view, the net yield increase, or portion of the 15.5-ton increase in tomato yields attributed to drainage improvements, was 13.5 tons (table 5). The value of this increase, at the average price received during 1983 through 1986, was $698 per acre. Similar values ranged from $37 per acre for wheat to $109 for alfalfa seed.

Conclusion

Increases in average crop yields in the four years after installation of a drainage outlet in the Broadview Water District provide compelling evidence of crop responsiveness to improvements in drainage conditions. Average yields of the six crops examined in this study exceeded county averages during those years. Yields of salt-sensitive tomatoes and alfalfa seed responded by 80 percent and 56 percent, respectively. Average yields of salt-tolerant barley, wheat, and sugarbeets also improved in Broadview, at a rate exceeding Fresno County yield increases, during the most recent period. This finding suggests that even crops considered to be tolerant of soil salinity may be adversely affected by continuous recycling of all drain water over a prolonged period. Yields of these crops responded positively to improvements in the quality of irrigation water and reductions in soil salinity made possible by improving the drainage situation in Broadview.

Our data, while pertaining specifically to salinity conditions and yields of selected crops in the Broadview Water District, indicate the costs associated with salinity and high water tables and the value of obtaining the drainage outlet and improving soil and water conditions.

These results agree with those of other researchers regarding yield responses in regions with saline high water tables. They also indicate that the effectiveness of leaching programs may be limited in an area that does not have a drainage outlet. Cotton and wheat yields remained constant or increased after subsurface drains were installed in Broadview, but yields of tomatoes, alfalfa seed, and sugarbeets declined before installation of the drainage outlet. This finding supports the belief that leaching and recycling are temporary solutions to salinity problems. An outlet for collected drain water is required to maintain productivity in the long run.

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Bench-top heating required less energy than the conventional perimeter heating system in this commercial greenhouse, but provided less uniform temperatures in the plant canopy.

A comparison of bench-top and perimeter heating of greenhouses

Bryan M. Jenkins ❑ Roy M. Sachs ❑ Glen W. Forister

Soil, floor, and bench-top (root-zone) heating systems for greenhouses have been reported to conserve energy compared with conventional hot air or radiation systems. Since plant growth and development have been found to proceed normally at temperatures below otherwise optimal air temperatures if the root zone is maintained at a higher level, energy savings would occur from heating the relatively smaller region. If the inside air temperature next to the walls and roof of the greenhouse is reduced through zone heating, the heat loss from the greenhouse to the outside will be reduced.

In this study, we compared two types of heating systems: a bench-top system with hot water carried through tubes arrayed in continuous loops fixed to the benches, and a conventional perimeter heating system that circulates hot water through finned tubes along the lower inside perimeter of the greenhouse. Temperature and energy consumption data for both systems were recorded over the 1986-87 heating season to compare temperature distributions and heating costs.

Methods

A grid of thermocouples was installed in a cross-section of a 195-square-meter (2,100-square-foot) greenhouse on the University of California campus at Davis to record the heating patterns of the bench-top and perimeter systems (fig. 1). On alternating days, the grid was moved along the length of the greenhouse so that, in a period of two weeks, temperature distributions for approximately seven locations were obtained for each heating system.

The bench-top system consisted of eight small-diameter plastic tubes laid along each of the 10 benches in the greenhouse, with each tube making four passes over the bench. Each tube was connected to supply and discharge manifolds along the north wall of the greenhouse. The manifolding was arranged so that the total water transport distance (and pressure drop) was approximately constant for every tube in the system. Flowmeters were installed in the water delivery lines of each of the two heating systems. Thermocouples were installed at the water inlets and outlets to monitor temperature drop across each system.

Experiments usually started at 4:30 p.m. and continued through 8:30 a.m. the following day. During normal perimeter heating, jet-tube fans are activated to improve air mixing and achieve more uniform temperatures in the greenhouse. For these experiments, however, the fans were switched off, because they led to increased infiltration losses and excessive heat transfer coefficients in the greenhouse studied.

For each experiment we recorded the day, time, and average temperatures from 52 thermocouples, 44 on the sensor grid and 8 others placed in pots and other selected points in the greenhouse. Thermocouple readings were sampled every 5 seconds, and 15-minute averages were stored. We also monitored the average flow rate of water through the heating system and average temperatures of water entering and leaving the greenhouse. These sensors were sampled every 5 seconds, and 5-minute averages stored.

Isotherms for each transverse section were generated at each time interval. Energy consumption to maintain plant canopy temperature at the nighttime control setting was computed from the water flow rates and temperature differentials recorded for each system.

A value for the overall heat transfer to the outside was computed from the hourly means of the inside air temperature (as measured by the thermocouple nearest the thermostatic controller) and the outside air temperature, the cumulative hourly energy consumption, and the floor area of the greenhouse.

Inlet water temperatures were typically about 60°C (140°F) for the bench-top system, and 68°C (154°F) for the perimeter system. Temperature drop across the bench-top system averaged 21°C (38°F) for flow rates ranging as high as 20 liters per minute (5 gpm). With the circulating pump on, the temperature drop across the perimeter system averaged 8°C (14°F) with flow rates of 250 liters per minute (66 gpm).

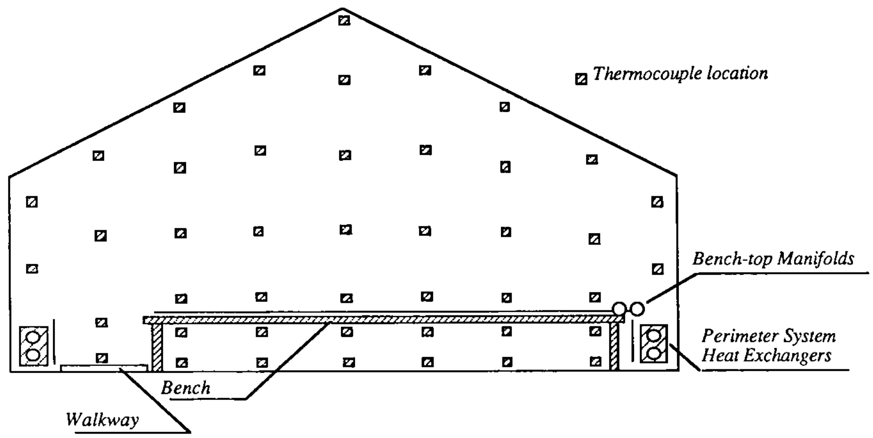

Fig. 1. Cross-section of test greenhouse showing locations of thermocouples, perimeter system heat exchangers along the lower walls, and bench-top heat exchangers.

Results

Temperature control. Both the perimeter and bench-top systems maintained canopy temperatures within the control range of 16° to 18°C (60° to 65°F). Greenhouse temperature oscillated about the set point more with perimeter heating than with bench-top heating, primarily because of the band width of the thermostat and the large thermal influx needed for convection of heat into the canopy. Placing the temperature sensor controlling the bench-top system at a height of either 0.3 or 1 meter (1 or 3 feet) above the bench had little effect on the accuracy of control or on fluctuation of temperature with time.

Temperature distribution. The perimeter heating system generated two large convection cells within the greenhouse. Warm air rose by natural convection along the walls and ceilings before mixing into the leaf canopy (fig. 2A). These large convection cells did not occur with the bench-top system, although smaller convection cells were visible directly on top of the benches (fig. 2B). Distribution along the benches was not entirely uniform, and local convection may have been disrupted by flats and other articles on the benches. Distribution higher in the canopy was more uniform.

Air temperatures near the walls and ceiling were higher with the perimeter heating system than with the bench-top system: 3° to 5°C (5° to 9°F) higher at the lower wall, and as much as 7° to 8°C (13° to 14°F) higher at the ceiling and ridge. Air temperatures in the walkways were 3° to 4°C (5° to 7°F) higher for the perimeter system than for the bench-top system (fig. 3A and 3B).

Energy consumption. The bench-top system consumed at least 25 percent less energy than did the perimeter system on comparable nights, but flow reversal in the perimeter system when the circulating pump was not operating suggests that the measured energy consumption for the perimeter system is low. An overall heat transfer coefficient ranging between 4 and 6 watts per square meter-Kelvin (0.7 to 1.1 Btu per hour per square foot-°Fahrenheit, normalized to the greenhouse floor area) was computed for the greenhouse with bench-top heating (an example for January 12 is shown in figure 4).

Heat transfer coefficients computed on an hourly basis on low-wind nights were not as uniform for the perimeter system as for the bench-top system. For the perimeter system, the heat transfer varied from 6 to 14 W/sq m-K (1.1 to 2.5 Btu/hr-sq ft-°F). The lower heat transfer observed for the bench-top system would be due primarily to the lower temperature of the inside air in direct proximity to the cover surface, although there may have been some influence from the reduced inside air velocity with the bench-top system. The overall heat transfer for the bench-top system also appeared to be less sensitive to outside wind conditions, which are known to influence infiltration losses.

Conclusions

The bench-top heating system tested maintained plant canopy temperature with a lower thermal energy requirement than the conventional perimeter system. The improved efficiency was directly re-

In the bench-top heating system, plant containers were placed either directly on the tubes carrying heated water or on porous polyethylene sheeting laid over the tubing.

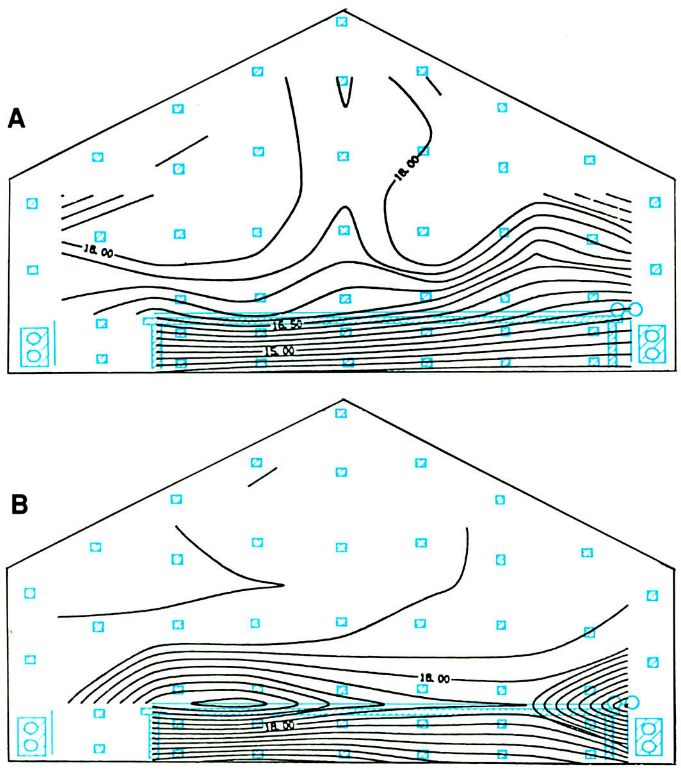

Fig. 2. Monitoring of isotherms in the perimeter-heated greenhouse showed that warm air rose by natural convection along the walls and ceilings before mixing into the leaf canopy (A). These convection cells did not occur with the bench-top system (B). There, high-temperature regions occurred directly over the benches.

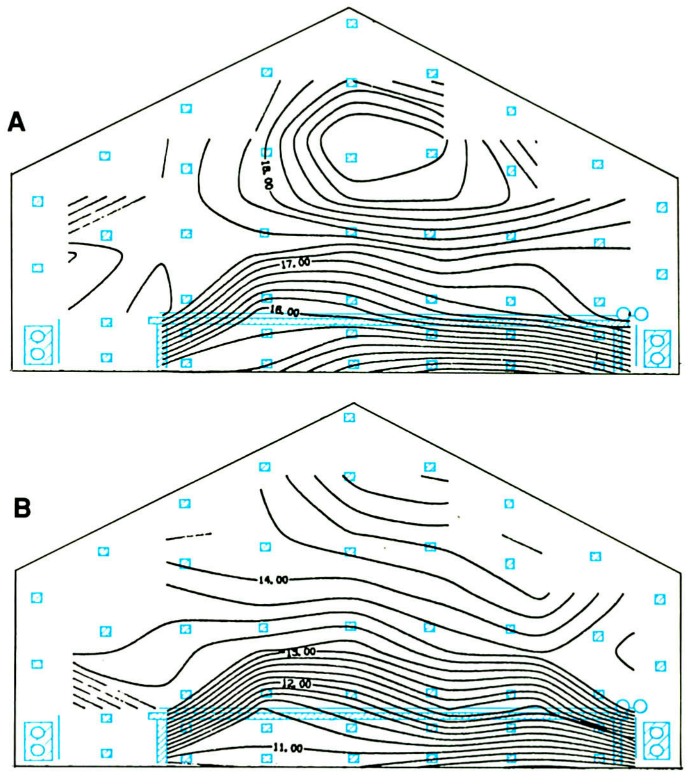

Fig. 3. Air temperatures in the walkways (along east wall) were higher for the perimeter system (A) than for the bench-top system (B) and were essentially the same as in the active growing region of the greenhouse. In the bench-top system, walkway temperatures were cooler than in the active growing region.

lated to the reduced volume of air heated and the lower temperature gradients across the external cover surfaces. The values for effective heat transfer determined for this greenhouse with the perimeter heating system may be high in comparison with commercial greenhouses employing energy conservation techniques such as thermal blankets and improved insulation. The results show, however, the potential for reducing total energy consumption with zone heating.

Although bench-top, floor, and soil heating systems raise temperatures in the root zone, this is probably not a contributing beneficial factor in crop development. Bench-top and soil heating systems may have a weakness in the extent to which the root zone temperatures need to be raised above the optimum for root growth and function to achieve optimal canopy temperatures. The study reported here did not compare crop performance in conventional and bench-top systems, but available evidence suggests that plant growth is essentially equivalent for both systems. Root zone temperatures above 20°C (68°F) can reduce growth of some species, but the system tested here maintained the desired canopy temperature with soil temperatures held at 20° to 22°C (68° to 72°F). Installing plenums to reduce the conduction transfer to the pot and soil while promoting greater uniformity in the canopy may further reduce soil heating.

The bench-top system used in this study with relatively small-diameter tubing may not be optimal. Tubing diameter may be increased to reduce friction losses and pumping requirements, although temperature distribution will change depending on the spacing of the tubing and the type of installation. Floor-heated greenhouses with porous floors have also been designed and evaluated. In any event, the potential to control both soil and canopy temperatures with these types of systems would appear to be of substantial benefit for overall greenhouse production.

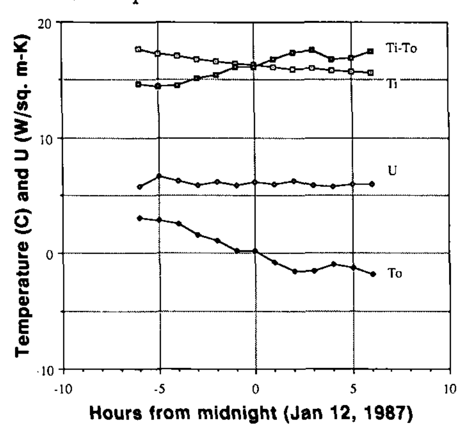

Fig. 4. Temperatures of inside air (Ti), outside air (To), temperature difference (Ti-To), and effective overall heat transfer (U) with bench-top heating, January 12.

Soil heating systems are being used as a means of increasing early and off-season production of outdoor crops, suggesting some potentially valuable applications in California nurseries. Since soil heating systems are well adapted for operation with low- and intermediate-temperature water, there is substantial opportunity to use these systems in cogeneration schemes with consequent savings in the base price paid for energy.

While energy used for heating has been shown to be lower for the bench-top than for the perimeter system, the less uniform temperature distribution in the canopy with the bench-top system is of interest. Further work will be conducted to investigate the heat transfer on the bench, and to identify techniques that improve uniformity and that may lead to improved control over both soil and canopy temperatures.

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