Efficacy of Unmanned Helicopter in Rainwater Removal from Cherry Canopies

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Abstract:

Rain-induced fruit cracking causes significant economic loss for fresh market sweet cherry growers annually. To prevent cherry cracking, timely removal of rainwater from fruit is the key. This study evaluated the efficacy of an unmanned middle-size helicopter to remove rainwater from Y-trellised cherry canopies. Helicopter downwash in hover at four altitudes, with and without a payload, was quantified with six anemometers deployed in tree canopies. Results showed that payload and altitude significantly affected hover downwash, which was greater at higher altitude of 7.6 m above ground level (AGL) than lower altitude of 4.9 m AGL with payload. In the absence of payload, hover downwash peaked at the altitude of 6.1 m AGL. In the efficacy study, 5.0-mm rainwater was applied to cherry canopies by a rainfall simulation system, followed by the helicopter flying over canopies at three altitudes (4.9, 5.5 and 6.1 m AGL), two travel speeds (1.3 and 2.7 m. s⁻¹) and with or without payload. Rainwater removal at bottom (1.1 m), middle (1.9 m) and top (2.7 m) of the canopies was calculated based on the change of leaf wetness of target canopies in 10 min after rain. Overall, helicopter with payload flying 2.7 m. s⁻¹

at 6.1 m AGL removed significantly more rainwater (96.3%) from top section of canopies than groups without treatment (71.2%) and compared to other payload and travel speed conditions. Results also confirmed that the unmanned helicopter could provide sufficient downwash to remove rainwater effectively from bottom and middle canopy sections.

Keywords: Sweet cherry; fruit cracking; unmanned helicopter; downwash; canopy wetness

1. Introduction

Fresh-market sweet cherry (*Prunus avium* L.) is a profitable crop for growers in the Pacific Northwest region of the U.S. In 2014, growers in Washington State produced ca. 217,000 tons of fresh-market sweet cherries with a farm gate value of approx. 488 million U.S. dollars (USDA-NASS, 2015). However, annually, rain-induced cherry fruit cracking results in substantial economic loss to growers through reduced marketability of cracked fruit. Rainfall, particularly during last three weeks prior to harvest can cause 60% of fruit cracking (Cline et al., 1995), up to 90% in some susceptible cultivars and areas (Vittrup Christensen, 1995; Wang and Long, 2015).

It is generally recognized that cherry fruit cracking is due to excessive water uptake by maturing fruit through either tree roots or rainwater on the fruit cuticle (Considine and Brown, 1981; Simon, 2006). Therefore, the key methods of preventing cherry cracking are to reduce potential uptake of rainwater or remove rainwater from cherry fruit surface quickly and effectively during and after rainfall events. Existing fruit cracking prevention solutions include use of canopy covers, chemical application, and rainwater removal by machines. The methods of using canopy covers (Børve et al., 2003; Thomidis and Exadaktylou, 2013; Meland et al., 2014) and mineral-based chemical (e.g. CaCl_2) applications prior to rainfall (Jedlow and Schrader,

2005; Simon, 2006) are effective and currently used in commercial farm operations. A new hydrophobic food-grade polymer product was recently introduced and shows promise in prevention of fruit cracking (Kaiser et al., 2014). However, the cost of installation of canopy covers limits their adoption to growing regions that face high rain pressure during harvest. Meanwhile, in the case of spray applications, multiple spray passes are needed to keep fruit protected due to the significant washout of chemical by rainwater (Kafle et. al, 2016). Also, spray residue on the fruit surface has an unsightly appearance (Jedlow and Schrader, 2005) reducing marketability of the fresh-market produce.

Mechanical methods for removing rainwater use either the crosswind from an orchard air-blast sprayer or the downwash of manned helicopters (Jedlow and Schrader, 2005) immediately after rain events. Empty air-blast sprayers can generate strong crosswind and blow rainwater off tree canopies when driving through orchard alleyways. Zhou et al. (2016) gave a pertinent discussion on the feasibility of above technique in rainwater removal. This method is however, relatively slow limited by safe travel speed of orchard sprayers (approx. $0.9 \text{ m}\cdot\text{s}^{-1}$). In contrast, manned helicopters can fly at speeds of 2.3 to $4.5 \text{ m}\cdot\text{s}^{-1}$ above tree canopies to remove/disperse rainwater off fruits and leaves using rotor downwash (Pihl, 2012). Such speeds allow the coverage of acreage more quickly and hence are preferred by growers to remove rainwater considering time-sensitive issues. However, seasonal helicopter rental costs and timely availability of the helicopters are limiting factors. Additionally, low flying altitude and resulting downwash of manned helicopters can cause damage to fruits and may also cause serious injury, even death, to pilots. For example, in central Washington State alone, four fatal helicopter crashes were reported during 2010 to 2014 (Wheat, 2014).

To seek a safe and economical solution for rainwater removal from cherry tree canopies, unmanned middle-size helicopters (UMHs, take-off weight more than 25 kg but less than 600 kg, categorized in Group 3 in Department of Defense UAS Groups [DoD, 2011]) are a possible option. Such platforms may generate sufficient downwash with better altitude control in auto-pilot assisted flights, provide pilot safety due to remotely controlled operations and may lower operating costs in comparison to manned helicopters. Currently, UMHs are being used in precision agriculture for low altitude remote sensing and targeted spray applications for pest and disease control (Huang et al., 2013; Qiu et al., 2013; Sampson, 2014). More than 30% of rice acreage in Japan is being sprayed with such helicopters (Lan et al., 2010; Sampson, 2014). Recent research efforts have been focused on determining the optimal spraying parameters of such UMH platforms including flight altitude and travel speed for wheat (Bae and Koo, 2013; Qiu et al., 2013) and other crops.

There are no studies reported on the applicability of UMHs on rainwater removal from canopies to prevent fruit cracking. Therefore, the goal of this study was to evaluate the feasibility of an UMH and pertinent operating parameters towards effective rainwater removal from cherry tree canopies. The specific objectives were 1) to quantify the helicopter downwash in hover above Y-trellised cherry tree canopies at different altitudes and payload conditions, and 2) to evaluate efficacy of helicopter downwash under different flight altitudes, speeds and payload conditions in rainwater removal from trees canopies.

2. Materials and Methods

2.1 Unmanned mid-size helicopter

Sufficient downwash over and through tree canopies is the key requirement for successful rainwater removal applications. The velocity of downwash is determined by rotor diameter, helicopter weight, and air density around rotors (Johnson, 2012). Downwash velocity directly underneath the helicopter is defined as wake-induced downwash velocity, termed as downwash henceforth, and can be estimated using equation 1 (Johnson, 2012; Shi, 2015):

$$\omega = \sqrt{\frac{2T}{\rho A}} \quad (1)$$

where, ω is the wake-induced downwash ($\text{m}\cdot\text{s}^{-1}$), T is the total thrust (equivalent to the weight of helicopter, N), A is the disk area (m^2) and ρ is the air density ($1.2 \text{ kg}\cdot\text{m}^{-3}$ at sea level). The UMH used in this study was a remotely-piloted helicopter (RMAX, Yamaha Corp., Cypress, CA, USA) designed for agriculture purposes (Fig. 1a). Specifications of the UMH are listed in Table 1. Based on these attributes, estimated (theoretical) helicopter downwash with and without payload (the 16.0 kg spray tanks filled with water) for the experimental helicopter was $13.5 \text{ m}\cdot\text{s}^{-1}$ and $12.2 \text{ m}\cdot\text{s}^{-1}$, respectively.

Table 1: Specifications of the unmanned middle-size helicopter used in this study*

Parameters	Description
Model	Yamaha RMAX
Empty weight (with fuel)	64.0 kg
Sprayer weight	7.4 kg
Spray tank (full)	$2 \times 8.0 \text{ kg}$
Main rotor diameter	3.1 m
Overall length	2.8 m
Overall width	0.7 m
Overall height	1.1 m

*Data were obtained from: www.yamahaprecisionagriculture.com.

Fig. 1. (a) Unmanned middle-size helicopter (UMH) with detachable spray tank on either side; (b) Test trees were trained to Y-trellised canopy architecture. During field trials, the UHM was flying above the canopy at different altitudes and speeds.

2.2 In-field sensing system

An in-field sensing system was developed to monitor the leaf wetness, wind velocity and direction, temperature and humidity of cherry canopies. The sensing system consisted of data loggers (CR1000, Campbell Scientific, Logan, Utah, USA) and various sensors, including leaf wetness sensors (LWS, Decagon Device, Pullman, WA, USA), sonic anemometers (DS-2, Decagon Devices, Pullman, WA, USA), and temperature and humidity sensors (VP-3, Decagon Devices, Pullman, WA, USA). In the system, leaf wetness sensors (LWSs) were used to quantify the wetness level of tree canopies. LWSs quantify wetness level based on measuring the dielectric constant of the sensor upper surface, which is sensitive to moisture. Integrated with the conditioning circuit, the output voltage of a LWS is proportional to the surface wetness level (LWS Operation Manual, 2014). The wind velocity and direction was measured by 2D sonic anemometers, which have no moving parts and can be easily mounted in tree canopies. These sonic anemometers can measure wind velocity of 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 relative humidity (RH) and temperature probe used in this system is a pre-calibrated, marine grade product. Probe error is in the ranges of $\pm 2.0\%$ to $\pm 4.0\%$ when used in the test orchard environment (temperature: 20.0 to 40.0°C , RH: 10 to 90%).

The temperature output has an error of less than $\pm 0.5^{\circ}\text{C}$ while measuring temperature from 0.0 to 70.0°C .

The excitation voltage for LWSs was provided by the CR1000 to accurately measure and log the LWS data at frequency of 1 Hz. Meanwhile, the anemometers' data were also recorded by the data loggers at 1 Hz sample rate. The data loggers were configured and controlled through LoggerNet[®] software (V4.3, Campbell Scientific, Logan, Utah, USA). The sampled data were saved in the internal storage of the CR1000 and later copied to the hard drive of a laptop. Communication between data loggers and laptop was through a serial port RS-232 or wireless radio model RF401 (Campbell Scientific, Logan, Utah, USA). The sensing system was powered using a 12 VDC lead-acid battery and was protected with a rugged and weather-proof enclosure.

2.3 Rainfall simulation system

A rainfall simulation system was developed to mimic different rainfall levels in orchard condition. The system consisted of a water pumping system and a spray system (Fig. 2). To provide consistent pressure water flow to nozzles, a centrifugal pump (1538, Hypro, New Brighton, MN, USA) powered by a gas engine (GX 120, Honda Engines, Alpharetta, GA, USA) were included in the pumping system. The water pumping system was mounted on an agricultural vehicle (4210, Deere & Company, Moline, IL, USA) and connected to a 0.2 m^3 (55 gallons) water tank through a manual valve used to regulate the water pressure. The spray system consisted of eight sets of full cone spray tips (FCX80, Hypro, New Brighton, MN, USA). Each nozzle had a cone angle of 80° and output flow rate of $2.2 \times 10^{-5}\text{ m}^3 \cdot \text{s}^{-1}$ at 275.0 kPa. The spray tips were installed on a quick connect adaptor (QJ90-2-NYR, Teejet technologies, Wheaton, IL, USA) which was fitted on a 2.5 cm inside diameter polyvinyl (PVC) hose through a check valve

nozzle body at an interval of 0.3 m. The PVC hose with nozzles was fitted to an aluminum structure and then mounted on a telescoping mast (LM20-S, Floatograph, Santa Barbara, CA, USA), which could raise the nozzle assembly up to 7.0 meters from ground surface. The mast was also mounted on an agricultural vehicle to improve the mobility of the rainfall simulation system. In the test, the nozzles were adjusted at 0.5 to 1.5 m above the top of the tree canopies according to the local wind condition, which allowed the artificial rainfall to cover 3.0 to 5.0 trees at one time (see Fig 2a).

Fig. 2. (a) Rainfall simulation system and (b) configuration of nozzles sets. Two nozzle tips in a quick connector were 90° from each other.

The coverage and discharge rate of the spray system was determined by the height and water pressure, respectively. With the fixed cone angle of the spray tips, the higher the nozzles were, the larger the area would be covered. In the trials, the pressure of the spray system was set at 200.0 kPa and the height of spray system was set at approx. 5.0 m above the ground while generating different rainfall levels through counting operation time and checking readings of manual rain gauges.

2.4 Experimental orchard and treatment

The field experiments were conducted at the Washington State University (WSU) Roza experimental orchard located at north of Prosser, WA, USA. According to the historical data from WSU AgWeatherNet (www.weather.wsu.edu), the maximum daily rain levels were 18.3, 7.9 and 7.4 mm in June, July and August, respectively, from 2008 to 2015. The test trees were ‘Skeena’ sweet cherry (*Prunus avium* L.) cultivar grown on Gisela® 6 (Gi6) root stock, which were trained as a Y-trellised fruiting wall canopy with branches on both sides growing at a 55° angle to the ground. The cherry trees were planted seven years ago (2009) with an inter-row and intra-row spacing of 4.6 m and 0.9 m, respectively. The average tree height was 3.2 to 4.0 m above ground. The tree rows were orientated north to south with approx. 100 trees in each row. Experimental runs were conducted at cherry growth stage (BBCH stage) of the end of 8.9 to stage 9.1 (Fadón et al., 2015), which were a few weeks after commercial harvesting window, i.e. August, 2016. Trees had good vigor and leaves were green (see Fig. 2a).

2.4.1 Evaluation of helicopter downwash in hover

As analyzed in section 2.1, the helicopter downwash in hover is determined by helicopter weight, rotor diameter and flight altitude. The weight of the test UMH varied by adding or removing the water tank with a weight of 16.0 kg full of water, which referred as condition of with and without payload in the following content. The hover or flying height of the UMH was adjusted by the pilot through a telemetry reading and position hold settings. In this study, four hover altitudes of 4.9, 5.5, 6.1 and 7.6 m above ground level (AGL) were evaluated. The experimental setup of hover downwash evaluation was shown in Table 2. To measure the downwash at different locations in the tree canopies, six 2D sonic anemometers were mounted on different trees with four of them in the top section (3.1 m AGL) and two in the middle section (2.1 m AGL), as shown in Fig. 3. The four anemometers were at the same height to measure the

downwash on the top section of canopies and at adjacent locations in the horizontal direction.

The two lower anemometers measured the downwash transmitted through canopies. All

anemometers were wired to two data loggers, and their data were logged at 1 Hz.

Table 2. Studied experimental parameters to evaluate of hover downwash of the UMH.

Payload	Altitude (m)	Hover time (s)
With	4.9, 5.5, 6.1, 7.6	60 - 120
Without	4.9, 5.5, 6.1, 7.6	60 - 120

Fig. 3. Illustration of anemometers placement within the canopies to measure the hover downwash at different altitudes. In the figure, *Ano-1* to *Ano-6* indicate the mounting locations of six anemometers. Distances between anemometers were $d1 = 1.2$ m and $d2 = 2.8$ m. Four anemometers (*Ano-1*, *Ano-2*, *Ano-4* and *Ano-5*) were mounted in the top section of the canopies, which was 3.1 m above ground level. Two anemometers (*Ano-3* and *Ano-6*) were at the middle section of the canopies, which was 2.1 m above ground level. The downwash center located above *Ano-2*, and the horizontal distance to *Ano-1*, *Ano-4* and *Ano-5* was 1.2, 2.8 and 4.0 m, respectively.

2.4.2 Rainwater removal efficacy evaluation

To quantify canopy wetness due to rainwater and to monitor the micro-climate within the canopies, sensors were mounted on randomly selected branches of cherry trees to cover most of the canopy area as illustrated in Fig. 4. Three (3) LWSs were mounted at three heights of 1.1, 1.9, and 2.7 m above ground, henceforth referred as the bottom, middle and top LWS, along a

randomly selected branch. To mimic tree leaves, LWSs were configured onto small branches with the sensors facing up and tilting at 30° to 45° to the ground level. In each treatment, three branches were selected as replicates and the data from **nine LWSs** were collected by a data logger at a sample rate of 1 Hz. An air humidity and temperature probe were also mounted in the center of the canopy section to monitor the variation during different treatments and its data were also logged at 1 Hz.

Fig. 4. Configuration of experimental system, including sensing and data logging system. The instrumentation and equipment include: 1 - leaf wetness sensors (**nine in total**); 2 – rain gauge; 3 – anemometer; 4 – temperature and humidity probe; 5 – data logger and radio module; 6– Data logging with wireless receiver.

To evaluate rainwater removal efficacy of the UMH, treatments were randomized in a complete block design (Table 3). The payload condition (with and without payload) was considered as a fixed effect, and the effects of flight altitude and travel speed were evaluated for their effectiveness in rainwater removal from tree canopies. Four groups of target trees (3 to 5 trees for each group) were randomly selected in one row, with one group serving as the control. Three other groups were used to evaluate downwash from different treatments, i.e. payload, flight altitude and travel speed, as shown in Table 3. In each treatment, 5.0-mm of rain was applied on the target canopies using the developed rainfall simulation system. The rainfall levels

were monitored by timing and also through rain gauges distributed at different locations on target trees. After rainfall was applied, the UMH would fly over the top of target trees with respective treatment parameters in Table 3. Trees in control group were also applied same amount of rainwater of 5.0 mm, but without downwash-based water removal.

Table 3. Studied experimental parameters to evaluate the efficacy of unamned helicopter downwash in rainwater removal.

Block (fixed effect)	Treatment (random effect)		Replicate	Control treatments
	Helicopter speed ($\text{m}\cdot\text{s}^{-1}$)	Altitude (m)		
With payload	1.3, 2.7	4.9, 5.5, 6.1	3	5
Without payload	1.3, 2.7	4.9, 5.5, 6.1	3	

The micrometeorological conditions recorded by the nearby in-field weather station (AgWeatherNet WSU, Prosser, WA), included wind speed, wind direction, air temperature, and humidity, were 1.5 ± 0.3 (mean $\pm$ std. dev.) $\text{m}\cdot\text{s}^{-1}$ NW to S, $21.8 \pm 3.8^\circ\text{C}$, and $39.5 \pm 8.0\%$, respectively during the experiment period (7:00 am - 12:00 noon) on August, 2015.

2.5 Data analyses

The outputs of LWSs approximated the canopy wetness levels during each of the treatments. A typical sensor output is shown in Fig. 5, which illustrates the procedure of cherry canopy wetting and drying during an experimental run. Before rainfall, the outputs of LWSs were considered as ‘dry’ outputs (V_d), which were the lowest values in each treatment. The outputs of LWSs would increase with more water falling on the sensing surface. However, since the surface of LWS could hold a limited amount of water and extra water would slip off the sensor, the LWS outputs would keep constant after a certain time (saturation). The saturation outputs were considered as ‘wet’ outputs (V_w), which were the highest values of the LWS. Due to

the systemic error of sensors and the variation of mounting angle, the wet outputs might be different from sensor to sensor. To reduce the effect of LWS's reading variation, a normalized parameter of canopy wetness (CW , %) was defined as the ratio of the difference between current sensor output (V_r) and dry output to the difference between the dry output and wet output, calculated as:

$$CW = \frac{V_r - V_d}{V_w - V_d} \times 100 \quad (2)$$

where, V_r is the arbitrary output of the sensor (mV), V_d and V_w are dry and wet outputs (mV) of LWS.

Fig. 5. Typical output of a leaf wetness sensor during one of the experimental run. Data indicate several stages: dry period (before rainfall), rainfall, wet (saturation) period, natural drying and assist-drying with UMH.

Canopy wetness after rain depends on many factors, such as wind velocity, temperature, humidity and rainwater interception storage capacities (Huber and Gillespie, 1992). The rainwater removal efficacy of an UMH in this research was quantified by *rainwater removal* (RR , %), which is the difference of canopy wetness between saturated condition ($CW = 100\%$) and CW at 10-min after the saturated canopy wetness.

Pertinent data was analyzed in SAS® (ver. 9.2, SAS Institute, Cary, NC, USA). Raw data were plotted using box-and-whiskers plots, and outliers in the data were identified using the BOXSTYLE = SCHEMATICID option. Outliers were usually from sudden water drops from other leaves in the drying process and they were removed for further statistical analysis. The treatment effects were assessed using ANOVA ('PROC MIXED') analysis. In the hovering test, the height of anemometer (top and middle of canopy) was considered as fixed effect, while the payload and flight altitude were random effect. In rainwater removal test, payload was considered as fixed effect (block), while flight altitude and travel speed were randomized factors. The fixed effect was evaluated independently, while both the individual and interaction effect were evaluated for random factors. The effect of sensor location on the rainwater removal was analyzed to compare the difference in rainwater removal from different sections of canopies. Least-squares mean difference ('LSMEANS/PDIFF') option was used to compare the treatments at 0.05 level of significance. The output data were plotted using SigmaPlot® (ver. 11.0, Systat Software, San Jose, CA, USA).

3. Results and Discussion

3.1 Evaluation of helicopter downwash in hover

Downwash generated by the UMH hovering at four altitudes of 4.9, 5.5, 6.1 and 7.6 m AGL was measured at two heights within the tree canopies. The effects of payload and hover altitude on downwash were significant (Fig. 6). Overall effect of the location on the downwash was significant with the average downwash on the top section of canopies (3.1 m AGL) was significantly higher than that in the middle sections (2.1 m AGL) at each hover altitude ($p < 0.01$ in every treatment). Comparing to the downwash in the top section of the tree canopies,

downwash in the middle section was reduced in the ranges of 37% to 50% and 25% to 46% for with and without payload conditions, respectively. The downwash from the helicopter rotors was likely reduced by the tree branches, twigs and leaves in canopies.

Fig. 6. Unmanned middle-size helicopter downwash in relation to the hover altitude above ground level (AGL) at with and without payload conditions. (a) Downwash measured at the top section of canopies (3.1 m AGL) and (b) Downwash measured at the middle section of canopies (2.1 m AGL). Small letters indicate the significance of the difference in downwash with different treatments at 0.05 level. There is no single effect of payload and hover altitude on downwash, while the interaction effect was significant ($p < 0.001$) in both figures.

Downwash varied significantly with different hover altitudes and payloads, which interactively affected the downwash (interaction effect $p < 0.001$). From Fig. 6a one can find that the downwash at the top of the canopies increased from 8.0 to 10.9 m·s⁻¹ as an UMH hover altitude increased from 4.9 to 7.6 m AGL with payload. However, when the payload was removed, the highest downwash was in the middle flight altitude of 5.5 and 6.1 m AGL, where the downwash was significantly higher than that of lowest and highest test altitudes of 4.9 and 7.6 m AGL. A similar downwash trend was evident at the middle section of canopies (Fig. 6b), where downwash with payload showed increasing trend as an UMH hover altitude increased

above the ground level, whereas an UMH without payload had a peak downwash in the middle of the test hover altitudes, again in an interactive effect ($p < 0.001$). Overall, the payload and hover altitude affected the downwash as a mixed effect. Optimal hover altitude to generate the highest downwash for the tested helicopter can be about 7.6 m with payload, and 5.5 m to 6.1 m without payload.

Downwash is affected by the diameter of helicopter rotors, which also determines the coverage. Fig. 7 shows relationship of downwash at the top section of the canopies in horizontal direction perpendicular to the nose of the helicopter. Compared to the center point, downwash measured in the adjacent locations dropped substantially with the increase of distance regardless of the hover altitude. As shown in Fig. 7, the measured downwash was as low as $0.3 \text{ m}\cdot\text{s}^{-1}$ at the location of 2.8 m or farther away from center point. The location having downwash of $4.0 \text{ m}\cdot\text{s}^{-1}$ might be about 1.3 m from center point at the hover altitude of 4.9 m if downwash was considered as somewhat linear function of distance (as shown in Fig. 7). It indicated that the diameter of covered area with the downwash of $4.0 \text{ m}\cdot\text{s}^{-1}$ or higher was approximately (1.3×2) 2.6 m. In this study, the canopy width of the test trees (with both sides) was approx. 2.8 m, which means that the UMH could cover one row with every pass. In Washington State, the cherry tree canopy width with traditional architectures (central lead and multiple lead open center) is in the range of 3.5 to 5.0 m (Ampatzidis and Whiting, 2013). However, for the modern trained architectures (Y-trellised, upright fruiting offshoots [UFO], Kym Green Bush [KGB]), the canopy width falls into the ranges of 0.3 to 3.5 m (Ampatzidis and Whiting, 2013). Therefore, the test unmanned middle-size helicopter would be ideally suitable in modern orchards with canopy width of about 3.0 m or less.

Fig. 7. Unmanned middle-size helicopter downwash measured in the top section of tree canopies at adjacent locations with payload. In the figure, ‘Center’ (0.0 m) locates in the top section of canopies (3.1 m AGL) and underneath the helicopter hover position. The number of 1.3* was a calculated distance of having downwash of $4.0 \text{ m} \cdot \text{s}^{-1}$ based on linear interpolation between 1.2 and 2.8 m at the 4.9 m hover altitude. The adjacent locations in different trees are all at same height as the center point.

3.2 Rainwater removal efficacy

Rainwater removal efficacy of the UMH was quantified by *rainwater removal* (%), which was analyzed using ANOVA to determine the significance of effect of payload, flight altitude and travel speed on the rainwater removal at 10-min after rain events. As discussed in experimental design and data analysis sections, the helicopter flight altitude and travel speed was randomized within the “blocks” of with payload and without payload. The effect of payload on rainwater removal was analyzed independently using all the data of rainwater removal from all locations. The results of ANOVA show that least-squares mean (LSMEAN) of the rainwater removal in all locations with payload was of 87.3%, which was significantly higher than that of 83.2% without payload ($p = 0.04$). The flight altitude and travel speed interaction significantly affected on rainwater removal ($p = 0.048$). Fig. 8 shows the difference in the means of rainwater removal from tree canopies under different treatments and means of water removal of control groups. Fig. 8a shows the difference in the effect of the helicopter travel speed and flight altitude

at the condition of with payload, where rainwater removal was significantly higher at the speed-altitude combinations of 1.3-5.5, 1.3-6.1 and 2.7-6.1 ($\text{m}\cdot\text{s}^{-1}$ - m) than other conditions, including control group. Within each travel speed, the UMH at the flight altitude of 6.1 m AGL removed more rainwater than that of lower altitude of 4.9 m AGL, which was in agreement with the trend that hover downwash at 6.1 m AGL with payload was significantly higher than that of at lower altitudes (Fig. 6a). Therefore, an UMH with payload at 6.1 m AGL and the preferred higher speed of $2.7 \text{ m}\cdot\text{s}^{-1}$ might be an ideal operation condition to remove rainwater from Y-trellised tree canopies.

Fig. 8. Rainwater removal as a function of the helicopter flight altitude and travel speed under the condition of (a) with payload and (b) without payload. The figures show difference in the means of rainwater removal from all three locations of each treatment. The small letters indicate significant difference in the means of each treatment at 0.05 level.

Results pertinent to rainwater removal due to the UMH downwash without payload and at different travel speeds and flight altitudes are shown in Fig. 8b. Similarly with condition of with payload, interaction effect of flight altitude and travel speed was significant with $p =$

0.0001. Rainwater removal was significantly lower at the low altitude of 4.9 m and slow speed of 1.3 m·s⁻¹ than that of the rest treatments. Considering the results from both with and without payload conditions, a high travel speed (2.7 m·s⁻¹) and altitude (6.1 m) might have better performance in terms of effective rainwater removal from tree canopies.

Considering LWS locations effect into the ANOVA, most of the interaction effects were not significant at 0.05 level. In this scenario, percent rainwater removal varied substantially (Table 4). Data showed that middle section of the canopies had significantly less rainwater removals compared to other two sections. It might be due to rainwater from top sections blown down to the middle sections due to downwash. Ground temperature and low canopy vigor at lower sections might have resulted in higher rate of water removal than that of middle sections. Further studies are needed to quantify this effect.

Table 4. Rainwater removal by the unmanned helicopter under different treatments and locations. Payload was considered as fixed effect. The interaction of travel speed, flight altitude and sensor locations was analyzed. Different small letters, or different * indicate significant differences in the means of rainwater removal at 0.05 level. Bold numbers are significantly higher than italic numbers.

Treatment	Travel speed (m·s ⁻¹)	Flight altitude (m)	Rainwater removal (%) (Mean ± std. dev.)		
			Sensor location		
			Top (2.7 m)	Middle (1.9 m)	Bottom (1.1 m)
Control	--	--	71.2 (18.6) ^{ab**}	81.4 (12.1) ^{ab**}	77.1 (20.2) ^{ab**}
		4.9	76.0 (3.0) ^{ab}	87.0 (10.8) ^{ab}	75.7 (20.1) ^{ab}
With payload	1.3	5.5	93.3 (3.6) ^{ab}	93.1 (3.6) ^{ab}	99.6 (0.0) ^a
		6.1	92.6 (1.5) ^{ab}	97.2 (1.9) ^a	94.5 (3.7) ^{ab}
		4.9	90.0 (10.3) ^{ab}	<i>70.4 (5.2) ^b</i>	82.1 (4.7) ^{ab}
	2.7	5.5	80.9 (1.9) ^{ab}	<i>73.6 (1.6) ^b</i>	90.4 (0.1) ^{ab}
		6.1	96.3 (2.4) ^a	87.6 (3.2) ^{ab}	92.1 (1.3) ^{ab}
		4.9	66.3 (4.6) ^{**}	<i>62.6 (11.9) ^{***}</i>	63.2 (18.6) ^{**}
Without payload	1.3	5.5	83.5 (7.2) ^{**}	87.1 (11.5) ^{**}	82.2 (10.4) ^{**}
		6.1	92.4 (3.2) [*]	94.5 (5.5) [*]	90.6 (10.2) [*]
		4.9	84.8 (9.3) ^{**}	84.1 (0.6) ^{**}	83.7 (0.8) ^{**}
	2.7	5.5	90.3 (8.5) [*]	87.0 (4.2) ^{**}	89.7 (4.1) ^{**}
		6.1	83.4 (2.9) ^{**}	84.0 (9.3) ^{**}	90.2 (10.5) ^{**}

The coverage efficacy, defined as hectares of the area effectively covered by the unmanned helicopter towards rainwater removal in one hour ($\text{ha}\cdot\text{h}^{-1}$) is a key factor for growers. In this study, we estimated coverage efficacy of the UMH by the coverage area per flight and its travel speed. Considering the tree spacing of the test orchard of $4.6\text{ m} \times 0.9\text{ m}$, about 2391 trees per hectare have to be treated for rainwater removal. Assuming an UMH was flown at the speed of 1.3 to $2.7\text{ m}\cdot\text{s}^{-1}$, the rainwater removal efficacy (coverage efficacy) would be 2.2 to $4.5\text{ ha}\cdot\text{h}^{-1}$. For an orchard air-blast sprayer, the safe travel speed is about $0.9\text{ m}\cdot\text{s}^{-1}$ leading to a coverage efficacy of $1.5\text{ ha}\cdot\text{h}^{-1}$. Meanwhile, a manned helicopter can fly at the speed of $4.5\text{ m}\cdot\text{s}^{-1}$ or less and can cover two to three rows at one pass, resulting in the coverage efficacy of $7.5\text{ ha}\cdot\text{h}^{-1}$ in the test orchard. However, outside of safety concerns, manned helicopter rentals are very expensive, which is beyond the reach of small to mid-size ($< 81\text{ ha}$) growers. Overall, an unmanned middle-size helicopter that can remove the rainwater and also be used for other precision agricultural application, may be an alternative in such scenario. In coming season, our team plans to specifically evaluate efficacy of manned helicopters in rainwater removal from cheery canopies. More studies at different rainfall levels and relating rainwater removal to fruit cracking are needed along with detailed economic analysis to fully understand the operational feasibility of such platforms for commercial operations.

4. Conclusions

Towards effective and economical rainwater removal from cherry tree canopies, an alternative technology of an unmanned middle-size helicopter was evaluated for the first time. An in-field sensing system was developed to quantify the downwash of the test helicopter at different hover altitudes and payload conditions. Rainwater removal efficacy of the helicopter

was quantified at different payloads, flight altitudes and travel speeds. Based on the results, the following are concluded from the study:

(1) Downwash generated by the test helicopter might be significantly affected by payload and flight altitude. Downwash increased from 8.0 to 10.9 m·s⁻¹ with the hover altitude increasing from 4.9 to 7.6 m at the condition of with payload. At the condition of without payload, the peak downwash of 10.2 m·s⁻¹ was at the altitude of 6.1 m above ground level, while downwash was around 7.4 m·s⁻¹ at altitude of 4.9 and 7.6 m.

(2) Rainwater removal efficacy by an UMH downwash was significantly affected by the interaction of flight altitude and travel speed. Pertinent to studied flight attributes, a combination of a 6.1-m flight altitude AGL with a 2.7-m·s⁻¹ travel speed generated downwash either with or without payload that had significantly higher rainwater removal and coverage efficacy compared to other treatment combinations.

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