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Effects of operation height and tree shape on droplet deposition in citrus trees using an unmanned aerial vehicle

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ABSTRACT

The effects of operation height and tree shape on droplet deposition in citrus trees using an unmanned aerial vehicle (UAV) were investigated in this study. When the operation height was 1.2 m and the flight speed was 3.5 m s^{-1}, the droplet density and droplet coverage rate were maximized in all the canopies. The droplets exhibited the most uniform distribution ($CV = 32.44\%$) in the lower layer of inverted triangle-shaped trees. The droplet density in the lower layer of inverted triangle-shaped trees was 48.04% higher than that in triangle-shaped trees. There was no statistically significant difference between the middle and lower layers of inverted triangle-shaped trees. The uniformity of the droplet deposition distribution was studied in six parts of the citrus trees at an operation height of 1.2 m. The results indicated that the front, middle, rear, left and centre parts displayed uniform distributions, but the right part of the inverted triangle-shaped trees did not. This difference might have been caused by a deviated flight route due to manual control error or by droplet drift from the wind originating from the right.

1. Introduction

Citrus has the potential to be damaged by insects, such as the citrus red mite, Asian citrus psyllid, leaf miner, citrus thrips, citrus whitefly, and others. Chemical control by manually or mechanically spraying insecticides has been the general approach for managing citrus pests. However, because citrus is traditionally cultivated on hillside orchards in China, the hilly topography, high-density planting pattern, irregular spacing, and fragmented holdings restrict the use of agricultural spraying machinery (Li et al., 2011). Recently, the use of unmanned aerial vehicles (UAVs) has become increasingly popular for this task due to their flight speed and effectiveness in spraying operations (He et al., 2017; Morey et al., 2017). UAVs can vertically take off and land in small convenient areas without a runway; therefore, they can be used to spray hard-to-reach areas (Yang et al., 2017).

Many studies of rice, wheat, corn diseases and insect damage prevention have been systematically conducted using UAV spraying technology (Gao et al., 2013; Zheng et al., 2017; Pederi and Cheporniuk, 2015). Qin et al. (2016) studied droplet deposition and the control effect of insecticides sprayed with a UAV on plant hoppers and found that the UAV provided a low-volume and highly concentrated spray pattern that enhanced the duration of efficacy. Pelosi et al. (2015) studied UAV spraying in the early post-emergence stage of maize and achieved a decrease of approximately 37% in the use of herbicides. Giles and Billing (2015) investigated UAV spraying based on different swath width and flight pattern settings. Their results showed that the UAV achieved 2.0–4.5 ha h^{-1} work rates for application volumes of 14.0–39.0 L ha^{-1}. Spray deposition on grape foliage increased with the volumetric rate of application. Xue et al. (2014) studied various techniques for measuring spray deposition and aerial drift during spray applications in a paddy field. Specifically, RhodamineB was used as the fluorescent tracer to identify and quantify the deposition in the spray area and drift area by polyester cards and fibres. Their results showed that the droplets can penetrate to the lower part of rice plants. Droplet penetration can be strengthened by the rotor airflow of a multi-rotor UAV (Zhou and He, 2016). To improve the UAV spraying performance, Gao et al. (2013) studied the influence of the operational parameters of the UAV on the droplet distribution associated with corn borer spraying to determine the best liquid concentration of chlorpyrifos and the optimal flight height. Xue et al. (2016) integrated a UAV (model N-3) with an unmanned navigation spraying system and determined the swatch width that provided the optimal spraying quality. Faiçal et al. (2014) proposed a methodology based on particle swarm optimization to reduce the drift of pesticides by fine tuning the control rules during the

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Fig. 1. ZHKU-0404-01 UAV used in the experiment.

Table 1
Key parameters of the ZHKU-0404-01 UAV.

Items	Parameters
Rotor	Four rotors
Flight speed	1–5 m s^{-1}
Tank capacity	15 L
Nozzle numbers	2–4
Nozzle type	Flat fan
Spray boom length	2.2 m
Spraying pressure	0.2–1.0 MPa
Payload	27 kg
Flight time	10 min

spraying of pesticides in crop fields. Chen et al. (2017) studied the effect of the wind field below unmanned helicopter rotors on the droplet deposition distribution, and the effects in the Y- and Z-directions were significant.

However, little research has been conducted on aerial spraying and the optimal operating parameters for citrus trees. It is difficult to achieve a uniform spray distribution over tree canopies, and the performance in the lower layer of the tree canopy is fairly poor (Derksen et al., 2006). Droplet deposition in the lower canopy is closely related to tree shape, operational parameters, and nozzle type when using a UAV. In this paper, we explore the effects of the operation height and tree shape on droplet deposition in citrus trees using a UAV.

2. Materials and methods

2.1. Materials

The four-rotor UAV (ZHKU-0404-01) manufactured by Zhongkai University of Agriculture and Engineering was used in the experiments, as shown in Fig. 1. Its key parameters are listed in Table 1.

The experiment was performed over a hillside orchard of the Conghua Hualong Co. Ltd. (23°30′20″N, 113°33′34″E) in Guangzhou city, Guangdong Province, China. The climate is type Cfa (humid subtropical) according to Köppen's classification. The experimental area was established on a level terrace with a plant spacing of 3.5 m and row spacing of 4.5 m.

Mandarins (*Citrus reticulata* Blanco 'Shantanju') grafted on the rootstock of *Citrus nobilis* Lour were used in this experiment. As shown in Fig. 2, the longest spread of the crown of citrus trees was approximately 2.5 m, and the plant height was approximately 2.4 m. Healthy plants with consistent growth were selected as test materials. In particular, nine citrus trees with triangle and inverted triangle shapes were carefully chosen along the UAV flight route to reduce errors.

The environmental monitoring system included a portable anemometer and digital temperature and humidity metre. The anemometer (Peakmeter MS6252A) was used to continuously monitor and record wind speed and direction during the experiment, and wind speed data were averaged for each spraying period. The temperature and humidity metre (Anymetre TH603A) was used to measure the temperature and humidity at the orchard location.

2.2. Spraying system

The spray system consisted of a pesticide tank, miniature direct current diaphragm pump, nozzles, and electronic speed control, as shown in Fig. 3. The tank capacity was 15 L. The diaphragm pump (JMRRC BPP-25) operated at DC 22–25 V and produced flow rates of up to 3.5 L min^{-1}, which support a spraying pressure ranging from 0.1 MPa to 1.0 MPa. The spray boom length was 2.2 m. There were two nozzles equidistantly distributed along the spray boom with a spacing of 1.4 m.

A properly selected nozzle is essential for proper pesticide application. The nozzle is a major factor in determining the amount of spray applied to an area, the uniformity of application, the coverage obtained on the target surface, and the amount of potential drift (Johnson and Swetnam; Grisso et al., 1996; Ru et al., 2014). Nozzle types commonly used in low-pressure agricultural sprayers include full-cone, hollow-cone, and fan types. Flat fan nozzles are ideal for the broadcast spraying of insecticides with low volume, and they can effectively produce a line

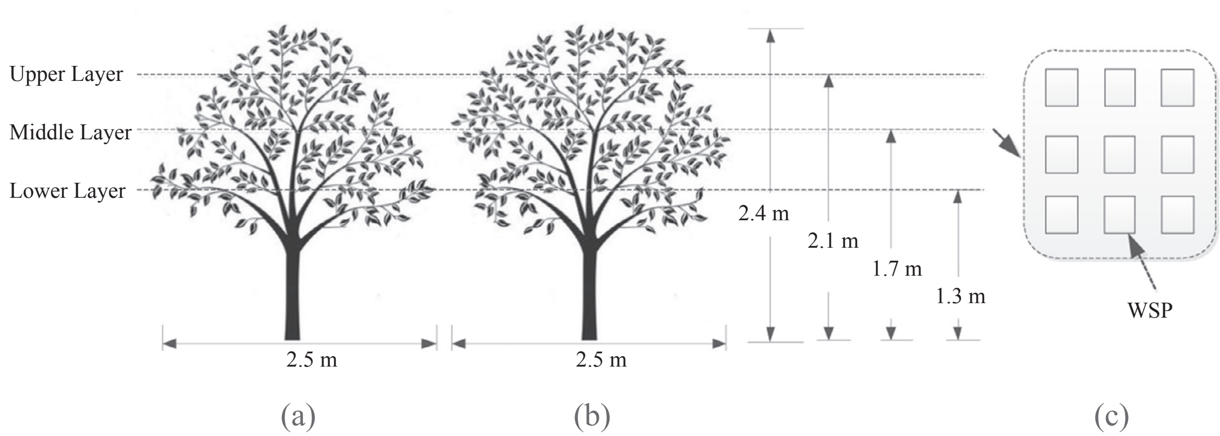

Fig. 2. Division of the upper, middle and lower layers of citrus trees with different tree shapes: (a) triangle-shaped tree, (b) inverted triangle-shaped tree and (c) nine WSPs within a canopy layer.