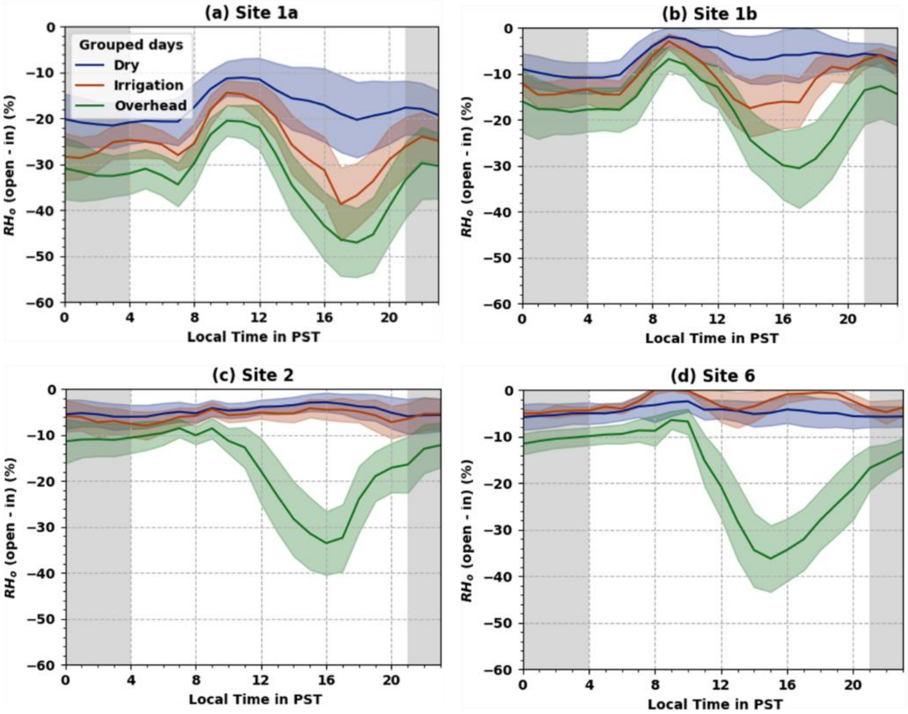

Fig. 5. Site-specific mean hourly RH_o (line) and 0.5 SD (shaded) between paired open- and in-orchard stations for dry, irrigation, and overhead sprinkler days at (a) site 1a, (b) site 1b, (c) site 2, and (d) site 6.

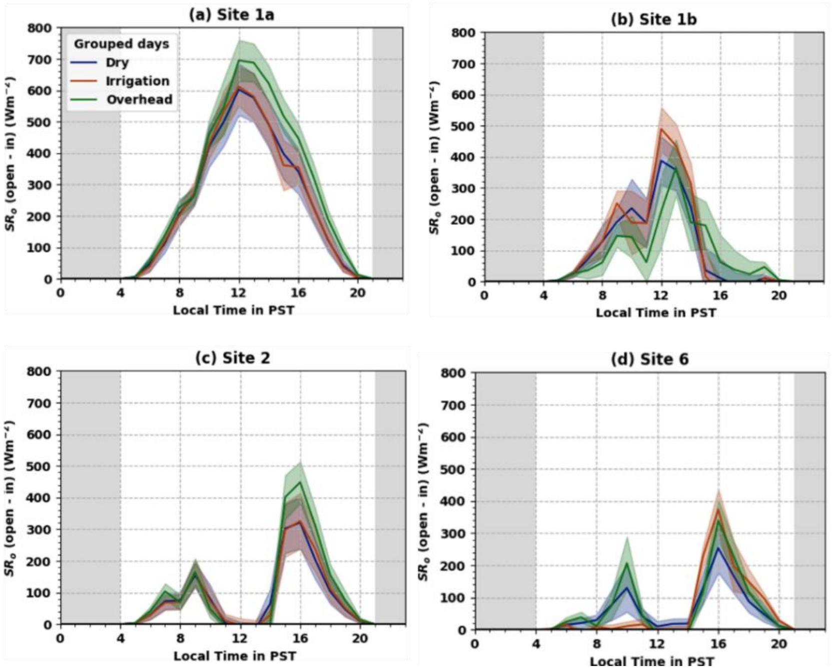

Fig. 6. Site-specific mean hourly solar radiation (SR_o) (line) and 0.5 SD (shaded) between paired open- and in-orchard stations for dry, irrigation, and overhead sprinkler days at (a) site 1a, (b) site 1b, (c) site 2, and (d) site 6.

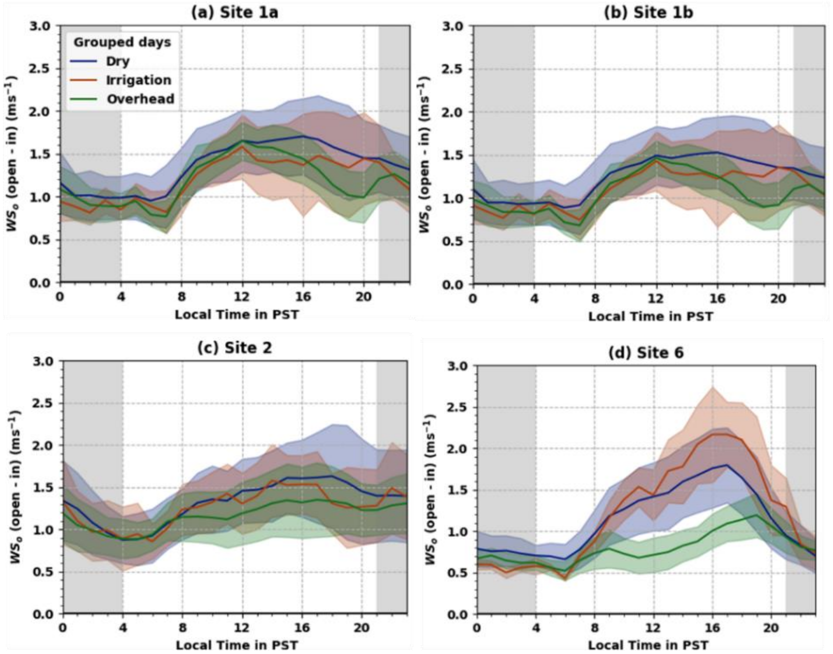

Fig. 7. Site-specific mean hourly wind speed (WS_o) (line) and 0.5 SD (shaded) between paired open- and in-orchard stations for dry, irrigation, and overhead sprinkler days at (a) site 1a, (b) site 1b, (c) site 2, and (d) site 6.

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

Modeling was done for each of the weather parameter (AT, RH, WS) separately using methodology flowchart depicted in the figure below. For example, Multiple linear regression (MLR) and two machine learning models namely K Nearest Neighbor regression (KNN) and Random Forest (RF) were developed to predict air temperature. Likewise, three separate models were developed respectively for WS and RH prediction. It total, 9 models were developed.

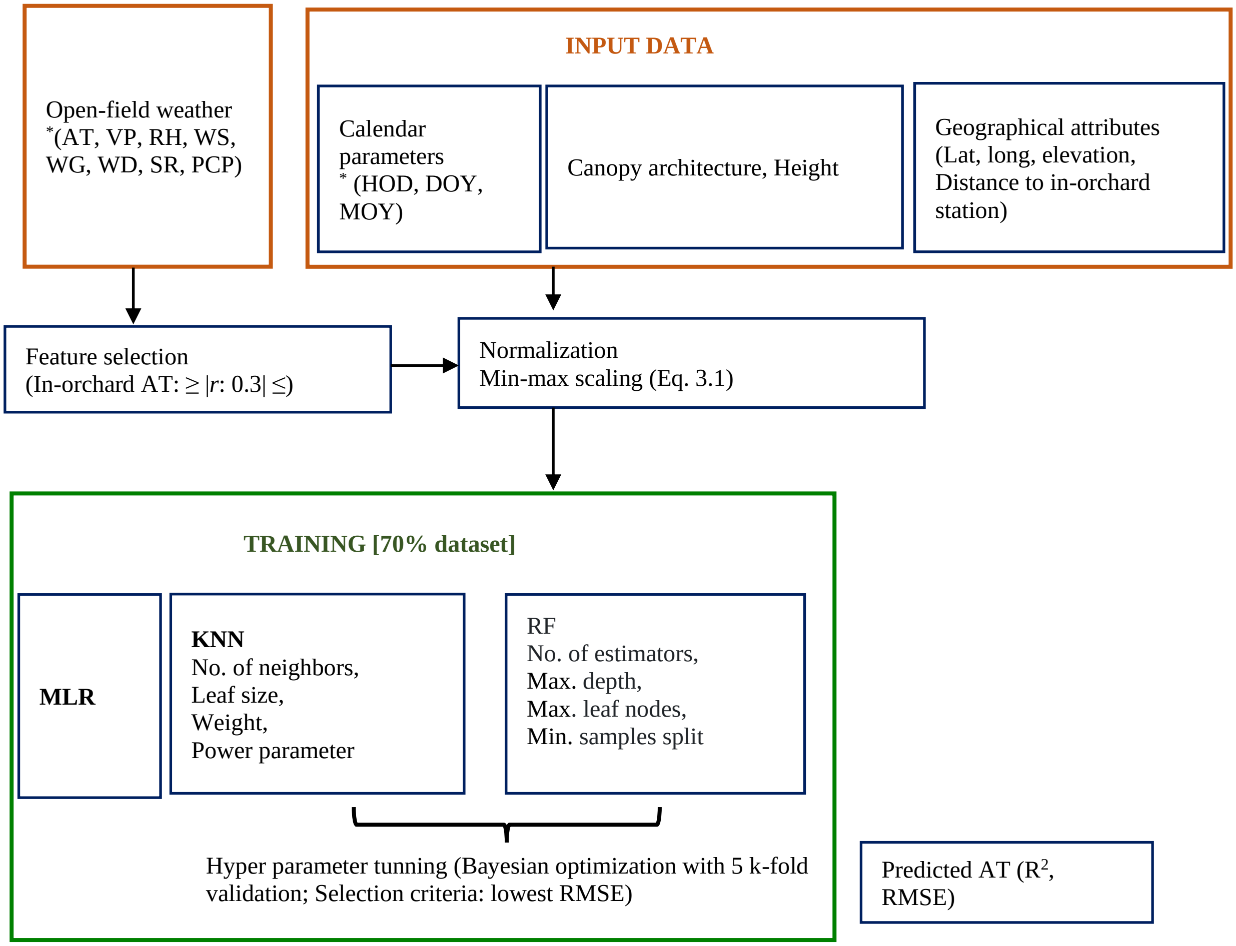

Fig. 8. Flowchart of in-orchard temperature weather prediction using open-field weather, calendar parameters, orchard canopy parameters and geographical attributes. The same approach was used to model in-orchard relative humidity and wind speed.

Results and Discussion

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

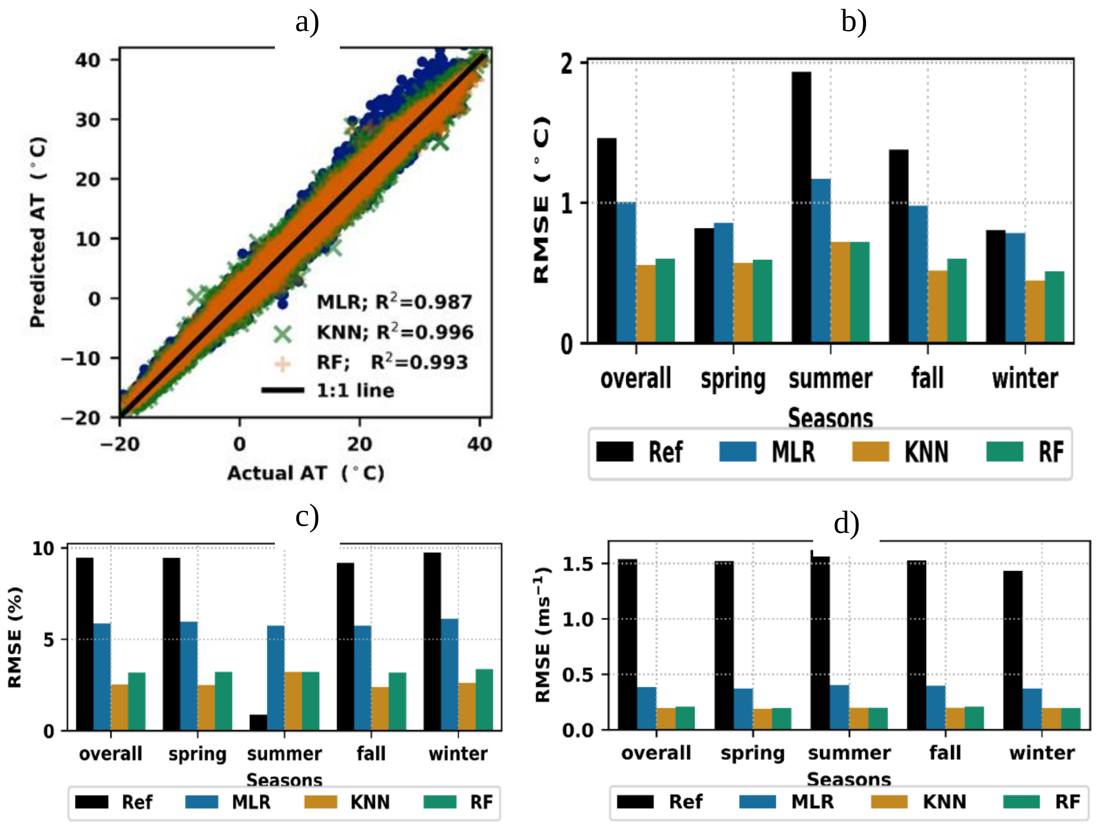

Fig. 9. a) Model performance metrices on the test dataset for in-orchard air temperature prediction, and root-mean-squared-error (RMSE) of predicting in-orchard **b)** AT, **c)** RH, and **d)** WS using Multiple Linear Regression (MLR), K-Nearest Neighbor Regression (KNN) and Random Forest Regression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

Executive summary

Project title: Modeling Orchard Effects on Meteorological Measurements

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

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