Cover Page**BARD Project Number: US-3189-01****Date of Submission of the report: March 31, 2006****Project Title:** Comparing the Performance of Naturally Ventilated and Fan-Ventilated Greenhouses**Investigators****Institutions****Principal Investigator (PI):**

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Total: \$ 325,000

Signature
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Authorizing Official, Principal Institution
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Sponsored Programs

	Joint IS/US authorship	US Authors only	Israeli Authors only	Total
Refereed (published, in press, accepted) BARD support acknowledged		3		
Submitted, in review, in preparation			1	
Invited review papers				
Book chapters				
Books				
Master theses			1	
Ph.D. theses		1		
Abstracts				
Not refereed (proceedings, reports, etc.)		3	3	

Postdoctoral Training: List the names and social security/identity numbers of all postdocs who received more than 50% of their funding by the grant.

Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings		1		
Longer Visits (Sabbaticals)				

Description Cooperation:

The two teams have communicated frequently via email during the project; setting up tests, exchanging data and setting/modifying objectives. In addition, the Israeli team met with the US team in Raleigh, NC, April 6 - 13, 2005. Both teams presented detailed reports on accomplishments and planned the final report during meetings held on 6 through 8 April. April 11 was spent exchanging data and working with the two models. On April 12 the teams visited Metrolina Greenhouses in Huntersville, NC, one of the largest greenhouse complexes in the US (100 acres).

Patent Summary (numbers)

	Israeli inventor only	US inventor only	Joint IS/US inventors	Total
Submitted				
Issued (allowed)				
Licensed				

Abstract:

The objectives of this project were to predict the performance of naturally and fan-ventilated greenhouses as a function of climate, type of crop, evaporative cooling and greenhouse size, and to estimate the effects of the two cooling systems on yield, quality and disease development in the different crops under study.

Background

In the competitive field of greenhouse cultivation, growers and designers in both the US and Israel are repeatedly forced to choose between naturally ventilated (NV) and fan-ventilated (FV) cooling systems as they expand their ranges in an effort to remain profitable. The known advantages and disadvantages of each system do not presently allow a clear decision. Whether essentially zero operating costs can offset the less dependable cooling of natural ventilation systems is question this report hopes to answer.

Major Conclusions

US

It was concluded very early on that FV greenhouses without evaporative pad cooling are not competitive with NV greenhouses during hot weather. During the first year, the US team found that average air temperatures were always higher in the FV houses, compared to the NV houses, when evaporative pad cooling was not used, regardless of ventilation rate in the FV houses or the vent configuration in the NV houses. Canopy temperatures were also higher in the FV ventilated houses when three vents were used in the NV houses.

A second major conclusion was that the US team found that low pressure fogging (4 atm) in NV houses does not completely offset the advantage of evaporative pad cooling in FV houses. High pressure fog (65 atm) is more effective, but considerably more expensive.

Israel

Experiments were done with roses in the years 2003-2005 and with tomatoes in 2005. Three modes of natural ventilation (roof, side and side + roof openings) were compared with a fan-ventilated (with evaporative cooling) house.

It was shown that under common practice of fan ventilation, during summer, the ventilation rate is usually lower with NV than with FV. The microclimate under both NV and FV was not homogeneous. In both treatments there were strong gradients in temperature and humidity in the vertical direction. In addition, there were gradients that developed in horizontal planes in a direction parallel to the direction of the prevailing air velocity within the greenhouse. The gradients in the horizontal direction appear to be larger with FV than with NV.

The ratio between sensible and latent heat fluxes (Bowen ratio) was found to be dependent considerably on whether NV or FV is applied. This ratio was generally negative in the naturally ventilated house (about -0.14) and positive in the fan ventilated one (about 0.19). Theoretical models based on Penman-Monteith equation were used to predict the interior air and crop temperatures and the transpiration rate with NV. Good agreement between the model and experimental results was obtained with regard to the air temperature and transpiration with side and side + roof ventilation. However, the agreement was poor with only roof ventilation. The yield (number of rose stems longer than 40 cm) was higher with FV than with NV. A simple economic analysis made on the rose cultivation showed that FV is better than NV since the initial cost of fans and pad is returned within about three years by the higher yield of longer stems.

Scientific Achievements

US

Evaporative Cooling

Early on, the US team found that air temperatures in the naturally ventilated (NV) house were about 2 C lower than in the fan ventilated (FV) house when no evaporative cooling was used in either house and no canopy was present. When a canopy was present, the NV house air temperature advantage was mitigated to about 0.8 C and canopy temperatures were not greatly different from each other. The conclusion was reached that without evaporative pad cooling, the NV house was superior in cooling ability to the FV house. All subsequent testing incorporated evaporative pad cooling in the FV houses and the task became one of finding a suitable alternative for the NV houses.

Fog

In 2004 and 2005, the US team operated low-pressure fog systems (4 atm) in both NV houses. Comparison with the 2003 data shows that low-pressure fog did mitigate some of the differences in canopy and air temperature; however, it was not able to mitigate them completely. In 2005, high-pressure fog (65 atm) was installed in one of the NV houses. Cooling performance was significantly better, but the expense was considerably higher. If either fog system is to be comparable to fan and pad systems, good ventilation will be essential. Canopy wetting was nearly impossible to avoid. Maximum cooling must be reconciled with minimum canopy wetting so that disease development will not occur. Fogging magnified environment inhomogeneity environment, but the degree of the inhomogeneity was not unacceptable.

Yields

Tomatoes were grown the first two years and sweet bell pepper the third. Yield comparisons during 2003 were not very helpful because of the various cooling regimes imposed in the houses. In 2004 the difference was one of quality, with the FV house producing more No. 1 fruit than the NV houses during the first 20 days of the harvest, the same period when temperatures were higher in the NV houses. In 2005, the total yield of sweet peppers was much higher in the FV houses by a factor of almost two. The No. 1 yield was also higher in the FV houses, but the difference was less. The cultivars *Waki* and *Zamboni* were most affected by the temperature differences between houses.

Israel

Roses were grown in 2003-2005 and tomatoes in 2005. Three modes of NV (roof, side and side + roof openings) were compared with a FV (with evaporative cooling) house.

Ventilation and air velocity

NV ventilation rate was estimated by the decay rate of a tracer gas (N_2O) and by the mass balance of water vapor in the greenhouse air. A comparison of the two methods gave a good agreement. The ventilation rate increased linearly with ambient wind and varied in the range of $0.01 - 0.03 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-2}$ (unit floor area) for wind speeds of $2 - 8 \text{ m s}^{-1}$. The summer the ventilation rate was usually lower with NV than with FV. It was observed that the mean air velocity, ventilation flow rate divided by the cross sectional area of the greenhouse, was a good estimate for the directly measured velocity when the greenhouse was naturally ventilated by side openings, but gave poor results when roof ventilation was applied.

Homogeneity of parameters within the greenhouse

The microclimate under both NV and FV was not homogeneous. Strong gradients existed in temperature and humidity in the vertical direction and in horizontal planes in a direction parallel to the air movement within the greenhouse. Gradients in the horizontal direction appeared to be larger with FV than with NV. Furthermore, non-homogenous conditions were observed with respect to the spatial distribution of net radiation, crop temperature and transpiration.

Energy balance and portioning to sensible and latent heat

The energy balance in the two treatments (NV and FV) was nearly closed with relatively good agreement between the sum of latent, sensible and soil heat fluxes and the net radiation above the crop. The ratio between sensible and latent heat fluxes (Bowen ratio) was found to be generally negative in the NV house (about -0.14) and positive in the FV one (about 0.19). This was because leaves were generally cooler than the adjacent air with NV and warmer than the adjacent air with FV.

Model verification

Theoretical models based on the Penman-Monteith equation were used to predict the interior air and crop temperatures and transpiration rate in the NV house for nine days, four hours each day (10:00 – 14:00). Good agreement between the model and experimental results was obtained for air temperature and transpiration with side and side + roof ventilation. However, agreement was poor with only roof ventilation, apparently due to the low coupling between internal and external conditions in this mode of ventilation. Agreement between simulated and measured crop temperatures was poor in all modes of NV.

Yield and quality

The number of rose stems per plant in the NV compartment was about 26-46% higher when stem lengths above 10 cm were counted. However, the average stem length with NV (38.7 cm) was smaller than with FV (43.4cm). When only stems above 40 cm were counted, the number was larger in the FV house. Leaf area index was higher with FV than with NV and, during the summer, plants in the FV house appeared to be more robust than in the NV

treatment. No significant difference was observed in average bud diameter and length. There was no significant difference in tomato yield and size of fruits with treatments but a significant difference was observed in blossom-end rot, occurring at a much higher rate in the NV treatment. A simple economic analysis on the rose cultivation showed that higher initial cost of FV is returned within three years by the higher yield of longer stems. The extra cost of electricity and water with FV is nearly balanced by the additional cost of pesticides, fungicides and labor needed in the NV house.

Agricultural and/or Economic Impact

The choice of NV vs. FV is a major one for greenhouse operators in the US and Israel. The results of this study quantify some of the differences that might be expected in each type of house, and the possible impact that might have on production. This should allow growers to make a better choice of greenhouse types relative to expected return on investment. Producers of low value crops, say tomatoes, may find that the lower investment and operating costs of NV houses are warranted if the major downside is a reduction in yield only during hot weather. On the other hand, producers of high value crops, such as roses, may find that the higher initial investment and operating costs of FV houses are justified by the increase hot weather production.

Details of Cooperation

The two teams have communicated frequently via email during the project; setting up tests, exchanging data and setting/modifying objectives. In addition, the Israeli team met with the US team in Raleigh, NC, April 6 - 13, 2005. Both teams presented detailed reports on accomplishments and planned the final report during meetings held on 6 through 8 April. April 11 was spent exchanging data and working with the two models. Since that meeting, both teams have exchanged data and run that data through their respective models (see research reports).

Publications

See Appendix A