In-field sensing for crop protection: efficacy of air-blast sprayer generated crosswind in rainwater removal from cherry canopies

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Abstract:

Rainwater-induced fruit cracking leads to serious economic loss to fresh market sweet cherry growers. To prevent fruit cracking, the key is timely and effective removal of rainwater from canopies during and after rain events. Current rainwater removal methods include use of orchard air-blast crosswind and manned helicopter downwash based on empirical judgement of growers. The goal of this study was to develop an in-field sensing system to monitor canopy wetness and micro-climate, which will help growers to decide upon when and how much rainwater needs to be removed from canopies. The developed sensing system was tested to evaluate the efficacy of an air-blast orchard sprayer in rainwater removal from cherry trees with Y-trellised (Skeena) and vertical (Selah) architectures. Results show that the sensing system could capture the wetness threshold rainfall level that may cause fruit cracking (2.5 mm). Crosswind generated by the orchard sprayer was unevenly distributed on tree canopies, especially in vertical architecture, where crosswind velocity in bottom-section of canopies (1.1

m above ground) was significantly higher than that in middle- (1.9 m) and top-sections (2.7 m). Overall, orchard sprayer crosswind had the highest rainwater removal than natural drying (control) in both architectures. Rainwater removal was significantly affected by rainfall levels studied, with significantly higher in lower rain level (2.5 mm) than those of medium (5.0 mm) and high level (10 mm) from vertical tee canopies. Also, in vertical architecture, the interaction effect of travel speed and location was significant on rainwater removal, and the rainwater removal due to crosswind at any travel speed was significantly higher than that of control at middle section of vertical tree canopies.

Keywords: Sweet cherry; Fruit cracking; Canopy sensing; Tree architecture; Mechanical rainwater removal.

1. Introduction

Sweet cherry (*Prunus avium* L.) is a high value tree fruit crop. In Washington State of U.S., there are 14,164 ha of sweet cherry trees with a production volume of 252,000 tons, accounting for approximately 66% of the total U. S. production as of 2014 (USDA-NASS, 2015). However, the marketability of fresh market sweet cherry due to fruit cracking (or splitting) during production and post-harvest has been a major concern to the growers. Crop losses induced by fruit cracking could be 63% of total harvest in some varieties (Cline et al., 1995).

The key hypothesis on the causes of cherry fruit cracking during last few weeks prior to harvest is the excessive water uptake by the maturing fruit through either tree roots or fruit cuticle (Simon, 2006). Rainwater induced mechanical stress on fruit cuticle and resulting fruit

core-cuticle interface changes are related to fruit cracking (Considine and Brown, 1981). Existing fruit cracking prevention solutions from rainfall include use of canopy covers, chemical applications, and mechanical methods of rainwater removal. Børve et al. (2003) studied the effectiveness of canopy covers and reported that covers improved marketability of fruit from 54% on uncovered to 89% on covered trees in a two years research. Thomidis and Exadaktylou (2013) studied effect of a plastic rain shield on fruit cracking. Such rain shields effectively reduced up to 38% of cracking in the cracking-susceptible sweet cherry varieties of Lapin, Germesdorfi, and Van. However, covered cherry trees had a higher incidence of ‘Shot Hole’, one of the most important foliar diseases of cherry trees. Additionally, canopy cover installation, operation, and recycling of used materials was labor-intensive and costly, limiting large-scale applicability (Meland et al., 2014). Besides canopy covers, methods of spraying cherry fruits with minerals or chemicals have been widely used in the U.S. Spraying fruit with CaCl_2 or similar mineral compounds can effectively delay or reduce the amount of water uptake into the fruit, and increase the transpiration of rainwater from the fruit surface (Simon, 2006). However, multiple spray applications needed to keep the fruit protected (Kafle et. al., 2016) and an unsightly fruit appearance caused by the spray residue (Jedlow and Schrader, 2005) are some of the challenges associated with mineral spray applications.

Another promising method to prevent fruit cracking is to remove rainwater as soon as possible after a rain event using crosswind air-blast of orchard sprayers and/or helicopter downwash (Jedlow and Schrader, 2005). Manned helicopters flying 3.0 to 6.0 m (10 to 20 feet) above tree canopies at the speed of 8.0 to 16.1 $\text{Km}\cdot\text{h}^{-1}$ (5 to 10 mph) can generate sufficient downwash and blow rainwater off fruits and leaves (Pihl, 2012). Similarly, the air-blast orchard sprayers driven in orchard alleys to shake the canopies after rainfall can also remove or disperse

rainwater. Rainwater removal from canopies using mechanical approach can reduce the effects of physical exclusion or spraying of fruits. However, low flying altitude and resulting downwash of helicopter can cause damage to fruits. The low-altitude manned helicopter flights may also cause serious injury, even death, to pilots. For example, four helicopters were crashed and four pilots died during 2010 to 2014 only in central area of Washington State (Wheat, 2014).

Therefore, there is a need to critically evaluate the efficacy of mechanical rainwater removal techniques so that growers can make informed decision on appropriateness of the technique to suit pertinent situation (e.g. varied canopy wetness due to varied rainfall levels). No research exists on this aspect, mainly due to lack of appropriate sensing tools to evaluate the efficacy of the rainwater removal techniques. The overall focus of this study was to develop an in-field sensing system that could provide real-time micro-climate information to growers/farm managers, leading towards better decision making in terms of canopy rainwater removal and crop loss management. The specific objectives of presented research were 1) to quantify the velocity of the crosswind generated by an air-blast orchard sprayer within tree canopies using an in-field sensing system, and 2) to evaluate the efficacy of the crosswind in rainwater removal from cherry tree canopies with different architectures.

2. Materials and methods

2.1 Experimental orchard and in-field sensing system

Field experiments were conducted at Washington State University's Roza experimental orchard near Prosser, WA, USA. Two varieties of sweet cherry (*Prunus avium* L.) with two canopy architectures were used in this study, specifically 'Skeena' variety with Y-trellised fruiting wall canopy (termed as Y-trellised architecture henceforth, Fig. 1a) and 'Selah' variety

with vertical fruiting wall canopy (termed as vertical architecture henceforth, Fig. 1b). Y-trellised cherry trees were planted on Gisela[®] 6 root stock at around 7 years ago with the inter- and intra-row spacing of 4.6 and 0.9 m, respectively. Approximate eight branches of each tree were trained to grow at both sides of the row with an angle of 55° to ground level. The average height of the trees is approximate 4.0 m above ground level. Vertical architecture trees also grow on the Gisela[®] 6 root stock planted approximately 10 years ago. The inter- and intra-spacing was 3.0 and 2.4 m, respectively. All branches grow vertically to the ground with the maximum canopy height of 4.2 m. The experiments were conducted at the cherry growth stage (BBCH stage) of 85-87 (Fadón et al., 2015), which was prior to the commercial harvesting window on 18-19 June, 2015.

Fig. 1. The canopy architectures of the cherry trees used in this research. (a) “Skeena” cherry trees trained as Y-trellised canopy architecture have three to five branches in each side at 55° to the ground level and (b) “Selah” cherry trees trained as vertical canopy architecture have branches growing vertically.

The micro-climate information within tree canopies, including wetness level, wind velocity, temperature and humidity, was measured using a custom designed in-field sensing system developed by our research group, which is illustrated in Fig. 2. The sensing system was developed based on a data logger (CR1000, Campbell Scientific, Logan, Utah, USA), which

consisted of an on-board controller (processor), memory and clock to make it work as an independent system. The data logger was able to collect analogue and digital signal from multiple types of sensors, including leaf wetness sensor (LWS, Decagon Device, Pullman, WA, USA), sonic anemometer (DS-2, Decagon Devices, Pullman, WA, USA), and temperature and humidity probe (VP-3, Decagon Devices, Pullman, WA, USA). In the system, leaf wetness sensors (LWSs) were used to quantify the wetness of tree canopies by measuring the dielectric constant of the sensor upper surface, which is sensitive to moisture level. Integrated with conditioning circuits, the output voltage of a LWS is proportional to the surface wetness (LWS Operation Manual, 2014). As shown in Fig. 2a, all LWSs were connected to different analogue inputs of the data logger, and excitation voltage of LWSs was provided by the data logger to achieve accurate measurement.

Fig. 2. Components of the developed in-field sensing system. (a) Sensors, data logger, management software and pertinent connections. A weather-proof enclosure was used to protect the data logger and its accessories from hazard environment. A set of radio modules was used to communicate between the computer and the data logger. (b) Actual field setup.

The wind velocity was measured using 2D sonic anemometers, which have no moving parts and can be easily mounted in tree canopies. The anemometers can measure wind velocity up to $30.0 \text{ m}\cdot\text{s}^{-1}$ with an error of $\pm 0.3 \text{ m}\cdot\text{s}^{-1}$ at the maximum sample rate of 1 Hz. The anemometers communicate with data logger using the protocol of SDI-12 (shorted for Serial Digital Interface at 1200 baud), which is a data communication standard to interface battery powered data loggers with micro-processor based sensors. SDI-12 allows data loggers to collect data from multiple types of SDI-12 sensors using a single input pin. Same as anemometers, the relative humidity (RH) and temperature probe is also a SDI-12 sensor that was connected to a digital input pin of the data logger (Fig. 2a). The probe error was in the ranges of $\pm 2.0\%$ to $\pm 4.0\%$ when used in the test orchard environment. The temperature output showed an error of less than $\pm 0.5^\circ\text{C}$ while measuring temperature from 0.0 to 70.0°C .

The collected data were temporarily stored in the internal memory of the data logger, and were downloaded to an external hard drive. In the test, the data logger communicated with a laptop through either a wireless radio module (RF401, Campbell Scientific, Logan, Utah, USA) or directly through a serial port. The data logger was configured and controlled through the software LoggerNet[®] (V4.3, Campbell Scientific, Logan, Utah, USA) to set the proper sample rate and connection protocol for different sensors. The sensing system was powered using a 12 VDC lead-acid battery which could be recharged through a solar panel. The data logger and battery were protected by a weatherproof enclosure to allow the sensing system working continuously in field conditions. Fig. 2b shows an example of the field setup of the sensing system. Some other application of the system can also be found in a companion paper (Zhou et al., 2016).

2.2 Rainfall simulation system and orchard sprayer

It is difficult to have natural rainfall events with the desired rainfall levels in a limited time window for research purpose. Therefore, a rainfall simulation system was developed to mimic different rainfall levels in the orchard conditions. The details on the development of the rainfall simulation system were described in the pertinent papers (Kafle et. al., 2016; Zhou et. al., 2016). The system mainly consisted of eight sets of nozzles and a water pump system to provide pressurized water to the nozzles. The system has the ability to adjust the water pressure and the height of nozzles to tree canopies, such that three to five test trees could be covered at the same time. The system was mounted on an orchard vehicle to make it easy to relocate within the orchard. In the experiment, the pressure of the spray system was set as 200 kPa (30 psi) and the height of spraying system was adjusted at 5.0 m above ground (approximately 1.0 m above tree canopies).

Air-blast sprayers operated without spray materials can provide crosswind to remove or disperse rainwater off cherry fruit and canopies. This technology is currently used in Pacific Northwest regions of U.S. to reduce the incidence of fruit cracking during or after rainfall events. In this study, an empty air-blast orchard sprayer (Pul-Tank blast, Rear's Manufacturing, Eugene, OR, USA) pulled by an orchard tractor (T4040F, New Holland Agriculture, New Holland, PA, USA) and driven through the PTO system of the tractor, was used to evaluate the rainwater removal efficacy of this technology.

2.3 Orchard sprayer Crosswind and rainwater removal efficacy

Field experiment (experiment-1) was first conducted to quantify the orchard sprayer crosswind at different sections of tree canopy in static condition. [In the experiment, three](#)

anemometers were mounted on the fruit wall canopy of both architectures at 1.1, 1.9, and 2.7 m above ground level (henceforth referred as bottom, middle and top section) to measure the orchard sprayer crosswind. Such test was replicated once in three locations for each of the canopy architectures, i.e. total of six runs. Each run encompassed operating sprayer for around 60 s to record crosswind at above mentioned heights. The crosswind velocities were measured seven times in the middle period, where the wind velocity was stable. The mean of these subsamples was used to obtain an estimate of the average crosswind in different sections of tree canopy.

The orchard sprayer efficacy in rainwater removal was evaluated in the two selected orchards (Y-trellised and vertical architecture) in a separate experiment (experiment-2). Travel speed (3 levels) and rainfall level (3 levels) were evaluated using a completely randomized full factorial design with subsampling. In each architecture (orchard), 12 treatment plots, with three to five consecutive trees in a row as one plot, were randomly selected for 9 different combinations of orchard sprayer travel speed and rain level treatments and 3 control groups. Between two treatment plots, a buffer area of about 7.6 m was maintained to reduce the rainfall and orchard sprayer interference.

Rainfall levels of 2.5, 5.0 and 10.0 mm were selected based on the maximum and average daily rainfall at the experimental site in the months of June and July for the past 7-years (2008 to 2014) from a nearby agricultural weather network (AgWeathernet, 2015). After the rainfall simulation, the orchard sprayer was driven passing that plot at one pre-defined travel speed of 1.9, 3.7 or 4.5 km·h⁻¹ (low, median and high speed) immediately in treatment plots, or not driven in control plots. The range of the selected travel speeds was based on the practical travel speed of approximately 3.2 km·h⁻¹ (2 mph) used by growers in the region due to the

complexity of orchard conditions. Prior to actual experiment, travel speeds of the sprayer in three gear combinations were calibrated by measuring the time required to travel the flagged distance of 100 m in the experimental orchard.

In experiment-2, three branches were randomly selected from each plot (three to five trees). Three LWSs were mounted (Fig. 2b) on each of the selected branches at three heights, as mentioned in experiment-1, to quantify the canopy wetness before and after the orchard sprayer pass. To mimic the real leaves, LWSs were tied onto small twigs of the branches with the sensors facing up and tilting at 30° to 45° to ground level. Each treatment had a total of nine LWSs (three heights × three branches) that were wired to the data logger to record the wetness data at the sample frequency of 1 Hz. A single parameter of rainwater removal (described in the following paragraph) was made at each of the nine LWSs at each plot.

The wetness of the tree canopies was quantified with the parameter of canopy wetness (CW), which is calculated using following equation (Zhou et al., 2016):

$$CW = \frac{V_r - V_d}{V_w - V_d} \times 100\%$$

where, CW is canopy wetness (%), V_r is the output of a LWS (mV), V_d and V_w are dry and wet outputs (mV) of the LWS, which are the outputs of LWSs before rainfall and after the rainfall saturation of canopies (Zhou et al., 2016). The rainwater removal efficacy of the orchard sprayer in this research was quantified by rainwater removal (RR, %), which is the difference in canopy wetness between saturated wet condition (CW = 100%) and CW at 10 min after stopping the rainfall simulation.

The nearby meteorological conditions recoded by the localized open field weather station (AgWeathernet, 2015), including wind speed and direction, air temperature and humidity, were $3.9 \pm 2.5 \text{ m}\cdot\text{s}^{-1}$ SW (mean ± std. dev.), $29.7 \pm 1.8^\circ\text{C}$, and $27.8 \pm 3.8\%$, respectively, during

the first day of experiment. Similarly, the meteorological parameters were $4.4 \pm 1.3 \text{ m}\cdot\text{s}^{-1}$ SW, $22.2 \pm 3.4^{\circ}\text{C}$, and $42.7 \pm 10.3 \%$, respectively, during day two.

2.4 Data analysis

Statistical analysis for both experiments was performed using a linear mixed model in PROC MIXED of SAS version 9.4 (SAS Institute, Cary, NC, USA). Differences in means of experimental factors were assessed using least squares means. When there were more than three levels of an experimental factor, *p*-values were adjusted for multiple comparisons using Tukey's procedure. Model assumptions of homogeneity of variance and normality were verified using plots of studentized residuals, and were acceptable in all cases. The significance level was 0.05, and figures were created using SigmaPlot (ver. 11.0, Systat Software, San Jose, CA, USA).

For experiment-1, each of the six runs included seven measurements close in time and taken simultaneously at each of three different heights. For analysis, the mean of the seven measurements was used. The fixed effect in the model was height. Because the averages at different heights within a run are not independent replications of the experiment, their correlation was incorporated using a random intercept for run. This allowed each of the averages at different heights within a single run to be equally correlated.

In the case of experiment-2, the effects of rain level and orchard sprayer travel speed were evaluated on the percentage of rainwater removal for each of the two canopy architectures. In this experiment, the experimental units were 12 plots in each architecture, while the observational units were LWSs, resulting in nine total subsamples in each plot (three subsamples for each of three locations). The linear mixed model included fixed effects for rain level, travel speed, and LWS location (high, middle, low) and their two- and three-factor

interactions, and a random effect for branch nested within plot. This random effect allows correlation among the measurements of each branch. Because the experimental conditions were not independently replicated, a random effect for plot was not estimable.

3. Results and discussion

3.1 Air-blast sprayer crosswind characterization

Descriptive statistics of crosswind velocities from the anemometers at different canopy heights have been summarized in Fig. 3. The 21 crosswinds measured at the heights of 1.1, 1.9, and 2.7 m in Y-trellised canopy were 12.6 ± 2.2 (mean $\pm$ std. dev.), 13.3 ± 3.5 and 10.1 ± 3.7 $\text{m}\cdot\text{s}^{-1}$, respectively, which were more uniform than those of 21.0 ± 3.4 , 13.5 ± 2.9 and 5.7 ± 2.2 $\text{m}\cdot\text{s}^{-1}$ at the corresponding sections of trees with vertical canopy. Crosswind at the canopy sections of 2.7 m in both architectures was significantly lower [$t(6) = 3.24$, $p = 0.040$ and $t(6) = 4.1$, $p = 0.015$ for Y-trellised canopy and $t(4) = 26.0$, $p < 0.0001$ and $t(4) = 13.3$, $p = 0.0004$ for vertical canopy] than that at low and middle height sections (1.1 and 1.9 m), respectively. The differences in degrees of freedom is due to the random run effect being estimated to be 0 for the Y-trellised canopy. The non-uniformity of crosswind in the canopy was predominant in trees with vertical architecture, where crosswind reduced 57.8% at middle and 72.9% at high sections of canopy compared to low sections. For trees with Y-trellised architecture, the average crosswind at low height sections was lower than that of vertical architecture, however, the velocity in high sections was significantly higher. Since more than 80% of cherry fruits are distributed in the middle and high height section of trees (Zhou et al., 2014), Y-trellised architecture might be better than vertical architecture in terms of prevention of cherry cracking.

Fig. 3. Air-blast sprayer crosswind at different heights of tree canopy with two architectures. The bars are standard deviation and the different letters on the bars indicate significant differences between treatment means at 5% level (capital letters for Y-trellised canopy architecture and small letters for vertical canopy architecture).

Distribution of crosswind in the same section of two canopy architectures might be different because of the varied level of accessibility of orchard sprayer air-blast to tree canopies. Y-trellised tree canopies are tilting at 55° to ground (Fig. 1a), which makes the canopies closer to the air-blast at middle and high sections than those of vertical trees. Air-blast crosswind trends suggest that uniform water removal from top and middle canopy sections could be possible in Y-trellised canopies as these sections are close to the air-blast of the orchard sprayer than bottom section. Crosswind trends in vertical canopy architecture are typical characteristics of air-blast orchard sprayer, where low and middle sections of vertical canopy receives higher air-blast when compared to that of top height sections.

3.2 Air-blast crosswind efficacy in rainwater removal

Rainwater removal from different canopy sections due to natural condition (control) and crosswind (treatment) with different travel speeds of orchard sprayer are summarized in Table 1. The presented data are the average of three branches in each condition. The fixed effect of rain

level, travel speed and LWS location on the rainwater removal was analyzed using a linear model for each of the respective canopy architecture. In vertical architecture, results are listed in Table 2, which shows that the interaction effect of travel speed $\times$ location was significant [$F(6, 69) = 3.14, p = 0.009$]. In addition, the effect of rain level [$F(2, 69) = 3.78, p = 0.028$] was also significant, with significantly higher rainwater removal in 2.5 mm rain than those in 5.0 and 10.0 mm. In the same architecture, Figure 4 shows the travel speed $\times$ location interaction effect on rainwater removal, which indicates that rainwater removal at the low, middle, and high travel speeds ($1.9 \text{ km}\cdot\text{h}^{-1}$, $3.7 \text{ km}\cdot\text{h}^{-1}$, and $4.5 \text{ km}\cdot\text{h}^{-1}$) was similar in all locations. Rainwater removal at these speeds was not different from that of control at the bottom or top branches but was significantly greater in the middle (all comparisons $p \leq 0.001$). The finding indicates that crosswind removed rainwater from tree canopies at any travel speed, but removal was significantly greater at middle branches compared to the control.

Table 1.

Rainwater removal in treatment groups (10-mins after rainfall).

Canopy type	Travel speed (km·h ⁻¹)	Rain level (mm)	Rainwater removal (%) (Mean ± std. dev.)		
			LWS location		
			Top (2.7 m)	Mid (1.9 m)	Bottom (1.1 m)
Vertical	Control	2.5	86.3±8.1	82.0±11.2	84.3±2.3
		5.0	80.8±6.4	64.9±10.6	87.3±9.7
		10.0	81.8±3.6	57.3±15.0	87.8±3.0
	1.9	2.5	95.5±2.3	93.0±3.9	97.9±1.6
		5.0	66.9±14.3	93.0±3.2	94.9±5.5
		10.0	81.2±20.9	85.1±12.3	88.1±15.2
	3.7	2.5	86.5±8.3	90.8±4.7	83.0±15.5
		5.0	81.7±3.1	73.3±18.5	89.8±2.1
		10.0	90.0±2.1	87.5±9.4	91.7±4.1
	4.5	2.5	85.6±10.8	94.5±4.0	85.9±14.9
		5.0	93.8±3.8	87.3±9.1	90.8±4.2
		10.0	68.1±16.6	84.1±2.3	90.7±3.9
Y-trellised	Control	2.5	86.5±8.7	79.4±3.7	79.7±3.6
		5.0	89.3±6.8	80.2±5.1	84.6±4.5
		10.0	76.1±3.3	67.6±2.3	69.7±3.4
	1.9	2.5	98.1±2.1	98.8±0.7	97.6±3.8
		5.0	96.5±3.9	96.2±2.1	93.2±2.8
		10.0	84.0±6.1	91.0±12.6	98.1±1.0
	3.7	2.5	--	--	--
		5.0	96.9±2.7	99.0±0.2	96.5±4.4
		10.0	98.7±0.8	98.4±1.3	96.5±1.0
	4.5	2.5	98.9±1.7	99.1±0.9	96.3±4.3
		5.0	--	--	--
		10.0	98.7±1.0	98.7±1.7	99.0±1.3

Table 2.

Type 3 tests of fixed effects on data from experiment-2.

Effect*	Numerator degree of freedom	Denominator degree of freedom	F Value	P _r > F
<i>RL</i>	2	69	3.78	0.0276
<i>TS</i>	3	69	4.69	0.0049
<i>RL</i> × <i>TS</i>	6	69	1.79	0.1140
<i>Loc</i>	2	69	4.99	0.0094
<i>RL</i> × <i>Loc</i>	4	69	2.03	0.1004
<i>TS</i> × <i>Loc</i>	6	69	3.14	0.0089
<i>RL</i> × <i>TS</i> × <i>Loc</i>	12	69	1.67	0.0937

* Fixed effect of rain level (*RL*), travel speed (*TS*) and LWS location (*Loc*) on the rainwater removal from vertical tree canopies.

Fig. 4. Rainwater removal at three [low (T1), medium (T2) and high (T3)] travel speeds and control (C) in low, middle and top sections of vertical tree canopies. The results show the interaction effect of travel speed and location on the rainwater removal.

In case of Y-trellised architecture, the 3-way interaction effect (rain level $\times$ travel speed $\times$ location) on the rainwater removal was significant [$F(8, 40) = 2.20, p = 0.048$]. Figure 5 shows that crosswind treatments had similar rainwater removal to each other but removed significantly more rainwater from tree canopies than control, with one exception. Specifically, the rainwater removal was not different from control at the combination of high rain level (10.0 mm) with low travel speed ($1.9 \text{ km}\cdot\text{h}^{-1}$) at the middle and top branches. Overall, similar to vertical architecture, crosswind effectively removed rainwater from tree canopies at all three travel speeds.

Fig. 5. Rainwater removal at three [low (T1), medium (T2) and high (T3)] travel speeds and control (C) in different rain level-location combinations [R1B indicates rain level 1 (2.5 mm) at bottom section] of Y-trellised tree canopies. The results show the interaction effect of travel speed, rain level and location on the rainwater removal.

Although the statistical analysis was not conducted to compare the effect of canopy architecture on rainwater removal, the mean rainwater removal at Y-trellised canopy was higher ($96.7 \pm 4.7\%$) than that of vertical canopy ($87.1 \pm 11.3\%$). The overall rainwater removal due to natural drying (control) in both architectures was similar, with $79.2 \pm 12.6\%$ for vertical and $79.2 \pm 8.1\%$ for Y-trellised architecture. The relatively less rainwater removal efficiency in vertical architecture might be due the uneven crosswind in different sections of tree canopies (Fig. 3). Rainwater removal was more uniform, with less variability, for Y-trellised architecture where crosswind could effectively reach higher canopy sections. The significance of the tree architecture on rainwater removal needs to be studied in future studies.

The small difference in rainwater removals between treatment and control might be contributed by the micro-climate during the field experiments. Year 2015 was termed as one of the hottest years in Pacific Northwest with summer temperatures in month of June reached ~ 43 to 46°C (AgWeathernet, 2015). The rainfall simulated at such high temperature and lower relative humidity was evaporating quicker than the real rainy days, which might have made the

344 effect of some treatments non-significant compared to control groups. Data in Table 1 also
345 show a typical trend in control group where less rainwater was removed from middle sections of
346 canopies compared to bottom and top sections. Possible reason for such phenomena could be
347 that the top sections were in open area and might have had higher evaporation than other
348 sections whereas bottom section with tree trunk approximately 1.1 m from ground might have
349 allowed wind movement and fast drying.

350 Other than the canopy wetness levels, the in-field sensing system also quantified the
351 micro-climate conditions (Table 3). Although the climate data can be obtained through weather
352 service providers, the weather stations are usually installed in open fields and may be far from a
353 specific orchard site. Such measurements may not reflect the canopy micro-climate, which is
354 critical for the prevention of cherry cracking. Table 3 summarizes canopy micro-climate which
355 had considerable variation among different treatments and need to be factored in for effective
356 rainwater removal in future studies. Pertinent information acquired by such in-field sensing
357 system may be an important aspect in the analysis of cherry cracking susceptibility of existing
358 as well as new breeding lines of sweet cherry cultivars.

Table 3.

Canopy micro-climate during the field experiments.

Parameters	Canopy type	Rain level (mm)	Micro-climate parameters (Mean $\pm$ std. dev.)			
			Control	Travel speed (km·h ⁻¹)		
				1.9	3.7	4.5
Wind velocity (m·s ⁻¹)	Vertical	2.5	0.23 $\pm$ 0.14	0.23 $\pm$ 0.14	0.39 $\pm$ 0.26	0.19 $\pm$ 0.13
		5.0	0.31 $\pm$ 0.20	0.25 $\pm$ 0.13	0.39 $\pm$ 0.27	0.31 $\pm$ 0.20
		10.0	0.37 $\pm$ 0.26	0.25 $\pm$ 0.13	0.26 $\pm$ 0.22	0.22 $\pm$ 0.18
	Y-trellised	2.5	0.71 $\pm$ 0.40	1.34 $\pm$ 0.72	--	0.74 $\pm$ 0.41
		5.0	0.93 $\pm$ 0.70	0.44 $\pm$ 0.27	1.56 $\pm$ 1.02	--
		10.0	0.95 $\pm$ 0.57	0.87 $\pm$ 0.53	1.38 $\pm$ 0.86	0.63 $\pm$ 0.56
Air temperature (°C)	Vertical	2.5	27.4 $\pm$ 0.3	27.3 $\pm$ 0.8	25.6 $\pm$ 0.6	25.0 $\pm$ 0.7
		5.0	23.1 $\pm$ 0.3	27.6 $\pm$ 1.0	24.7 $\pm$ 0.5	29.0 $\pm$ 0.5
		10.0	27.7 $\pm$ 0.3	27.6 $\pm$ 1.0	26.4 $\pm$ 0.3	23.3 $\pm$ 1.3
	Y-trellised	2.5	24.6 $\pm$ 0.4	22.9 $\pm$ 0.4	--	22.8 $\pm$ 0.7
		5.0	25.5 $\pm$ 0.4	19.3 $\pm$ 0.2	23.2 $\pm$ 0.8	--
		10.0	42.1 $\pm$ 3.1	44.4 $\pm$ 2.4	42.5 $\pm$ 1.5	45.2 $\pm$ 4.1
Humidity (%)	Vertical	2.5	43.8 $\pm$ 3.0	38.7 $\pm$ 2.3	42.7 $\pm$ 2.7	37.9 $\pm$ 3.9
		5.0	25.5 $\pm$ 0.4	19.3 $\pm$ 0.2	23.2 $\pm$ 0.8	--
		10.0	--	51.7 $\pm$ 1.8	--	--
	Y-trellised	2.5	--	41.3 $\pm$ 2.9	--	--
		5.0	--	51.7 $\pm$ 1.8	--	--
		10.0	--	--	38.8 $\pm$ 2.3	--

4. Conclusions

In this study, the rainwater removal efficacy of crosswind due to an air-blast orchard sprayer was evaluated with an in-field sensing system, which was used to monitor the wetness level and other micro-climate parameters of cherry tree canopies. A rainfall simulation system was used to simulate different rainfall levels on target cherry canopies with vertical and Y-trellised architecture. The sensing system quantified the crosswind of the orchard sprayer in different sections of tree canopies. Measured wetness level by the system was used to determine the rainwater removal from tree canopies due to natural drying and during different treatments. Based on the test results, the following conclusions were made:

- Y-trellised canopy had even distribution of crosswind in different sections of canopies and hence higher rainwater removal compared to vertical canopy which showed typical air-blast crosswind reach effect.
- Rainwater removal due to air-blast sprayer crosswind was significantly affected by rain level with significantly higher rainwater removal at lower rain level from vertical tree canopy.
- Interaction effect of orchard sprayer travel speed and location was significant on rainwater removal. The rainwater removal due to crosswind was significantly higher than that of control from middle section of vertical tree canopies regardless of travel speed.

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