Comparative experiments and effectiveness evaluation on vertical blowing fans (VBF) for frost protection

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Abstract: Experiments were conducted to evaluate the performance of vertical blowing fans (VBF) for frost protection in a vineyard on a steep slope near Napa Valley in Northern California, USA, and a tea plantation located on undulating terrain in Zhenjiang, China. Minimum temperature comparisons from within the grape vineyard on nights with and without VBF operation with control station minimum temperatures exhibited no temperature benefit. Profile measurements from the test in China indicated that there was an increase in temperature when the VBF was first started, but that benefit was lost over time. No clear benefit from using the VBF was observed. Observation of frost deposition and thermal imagery also showed no benefit except for within about 5 m of the VBF. Based on this work, the effectiveness of the VBF for frost protection was not validated.

Keywords: frost protection, thermal inversion, weather modification, wind machines, vertical blowing fans (VBF), temperature
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1 Introduction

Although crop damage from freezing is the major economic loss to farmers[1-6], there have been few advances in the science of frost protection in recent decades. As automatic and mechanized equipment, wind machines and sprinklers are widely used to prevent low-hardiness crops from frost damage in subtropical and temperate regions[7-13]. Besides the conventional wind machines[9-13], an upward vertical blowing (VBF) was developed and tested in Uruguay with positive results and only 14% losses to frost injury in the protected area relative to 42% losses in a nearby unprotected grove[14]. However, no temperature data were provided to support that the difference in frost damage was due to the VBFs' influence on temperature. Six VBFs (with 11 kW power) were used to protect a 54 hm^2 citrus grove. One VBF can protect 5-12 hm^2 using about 0.8-8.1 kW/hm^2 of energy[14-18]. The VBFs were introduced into the USA in a Northern California walnut orchard in 1999-2000. In 2007, the method was tested in a wine grape vineyard with smaller commercially available machines produced in California.

The main difference between the vertical blowing and

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traditional (horizontal blowing) wind machines is that the VBF draws air in near the surface and blow it upwards using a strong jet[14-18]. With traditional wind machines, the air is blown about 7° downward from horizontal to mix warmer air aloft with colder air near the surface. Generally, when conventional wind machines are used, the temperature at 2 m is increased by about 1/3 of the temperature difference between that measured at 12 m and 2 m[9-11]. Therefore, the wind machines are relatively ineffective under weak atmospheric inversion conditions. Although there is minimal literature on the topic, Battany[19] reported the both conventional wind machines and VBFs provided little or no protection under the weak inversion conditions.

The concept behind the VBF is that it draws in cold air near the surface and blows it upwards where it mixes with ambient air and/or advects horizontally away from the protected crop. The height of the jet clearly must depend on the VBF thrust as well as other factors, i.e., inversion strength, wind speed, etc. The theory presented in early papers on the VBF is that continuous upward jet selectively remove colder air near the surface, which would cause warmer air aloft to drop downwards and replace the removed colder air. However, if warmer air is dropping down to the surface to replace colder air, then the air temperature passing through the VBF should increase with time of operation, but this does not occur. If the VBF is effective, then the mechanism is not well understood[10], and more research is clearly needed.

Although the VBFs have existed since about 2000, there are few scientific publications on the method, and the effectiveness of the VBF is controversial. Yazdanpanah et al.[16] found that the VBF method was extremely effective as a frost protection method for an almond orchard in Iran during the spring 2006. But there was no information provided on inversion strength or wind speed, so it is difficult to evaluate the VBF effectiveness. Another study showed the similar findings when the VBF was applied in vineyards of the Napa Valley, California, USA and Alto Valle, Río Negro, Argentina[17]. However, Battany found little evidence that the method was effective when the inversion was weak or moderately strong, compared with a conventional wind machine in a vineyard in California[19]. The wind machines used in his study, however, were considerably less powerful than those used in Iran.

One of the characteristics described in the original report on the VBF[14] indicated that the VBF jet should rise to about 200 m in height. Using a smoke bomb test on two nights, Battany reported that the VBFs that he used only blew air upwards to about 25 m and Zhang's experiments with the jet height of 20-30 m[20].

Alternative methods for frost protection are desirable and the use of VBFs has been widely adopted without strong evidence for their effectiveness. Clearly, there is a big need for more research to validate if the VBFs are or are not effective for frost protection. An early study was conducted in California in a steeply sloped wine grape vineyard near Napa Valley in Northern California during the spring 2007. In 2011, a second experiment was conducted on a tea farm in Jiangsu Province, China. Both of the experiments are discussed in this paper.

2 Materials and methods

2.1 Vineyard protection with VBF

During the spring 2007, an experiment was conducted to assess the effectiveness of a VBF machine in a wine grape vineyard near Angwin, California, USA, which is located northeast of Napa Valley in Northern California. Figure 1 shows the vineyard and the locations of weather station #1 (38°33′15.93″N; 122°27′40.81″W; 399 m) and station #2 (38°33′13.42″N; 122°27′38.82″W; 413 m) within the vineyard. The land sloped downward from the upper to lower station with station #1 about 14 m lower. At the bottom of the slope, the cold air drainage was mostly blocked by trees and brush along a highway. A mid-sized model VBF, which is no longer commercially available, was located in the northwest corner of the vineyard (near the station #1). The VBF had characteristics similar to those in Table 1. There was about 2.4 m between flats of the shroud surrounding the VBF and it was powered gasoline engine. To the northwest of the vineyard, the land was steeply sloped downward towards Napa Valley.

Temperature data were collected using CR800 data loggers (Campbell, USA) and chromel-constantan unshielded (76.2 μm dia.) thermocouples mounted at cordon height where frost damage normally occurs in grapevines. The data were analyzed using least squares regression and the root mean square error.

Figure 1 Locations of the weather stations and the VBF in the experimental vineyard

On nights without VBF operation, minimum temperature data from station #1 and #2 were plotted versus the minimum temperature data from the closest CIMIS weather station (Oakville #77) for all of the nights when the temperature range from the previous day to the morning minimum at the CIMIS station was greater than 15°C. The Oakville #77 CIMIS station is located at latitude: 38°26′02″N, longitude: 122°24′35″W, and Elevation 57.9 m above mean sea level. The minimum 15°C temperature range was selected to insure that nights with strong wind and/or clouds were not included. The data and the regression provided a method to estimate the relationship between the vineyard station minimum temperature and the CIMIS minimums without VBF operation. Then, the minimum temperatures on the nights with VBF operation were plotted versus the CIMIS minimums. In addition, the nighttime temperature trends were measured on nights with VBF operation.

2.2 Tea plantation protection with VBF

A second experiment was conducted in spring 2011 in China to test the utility of a VBF for frost protection of tea plants. The VBF machines are not commercially available in China, so a similar machine was built by Jiangsu University to test its performance as a protection method. Specifications for the Jiangsu University VBF (JUVBF) machine (shown in Table 1) are similar to the small one used in the California vineyard experiment.

Table 1 Specifications of JUVBF

Item	Structure dimension		Wind machine			Motor Power /kW	Output air flow volume /$m^3 \cdot s^{-1}$
	Height /m	Duct diameter /m	Blade number	Diameter /m	Rotating Speed /$r \cdot min^{-1}$		
Description	2.0	2.8	4	2.39	335	5.5	40

Field experiments were conducted on March 23-24 and April 3-4. Fourteen temperature recorders (ZDR-3W1S, Zeda, China) were installed around the machine (Figure 2). Both the thermal inversion conditions and temperature rise resulting from JUVBF operation were measured. The measurements were at points A, B, C, D, E, F, G and H, which were set at 1.2 m height every 5 m along the radial direction from the VBF towards the northwest, with point A being 5 m from the center of the VBF. Starting with height B_1=1.0 m, temperature data were collected on a vertical pole every 1.0 m at points B_2, B_3, B_4, B_5 and B_6. The pole was located 5 m from the center of the VBF and about 2 m southwest of point A. The control pole was located 80 m to the northeast of JUVBF, where it was little affected by JUVBF operation. The temperature data were collected starting at 1.0 m height for $B_1'$and with 1.0 m between sensors up to 6.0 m for B_6'. The data were assigned to the variables B_1', B_2', B_3', B_4', B_5' and B_6', and they were compared with data from the pole near the VBF to evaluate the effect of JUVBF operation on the thermal inversion layer.

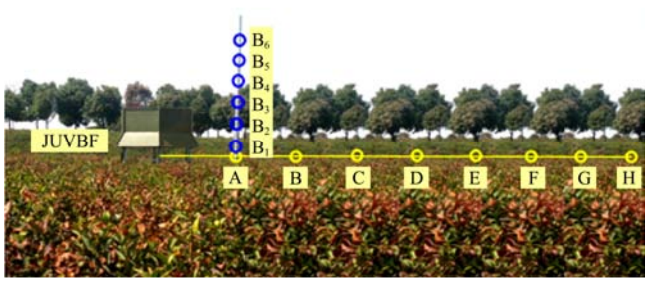

Figure 2 Temperature measurement set up around JUVBF

3 Results and analysis

3.1 Grape vineyard field results

The grape vineyard was located on steeply sloping land, and a positive response to operating the VBF was expected. The difficulty in evaluating the VBF lies in the fact that the vineyard has a unique microclimate, so there is no way to locate a control station nearby for comparisons with temperature measurements in the vineyard. To overcome this problem, it was decided to develop a predictive relationship between vineyard temperature measurements on nights without VBF operation and the closest CIMIS station (Oakville #77). Then, operating the VBF should increase the temperatures relative to temperature prediction as a function of the CIMIS station minimum temperatures. Only nights when the CIMIS station temperature range from the previous day's maximum to the current day minimum were greater than 15°C were included in the analysis. This was done to eliminate nights with clouds, fog or windy conditions.

To be unbiased, the data were first analyzed without knowing which nights the VBF machine was operated. The grower informed us that the VBF was operated on four nights and, based on the observed data and assuming the VBF was effective, the nights might be on 21-22 April, 5-6 May, 18-19 May and 19-20 May. These were nights when a big increase in temperature was observed at the vineyard but not at the Oakville #77 CIMIS station. The grower informed us that the VBF was not operated on any of those nights. Rather the operation dates were 11-12 April, 14-15 April, 17-18 April, and 18-19 April. This indicated that, during frost night conditions, natural weather events often result in bigger increases in temperature than from using the VBF, so one must be cautious when interpreting the effectiveness of protection methods.

Figures 3 and 4 show the change of the minimum temperatures from the Station #1 and Station #2 with the CIMIS #77 minimum temperatures on nights with or without VBF operation. For both Stations #1 and #2, the observed minimum temperatures on VBF operation nights were below the regression line, so there was no evidence that the VBF was beneficial for frost protection.

On nights when the VBF was operated, the temperature response recorded at either station was minimal except during the morning of 18-19 April when a sharp temperature rise was observed. This temperature jump, however, occurred several hours after the VBF started (Figure 5), so it is unlikely that the VBF caused the temperature rise.

The biggest temperature jumps occurred on nights when the VBF was not operated. Those sharp temperature increases likely resulted from clouds, fog or rain. In general, there was no evidence that the VBF beneficially raised temperatures in the vineyard. The natural variability was bigger than any VBF effect.

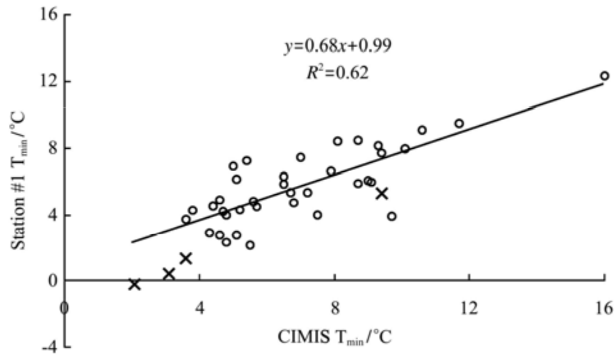

Figure 3 Station #1 (lower station) minimum temperatures versus the CIMIS #77 minimum temperatures

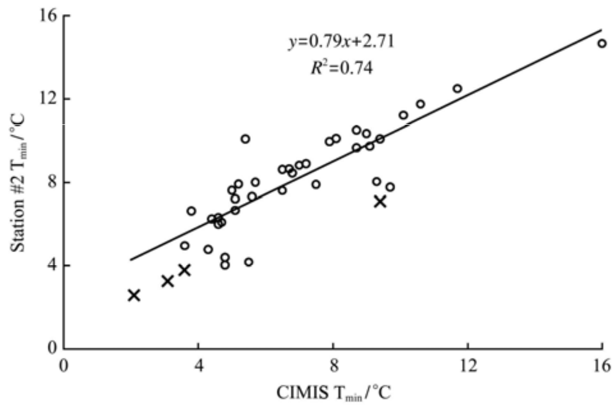

Figure 4 Station #2 (upper station) minimum temperatures versus the CIMIS #77 minimum temperatures

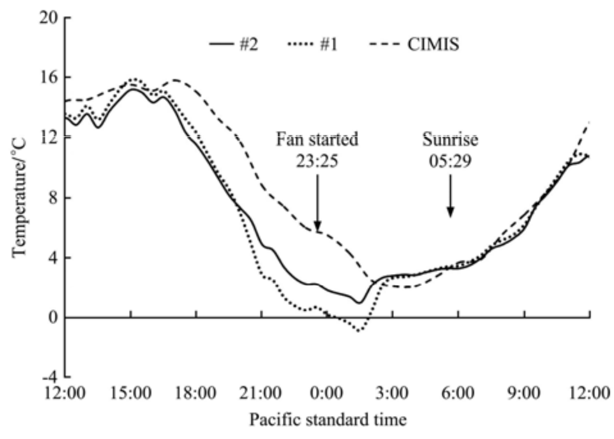

Figure 5 Temperature trends during the night of 18-19 April 2007

3.2 Tea plantation field results

JUVBF was operated on two nights during 2011 when a strong thermal inversion was observed. At 7:00 on March 23-24, the inversion between 1-3 m height was 1.6°C at 80 m from JUVBF and 2.9°C at 5 m from the operating JUVBF. At 6:00 on April 3-4, the inversion between 1-3 m height was 2.8°C at 80 m from JUVBF and 3.1°C at the 5 m pole. Based on the theory for the VBF operation, the VBF should selectively remove cold air from the surface to be replaced with warmer air from aloft as the cold air is blown upwards. That meant the inversion should weaken, especially near the VBF. That was not observed on either of the two nights during JUVBF operation. On both nights, there was a stronger inversion present at the 5 m pole near sunrise, so JUVBF operation was not reducing the inversion strength.

The horizontal change of temperatures at 1 m height after starting JUVBF on March 23-24 is shown in Figure 6. For a few hours, there seemed to be a big increase in temperature, but the temperatures dropped again after 3:00. It is difficult to discern whether or not the changes are due to JUVBF or to the natural variation from the data. The temperatures fluctuated during JUVBF operation, but temperatures near it were consistently the lowest, which contradicts what has been reported in the literature. Therefore, the horizontal variation was likely due to factors other than JUVBF operation.

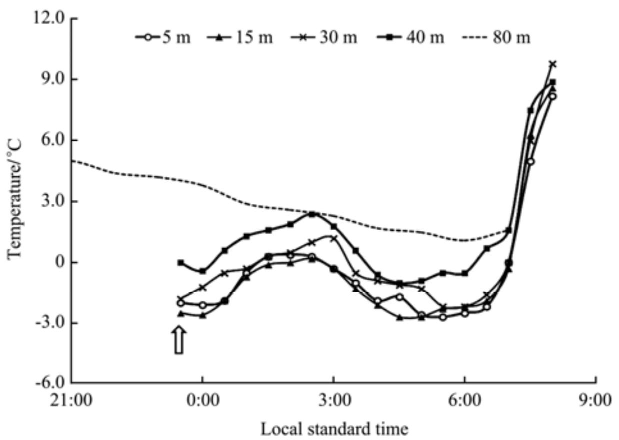

Figure 6 Horizontal change of temperatures at 1 m height after starting JUVBF on March 23-24

The horizontal change of temperatures at 1 m height after starting JUVBF on April 3-4 is shown in Figure 7. JUVBF was started at 1:30. The temperature at 40 m from JUVBF increased when JUVBF started and remained high from 2:00 to 4:20. The temperature at 30 m was slightly increased during the same period, but the 5 m and 15 m temperatures seemed relatively unaffected by JUVBF operation. There was a shelter belt nearby the 40 m pole, and perhaps it blocked cold air drainage and affected the temperatures at the 40 m and possibly the 30 m poles. The temperature readings from the poles close to JUVBF indicated minimal beneficial effect from its operation. In fact, the temperatures at the 5 m and 15 m poles dropped by approximately 2°C after JUVBF was started, which indicated that there was probably little or no benefit from its operation.

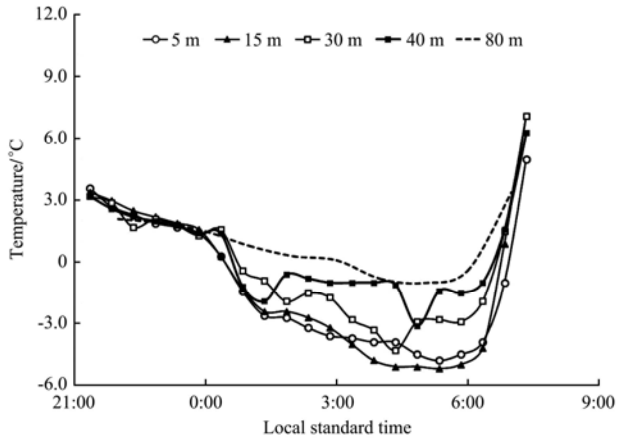

Figure 7 Horizontal change of temperatures at 1 m height after starting JUVBF on April 3-4

During the night of April 3-4, a white frost was accumulated on the tea plants except for a zone within about a 5 m radius from the center of the VBF (Figure 8). This indicated that JUVBF only benefited a small nearby area. Also, the infrared thermal imagery from April 3-4 (Figure 9) showed that JUVBF had almost no effect beyond about 10 m from the center of the VBF. Zhang[20] conducted computational fluid dynamics simulation on the operation of the same JUVBF and found similar results. Wu et al.[21] made an improved design of JUVBF by adding a rotatable airflow outlet to the narrowed top of the duct, which could draw and discharge the air at the bottom and disturb the warmer air on the top.

Figure 8 Area without frost under JUVBF operation

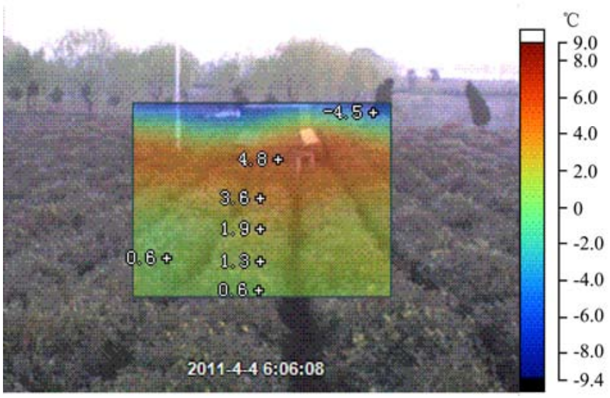

Figure 9 Thermal imagery of the area protected with JUVBF

4 Conclusions

An experiment in a grape vineyard of California was conducted in the spring 2007 to confirm if a VBF was beneficial for blowing cold air out of a pocket at the lower end of the vineyard to provide frost protection. Minimum temperature data measured at the upper and lower end of the vineyard were compared with minimums recorded at the weather station on nights with and without VBF operation. Linear regression was used to determine empirical prediction equations for the two measurement locations using data from the nights without VBF operation. Then the minimum temperatures from nights with VBF operation were compared with the predicted minimums. In all cases, the observed minimum temperatures were lower than the predicted, implying that the VBF was not effective at increasing temperature.

In China a VBF was developed for frost protection and tested in a tea plantation in 2011. Field results showed there was a horizontal difference in 1 m height temperatures measured at 5 m, 15 m, 30 m and 40 m from the VBF, but there was no conclusive evidence that the VBF operation was beneficial. On one night, the temperatures fluctuated, but there was little evidence that the VBF caused the fluctuations. On another night, the temperature seemed to increase, but temperatures near the VBF dropped approximately 2°C after operation. In addition, white frost observed on the tea plants and thermal imagery both showed that there was little benefit from VBF operation except in an area of 10 m radius around the center of the VBF.

While this study tends to support the conclusions of the last published paper[19], it contradicts the results from Yazdanpanah et al.[16]. The machines used by Yazdanpanah et al., however, were larger and more powerful than those used in the later experiments. Also, there is the possibility that a VBF might work in some environments and not others. The research reported in this paper, does not validate the effectiveness of the VBF for frost protection. Further study should focus on identifying the reasons why the larger machines seemed to be more effective than the smaller ones. Perhaps the difference is related to the maximum jet height of the VBF or the difference in power of the machines. These factors need to be investigated to determine the potential applicability of the VBF.

Acknowledgements

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