Original article

Frost protection efficiency evaluation in avocado with a horizontal wind machine

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Summary

Introduction – **Frost damage is an important factor in reducing avocado (*Persea americana* Mill.) yields, especially of the commercially important cultivar, 'Hass'. To mitigate frost, horizontal wind machines (HWM) are used, although little is known about their efficacy in protecting avocado orchards.** *Materials and methods* – **Here, we evaluated the frost mitigation efficiency of an HWM in a 'Hass' avocado orchard, by measuring air temperature, bud damage, flowering intensity and yield.** *Results and discussion* – **Minimum temperatures in the control reached -3.16 °C, which severely damaged inflorescence buds, with the result that flowering intensity in the following spring was low, with a rating of 1.66 out of 5, a small number of fruitlets at the end of June and an average yield of only 14.87 kg tree^{-1} at harvest. HWM effect was evaluated by comparing the corresponding data for two HWM orientations: parallel to and across the tree rows. With the parallel orientation air temperature elevation depended on distance; it was increased by up to 2.4 °C, resulting in significantly reduced inflorescence damage, and fruit yields reached 42.76, 30.87, and 20.46 kg tree^{-1}, respectively, at 20, 50, and 100 m from the HWM, but only 2.77 kg tree^{-1} at 125 m. With the transverse orientation air temperature was elevated only at 20 and 50 m, which significantly reduced inflorescence bud damage at these distances to 6.25 and 43.75%, respectively. Flowering intensity and fruit yield were higher than the control at 20 and 50 m, but similar or lower at 100 and 125 m.** *Conclusions* – **The performance of the HWM depended on its orientation with respect to the trees; it succeeded in reducing frost damage in an area of about 0.6–1.0 ha.**

Keywords
abiotic stress, avocado, frost mitigation, 'Hass', Israel

Significance of this study

What is already known on this subject?

- Frost damage is a major factor in reducing avocado yields. Horizontal wind machines (HWM) are used to mitigate frost, although little is known about their efficacy in protecting avocado orchards.

What are the new findings?

- In this study, it was found that the performance of the HWM depended on its orientation with respect to the trees; it succeeded in reducing frost damage in an area of about 0.6–1.0 ha.

What is the expected impact on horticulture?

- Understanding the limitations of the HWM in mitigating frost in avocado orchards and other sub-tropical crops with dense foliage, will help growers to evaluate the cost-effectiveness of this measure.

Introduction

Avocado (*Persea americana* Mill.) is an important evergreen fruit tree, grown in several countries with tropical and subtropical climates (Alcaraz *et al*., 2013). Accounting for over 85% of all avocados grown and sold worldwide, the 'Hass' avocado cultivar leads global avocado commerce. However, despite its popularity, one of the major drawbacks of this cultivar is its severe susceptibility to freezing temperatures (Silva and Ledesma, 2014). Damage from frost – defined as an environmental condition in which the temperature drops below the freezing point of water – is an important factor in reducing avocado crop yields (Perry, 1998); for example, during 2016 financial loss caused by frost damage to avocadoes in Israel was estimated at 15 million USD, almost all involving 'Hass' (Milopri Ltd., Israel., 2016). In addition to direct financial losses, frost risk is one of the most important factors that limits the distribution and expansion of avocado orchards (Charrier *et al*., 2015), thereby leading to decreased potential income from this crop.

In order to reduce the risk of frost damage growers consider various factors such as site selection, soil management, selection of species and cultivars, and cultural techniques (Melo-Abreu *et al*., 2016). Growers also use various active techniques to maintain air and plant-tissue temperatures above the frost-risk threshold (Wu *et al*., 2014). For example, active frost protection can be carried out by stirring air layers with wind machines (Hu *et al*., 2015), heating the surroundings of the crops with open air heaters, covering the plants with shading screens (Teitel *et al*., 1996) or sprinkling water over or under trees during frost events (Hu *et al*., 2016). Of course, cost effectiveness is one of the major considerations when selecting among these techniques, individually or in combination.

Two major types of wind machines are used for frost protection, both based on the same principle. During cold, clear

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nights, heat radiates out into space, causing temperatures near the surface to drop. In such conditions (radiative frost) a thermal inversion occurs – temperature increases with altitude, in contrast to normal daytime conditions under which air temperature decreases with height (Snyder and De Melo-Abreu, 2005). In general, wind machines protect plants from freezing temperatures by utilizing the warm air from the thermal inversion layer as a source of heat by mixing cold air within the canopy with warmer air from the upper level (Perry, 1998). The horizontal wind machine (HWM) blows air at a slight downward angle to the horizontal, thus drawing warmer air from aloft and pushing it towards the plants at ground level (Snyder and De Melo-Abreu, 2005), whereas the vertical wind machine (VWM) draws cold air from ground level, blows it upwards with a strong jet, thus mixing the cold air from the lower altitudes with the warmer air above (Yazdanpanah and Stigter, 2011). Both types of wind machines depend on the presence of a strong thermal inversion layer (Hu *et al.*, 2015; Wu *et al.*, 2014).

The efficiency of HWMs has been assessed for several frost sensitive crops. For example, a stationary tower-mounted wind machine increased air temperature by 0.3 °C at a height of 1.5 m, resulting in 60 and 37% decreases in apple blossom damage in two successive seasons (Ribeiro *et al.*, 2006). In another study, during nights with radiation frost a wind machine managed to keep temperatures high enough to protect about 3.2 ha and to provide partial protection over 4.7 ha in a commercial pear orchard (Bates and Lombard, 1978). However, not much is known about the efficacy of these methods in avocado orchards; therefore the main objective of the present study was to evaluate the efficiency of a HWM in frost mitigation in a commercial 'Hass' avocado orchard in Israel.

Materials and methods

Experimental site

Experiments were conducted during the winter of 2016–17 in a 5-ha avocado orchard located in Beit Ha'emek, in northwest Israel (32°58'N; 35°08'E, 33–36 m a.s.l.). The trees were planted in 2007 with 5 m spacing between the rows and 4 m between the trees. The rows were oriented north/south or north-west/south-east; canopy height was approximately 3.5 m. Freezing temperatures occurred in the experimental orchard in 2014 to 2017, mainly during January and February.

Wind machine

From December 2016 through April 2017 a portable HWM (Tow and Blow, Napier, New Zealand) was placed at 32°58'24.7"N; 35°08'08.2"E. The wind machine had a 2-m-diameter five-blade impeller made from glass-reinforced polyamide and powered by a 23.4 HP 3-cylinder Kohler liquid-cooled diesel engine (http://www.towandblow.co.nz). The fan head was mounted 8 m above the ground and was set to operate automatically when the temperature dropped below 1 °C. The fan was mounted on an axis tilted 75° downward from the horizontal, and it rotated through 360° to blow air around the tower. The fan speed was about 600 rpm and the fan completed a full circle around the tower every 3 min.

Temperature measurements

Air temperature data were collected by miniature, waterproof one-channel Hobo temperature data loggers (catalogue no. UA-001-64; Onset Corp., Bourne, MA, USA) that were placed 1.5 m above the ground on the west side of the trees and were shaded from radiation under the canopy. Air temperature was measured continuously at 10-min intervals from the beginning of January until the end of March 2017. The temperature data loggers were placed 20, 50, 100, and 125 m away from the wind machine in two different sectors – south and north-east, *i.e.*, parallel or perpendicular, respectively, to row orientation. Figure 1 shows the orchard with the locations of the wind machine and the two measured sectors.

Foliage and inflorescence damage observations

Following frost events, damage to foliage and inflorescences at 20, 50, 100, and 125 m from the wind machine was evaluated in the above-mentioned two sectors and in the control trees; at least 20 inflorescence buds were examined on each of 15 trees at each location. Foliage frost damage was assessed visually with a blind test in which two surveyors independently scored each tree in a scale of 0–5, with 0 representing no apparent damage, *i.e.*, all leaves green and vital,

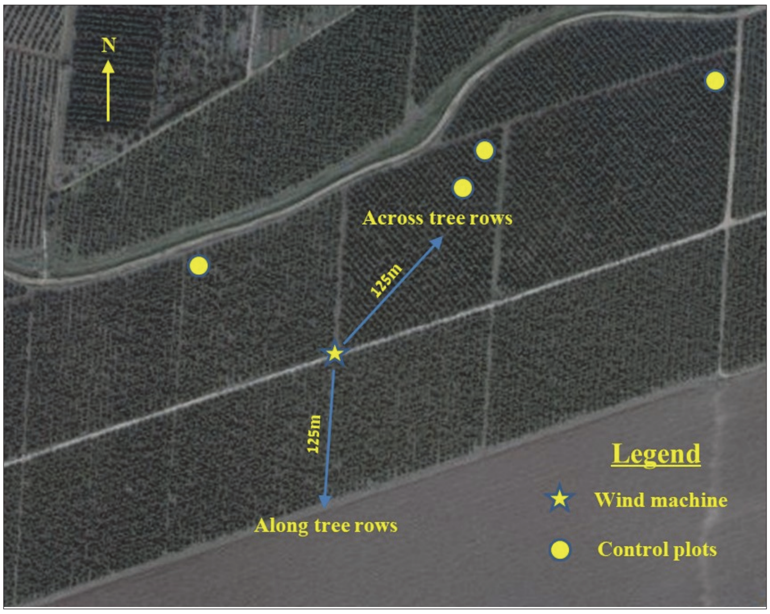

FIGURE 1. Satellite image of the experimental avocado orchard. The locations of the wind machine, the control plots, and the two measured sectors are marked with a star, circles, and arrows, respectively.

and 5 representing heavy damage, *i.e.*, leaves turned brown by frost damage. For inflorescence damage evaluation, 20 swelled inflorescence buds, at stage 511 according to the extended BBCH scale as described by Alcaraz *et al*. (2013) from each tree were cut crosswise and visually assessed for browning. An inflorescence was considered damaged when more than 25% of the cross-sectioned tissue area was browned by frost.

Frost protection efficacy measurements

Flowering intensity was assessed in the spring following frost events, during the bloom peak in mid-April 2017, with a blind test in which two surveyors independently scored each tree on a scale of 0–5, with 0 representing no apparent flowering and 5 maximum flowering intensity (Ziv *et al*., 2014). Fruit set was measured at the end of June 2017 by counting fruitlets from each individual tree ($n = 15$). Total fruit yield was measured for each tree at the beginning of December

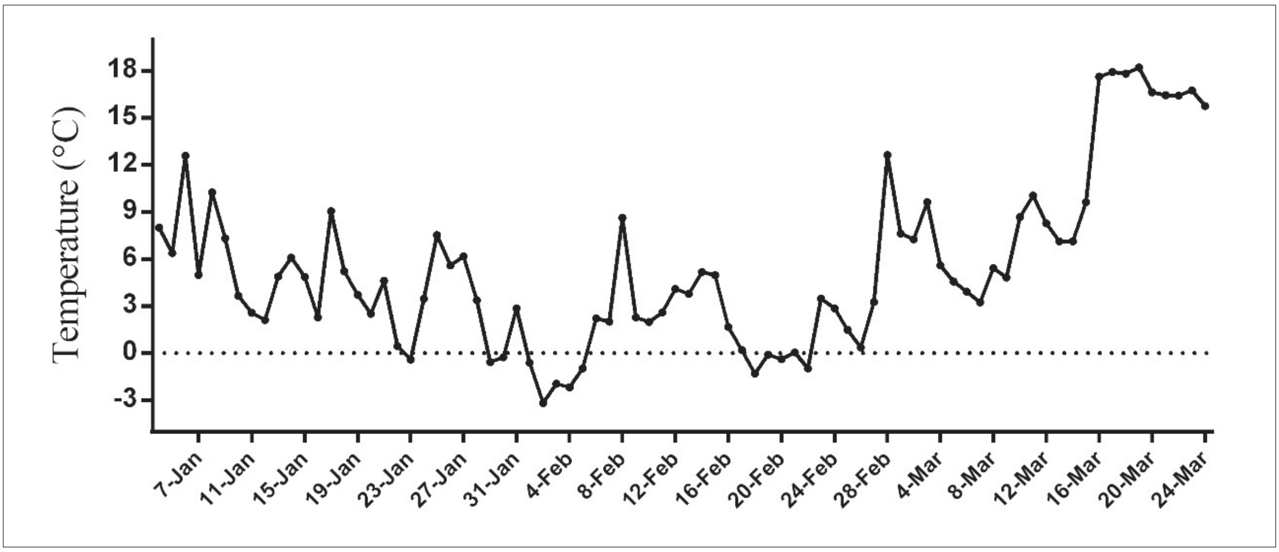

FIGURE 2. Minimum daily air temperature during the period of measurements.

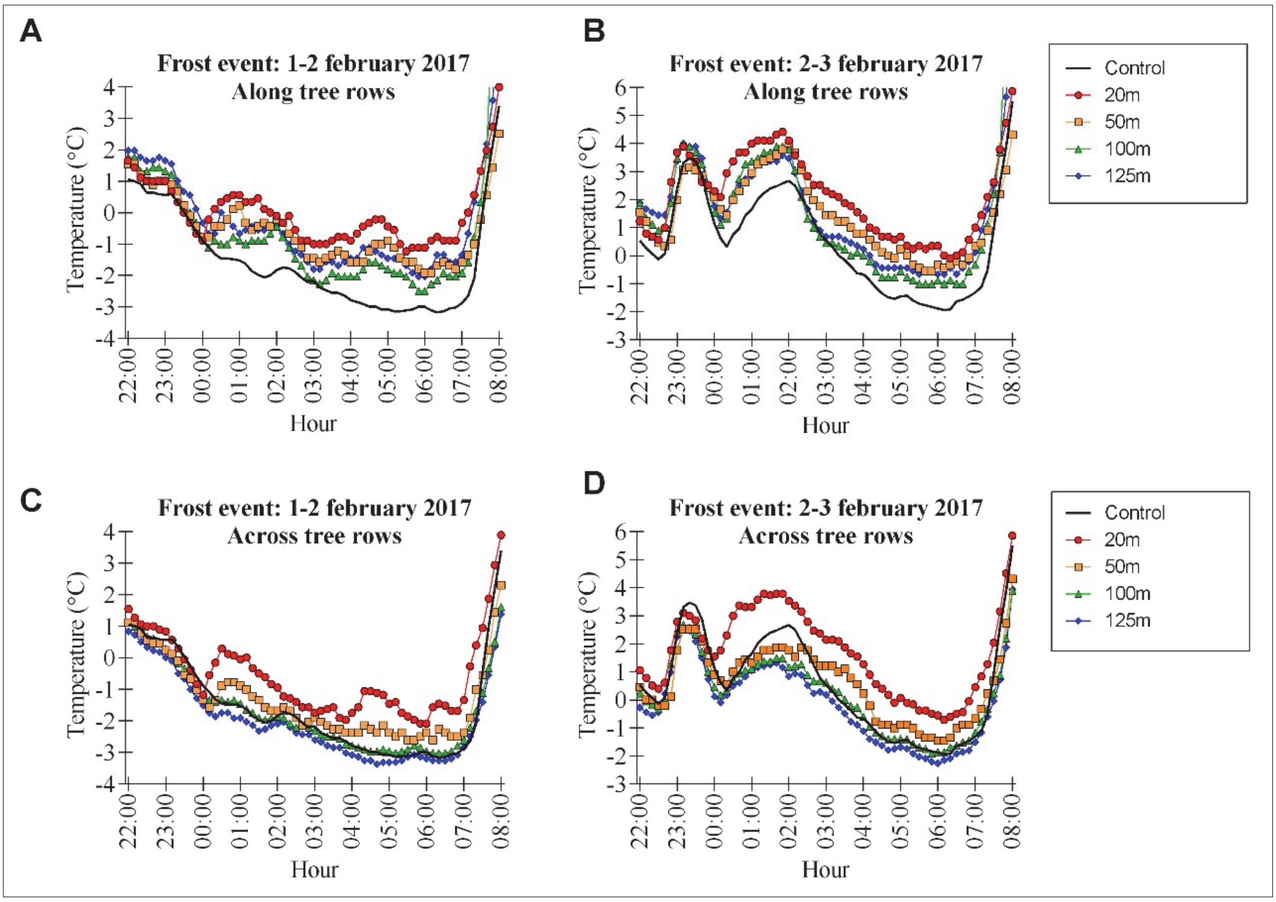

FIGURE 3. Night-time air temperature at 1.5 m above ground 20, 50, 100, and 125 m from the wind machine. A, B: parallel to the tree row on 1st to 2nd, and 2nd to 3rd of February, respectively. C, D: across the tree rows on 1st to 2nd, and 2nd to 3rd of February, respectively.

2017 and fruit size was calculated by dividing the tree's total fruit yield by the number of fruits.

Results and discussion

The mean air temperature dropped below 0 °C on 12 nights between the beginning of January and the end of March 2017 (Figure 2). The most significant frost event took place during two consecutive nights during 1st to 3rd of February.

Effect of wind machine operation on air temperature

Air temperature measured at 1.5 m height showed that there were no relevant, systematic deviations between the temperatures collected at any location and the mean temperature for all locations. Thus, differences in air temperature during the frost events could be associated principally with the effect of the air flow generated by the HWM fan. Figure 3 shows the air temperature measurements collected during 10:00 pm to 8:00 am on the nights of the two consecutive frost events that occurred during 1st to 3rd of February. Along the trees rows, where air flow created by the wind machine could pass relatively undisturbed, there was a general trend of distance-dependent air temperature elevation, *i.e.*, air temperature elevation decreased with increasing distance from the wind machine. For example, at 6:20 am on the first night, mean air temperature reached -3.17 °C in the control, whereas it was increased by 2.4, 1.48, 1.02, and 1.82 °C at distances from the wind machine, of 20, 50, 100, and 125 m, respectively. However, across the tree rows, where air flow was obstructed by the dense foliage of the trees, air temperature increased relative to the control only at 20 and 50 m from the wind machine by 1.71 and 0.9 °C, respectively. During the second night the minimum air temperature among the control trees reached -1.94 °C and there were similar responses of air temperature to the distance and orientation from the HWM.

Effects on foliage and inflorescences damage reduction

The severity of foliage frost damage was low in the control trees, with a mean score of 1.2, despite the frost events during that season (Figure 4A). Nevertheless, parallel to the tree rows, foliage damage was decreased in a distance-dependent manner, whereas transversely to the rows damage was reduced only at 20 and 50 m. Frost damage to inflorescences, which are more sensitive than the foliage to freezing temperatures, was much heavier and reached 94.3% in the control plot (Figure 4B). With the HWM revolving about a vertical axis, at distances measured parallel to the tree rows there was distance-dependent damage protection – damage affected only 5, 0, 12.5, and 20% of total inflorescences at

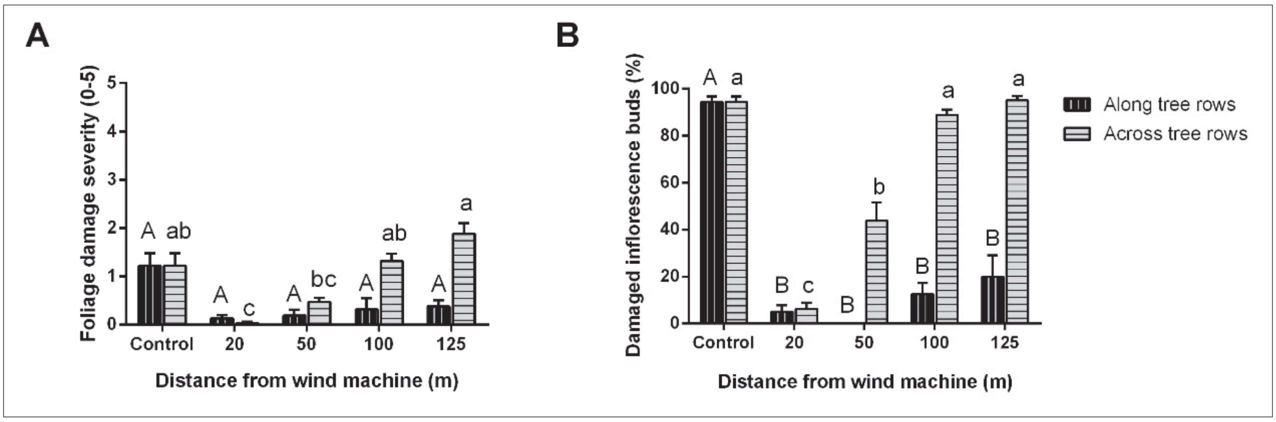

FIGURE 4. Frost damage Severity. A: Foliage damage severity was scored on a scale of 0–5, with 0 representing no apparent damage and 5 heavy damage. B: Percentage of damaged inflorescence buds. Results are expressed as mean ± SE of 15 trees per treatment, 20 inflorescence buds per tree; columns marked with different letters differ significantly ($p < 0.05$) (uppercase for distance along the row; lowercase for distance across the row).

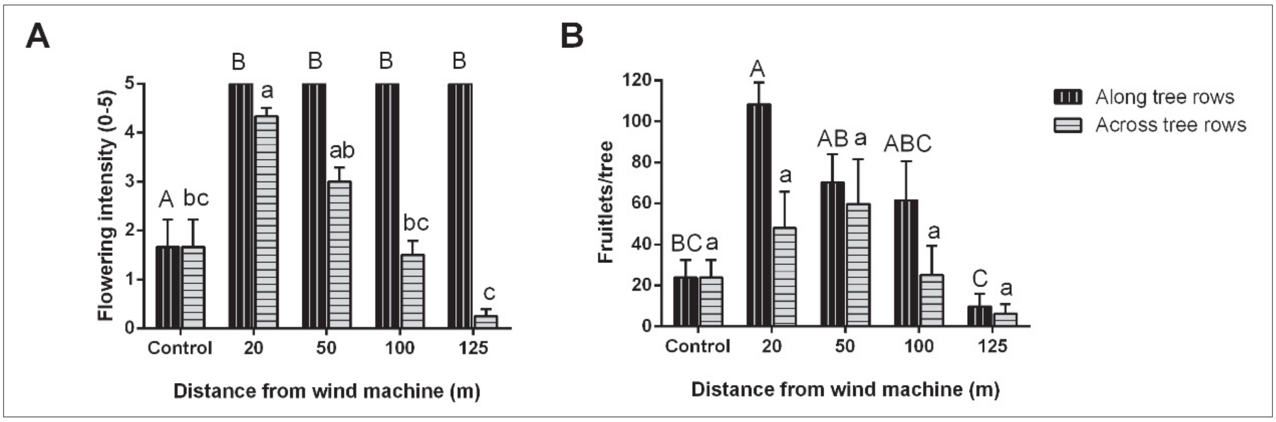

FIGURE 5. Flowering intensity and fruit set following frost events. Post-frost flowering intensity (A) was assessed and scored on a scale of 0–5, with 0 representing no apparent flowering and 5 maximum bloom. Fruitlet numbers per tree were measured and are depicted in (B). Results are expressed as mean ± SE of 15 trees per treatment. Different letters above the columns indicate significant differences ($p < 0.05$) (uppercase for distance parallel to the row; lowercase for transverse distance).

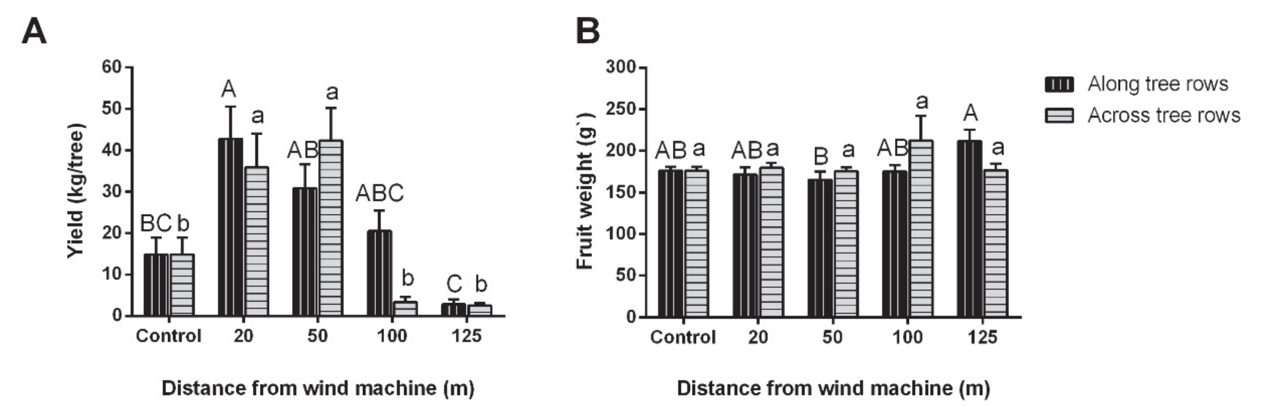

FIGURE 6. Total crop yield and average fruit size following frost events. Fruits were picked at the beginning of December 2017, *i.e.*, the commercial harvest date. For each tree total yield (A) was divided by number of fruits to determine average fruit weight (B). Results are expressed as mean ± SE of 15 trees per treatment; or of 24 control trees. Different letters above columns indicate significant differences ($p<0.05$) (uppercase for distance parallel to the rows; lowercase for transverse distance).

20, 50, 100, and 125 m, respectively. In contrast, at distances measured across the rows significant damage reduction was observed only at 20 and 50 m, where it affected 6.25 and 43.75%, respectively, of total inflorescences inspected.

Effects on flowering intensity and fruit set

During the bloom peak in mid-April 2017, flowering intensity was monitored in both control and treated plots. Flowering intensity in the control plots was rated as low, with a mean score of 1.66 (Figure 5A). In the treated plots, with the HWM revolving about a vertical axis, when the airflow direction was parallel to the tree rows flowering intensity was rated very high at all distances, but when the flow was across the tree rows flowering intensity decreased with increasing distance from the HWM and was negatively correlated with the percentage of damaged buds.

At the end of June 2017 (Figure 5B), with the HWM revolving about a vertical axis, at distances measured parallel to the rows fruitlet counts decreased with increasing distance from the HWM, mean fruitlet number per tree being higher than on the control trees at 20, 50, and 100 m, but lower at 125 m. At distances measured across the rows the fruitlet numbers were higher than on the control at 20 and 50 m, but lower at 100 and 125 m. In the light of the finding of a weak correlation between flowering intensity and fruitlet count along the tree, it is possible that even minor frost damage (not visible to the naked eye) to inflorescence buds led to low fruit set. It is also possible that factors unrelated to frost protection efficiency, *e.g.*, low pollination rate, led to the small numbers of fruitlets on trees that had had high flowering intensity.

Effects on total yield and fruit size

On the commercial harvest date, December 5, 2017, fruits were picked from the control and treated trees. In the control plots total crop yield per tree was low, at 14.87 kg tree^{-1} (Figure 6A). In the treated plots, with the HWM directed parallel to the rows, crop yield decreased linearly with increasing distance from the machine, from 42.8 kg tree^{-1} at 20 m to 2.8 kg tree^{-1} at 125 m. With the HWM directed across the rows crop yield reached 35.87 and 42.35 kg tree^{-1} at 20 and 50 m, respectively, from the wind machine and decreased dramatically to ~3 kg tree^{-1} at 100 and 125 m. The calculated average fruit size was similar to that in the controls at all distances in both directions (Figure 6B).

Conclusions

We aimed to evaluate the efficiency of a horizontal wind machine in frost protection of a commercial avocado orchard in Israel. Our results indicate that the performance of the wind machine depended on the orientation of the tree rows with respect to the wind flow direction. The HWM provided adequate frost-damage protection when its wind flow was parallel to the rows: air temperature was raised by about 2.4 and 1.82 °C at 20 and 125 m from the HWM, respectively, which reduced damage to the inflorescence buds, and led to high flowering intensity and consequently high crop yield compared with control trees. In contrast, as the HWM airflow passed across the tree rows and was obstructed by the dense foliage, frost protection efficiency was much lower and was limited to around 50 m from the machine.

The operation of the wind machine in the present experiment successfully reduced frost damage in an area of about 0.6–1.0 ha. Even though the protected area seems limited, when evaluating the cost-effectiveness of the wind machine, financial parameters should be taken into consideration. These considerations may include comparisons between machine purchase and operating costs, on the one hand, and, on the other hand, potential costs of lost income and post-frost treatments needed to rehabilitate damaged trees.

The current high commercial value of avocado fruits may justify investing more efforts in increasing the frost-protection efficiency of the HWM. It could be that installing a bigger HWM with greater air flow, and pruning trees to lower the foliage density and canopy height would improve air flow across the rows and thereby increase the protected area.

However, because HWMs were designed mainly to protect deciduous orchards during spring frosts when leaf coverage is very low, the potential frost-protection efficiency for evergreen trees seems to be limited. In the light of this limitation and of the limited efficiency of wind-based protection against advection frosts (Perry, 1998), other measures, such as overhead irrigation and shading screens (Teitel *et al.*, 1996), should be examined and their frost-protection efficiency evaluated. To achieve a sustainable long-term solution, efforts should be invested in developing frost-resistant avocado varieties; possibly through clone selection in orchards repeatedly exposed to frost stress. Another possible long-term solution may lie in the use of state-of-the-art techniques such as genome editing (Li *et al.*, 2013; Nishitani *et al.*, 2016) for developing avocado trees with enhanced agrotechnical traits, such as resistance to freezing temperatures.

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