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HEATED IRRIGATION COLD PROTECTION

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Additional index words. microsprinklers, heated irrigation, frost protection, windbreaks, dewpoint temperature.

Abstract. **Since the temperature of irrigation water is higher than that of the air under frost conditions, all systems operate as naturally warm water systems. A small, oil-fueled irrigation water heater was used to increase the temperature of the water above that of the source and study the effect on the cold protection potential during the 25-26 February 1989, frost. Heating the irrigation water as much as 100°F above ambient 60°F water temperature provided an average increase over a period of an hour of 61.2°F. But little effect on leaf temperature more than 10 feet from the sprinkler heads was found. Within the tree under which the sprinkler was operating leaf temperature varied from 10°F above to 0.5°F below the non-irrigated control. Average leaf temperature increase was 1.8°F to 4.2°F depending on location relative to the sprinkler head. The pattern of the leaf temperature modification suggests increased water evaporation to the air near the sprinkler, upward transport of latent heat in a buoyant plume of vapor rich air, the plume leaning with the drift, and condensation on those leaves beneath the dew point or as fog droplets.**

A recent survey of growers and production managers (9) showed cold protection to be the most serious problem (50% of respondents) facing young tree programs and that microsprinkling was the most popular irrigation method (39% of acreage). A cold protection methods section showed 64% of the growers and 81% of the acreage used irrigation for cold protection, by far the most popular method (23).

A microsprinkler irrigation system and an associated irrigation heater at the teaching orchard located on the main campus of the University of Florida provide an opportunity to learn more about how microsprinkler irrigation systems modify the orchard microclimate under frost and freeze conditions. The ability to vary water temperature and consequently, evaporation of water from the sprinklers into the orchard atmosphere, i.e. the water temperature, should increase the likelihood that the mechanism can be understood quantitatively.

Concern regarding the role of latent heat transfer in cold protection is far from new and reached a peak following the 1962 freeze (e.g. 6, 7). The negative demonstration of overtree sprinkling redirected attention to the undertree case and numerous observations have been reported of surprising effects (1, 2, 3, 4, 5, 8, 17, 18, 19, 20, 21, 22, 25,26, 27, 30). Apparently the mechanism involves more than the release of the heat of fusion as ice forms. It is suspected that condensation may be involved, a process that releases 7.5 times as much heat per unit mass of water as does fusion (11). Use of heated irrigation water for cold protection is the purpose of this report.

Materials and Methods

Irrigation system. A 5.2 acre grove with trees ranging in age from 0.5 to 10 years at the University of Florida in Gainesville is irrigated with an 8 zone system illustrated in Figure 1. Irrigation water supplied to each zone may be turned on and off remotely by electrical control. One sprinkler per tree provides 7 gph when the water pressure is maintained at 15 psi. The primary water source is a 4-inch diameter, 175 feet deep [casing to 105] well with a 5 hp electric submersible pump. When drilling was complete the water level stabilized at 47 feet.

Irrigation water heater. The heater system consisted of a fuel tank, a burner, coiled water pipes within a cylindrical heated chamber and electrical/mechanical controls as diagramed in Figure 2. The system was connected into the main line of the irrigation system to provide heated water to the SE and SW zones.

Temperature measurement. Copper-constantan thermocouples, 22 gauge, were taped to metal stakes driven into the sandy soil so that the thermocouple loop was 5 ft above the soil surface. Fresh detached citrus leaves were taped to the thermocouple loops with a small piece of masking tape (16), exposing the leaves uniformly in a horizontal plane. A leaf thermocouple was in the center of each of the SW and SE irrigation zones. Another assembly was located near the northwest corner of the orchard [designated T_c

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Florida Agricultural Experiment Station Journal Series No. N-00127. A demonstration Aquaheet system was granted by James E. Thompson, Raymond A. Rogers, and Tom Thayer. A Maxijet irrigation system from Tom Thayer had been previously granted. Partial funding is gratefully acknowledged from James E. Thompson, Raymond A. Rogers, and Norman Todd. James Thompson's and Ray Rogers' operation of the Aquaheet system was deeply appreciated. Windbreak materials from Weathashade and Chicopee; engineering from Dr. Raymond A. Bucklin, Dalton S. Harrison, and Eugene H. Hannah; and computer systems support by Ferris G. Johnson, Jr., are gratefully acknowledged. The use of trade names is for identification and does not necessarily imply endorsement.

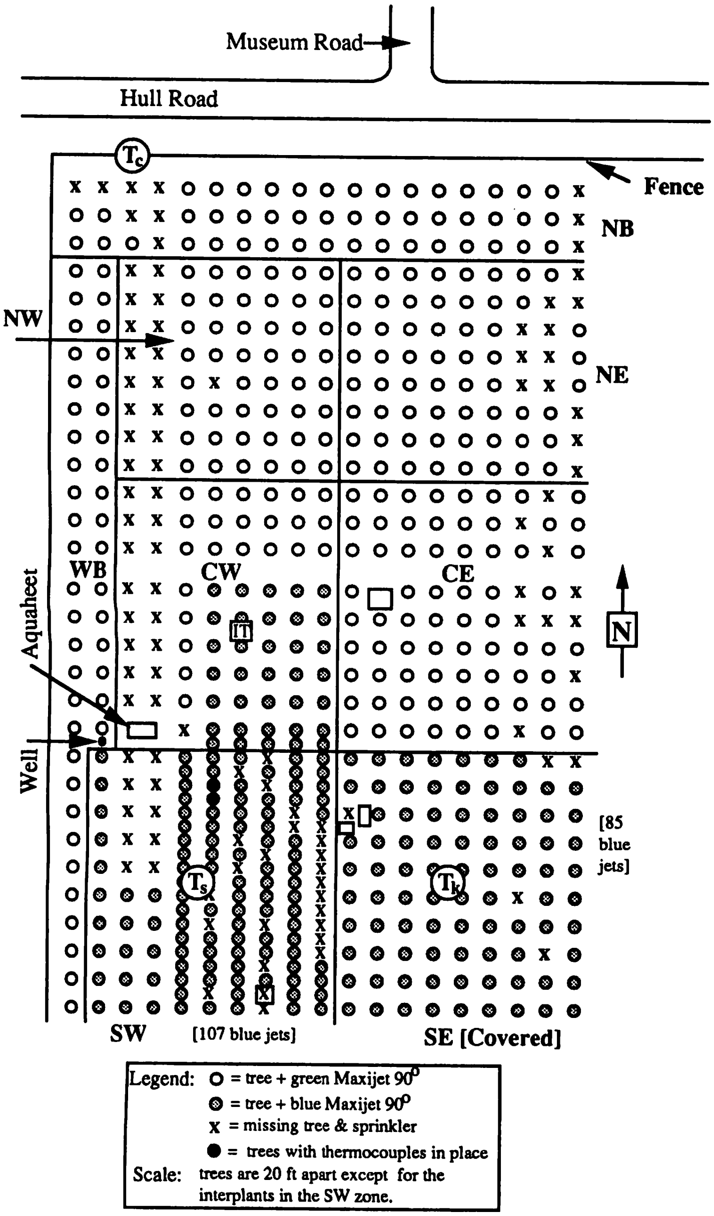

Fig. 1. Map of irrigation zones in a citrus orchard near Fifield Hall on the main UF campus. Each zone is marked with the short title of its name relative to the location of 3 leaf temperature sensors [T_c for control; T_s for center of SW zone; and T_k for center of zone SE], and sensors on two trees near the N border of the SW zone on which leaf temperature was observed at locations on the trees diagramed in Fig. 5.

in Fig. 1] outside and upwind of the irrigation treatments when the drift was from the northwest as it is typically during freezes.

Thermocouples were attached to leaves on two adjacent trees in the SW zone (location of trees shown in Fig. 1) and one thermocouple was placed in the sprinkler output in a pattern shown in Figure 5. Loop thermocouples without leaves were placed at 5- and 50-foot levels on the inversion tower [designated as IT in Fig. 1] to document temperature inversion strength. Two thermocouples were potted in waterproof plastic cylinders inserted within the subsurface horizontal mainline of the irrigation system, one between the heating system and the well and the other about 40 feet downstream from the heating system. Dew point temperatures were measured manually near the data acquisition trailer with a sling psychrometer and/or a fan aspirated psychrometer [Bendix].

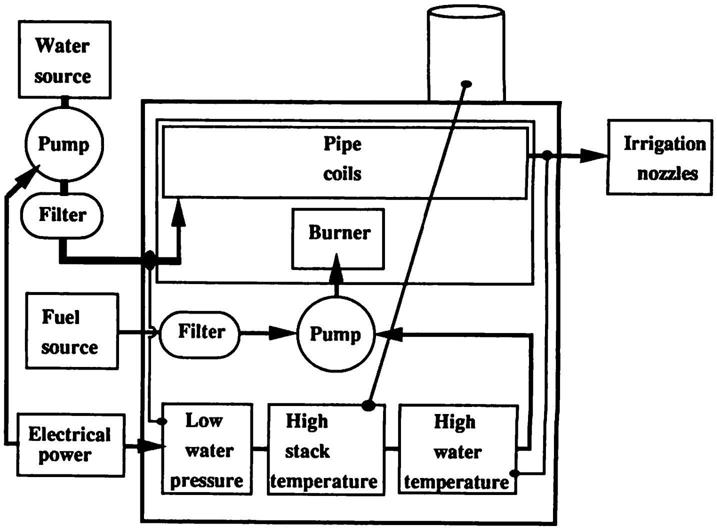

Fig. 2. Components of the Aquaheet irrigation water heater and their relative position in the flow of energy and fluids through the system. To protect the heater and the mainline of the irrigation system into which it is linked several electric switches can interrupt the power input to the fuel pump if the pressure of the water at the input falls below, or if the stack temperature exceeds, or if the output water temperature exceeds, preset limits. Clogging either fuel or water filters also interrupts the system. An electrical power failure interrupts both the heater and the water supply.

Wind speed sensing. The Thornthwaite cup anemometers and the manner in which they are utilized were described previously (12).

Data acquisition and reduction system (DAS). The DAS was the same as that described previously (16) except for a null modem used between the HP-1000-E and the Macintosh II. The system was housed in a small trailer near the NW corner of the covered area of the orchard (see Fig. 1).

Experimental treatments. These included a nonirrigated control at the north edge, irrigation with heated irrigation water in the SW area, and irrigation with heated irrigation water in the covered zone [SE]. While a comparison between the effects of heated and unheated irrigation water is not possible during the same time period, the effect of adding heat to the water is apparent through the comparison with unheated periods prior to and following the heat treatment. This technique is a variation on a theme that has been termed "pulsing the modification system on and off" which was found productive in demonstrating heating effect in previous studies (10, 24).

Results and Discussion

Operation. The heated water irrigation system was operated from approximately 10:00 PM to 11:30 PM on 25 Feb. 1989 during a typical radiant frost night (documented by the temperature trace shown in Fig. 3). Temperatures during the heated period and a previous period from 9 to 10 PM used in comparison were near but above freezing so that moderation of the temperatures by the freezing of dew was not expected.

Leaf temperature modification. Temperatures in the irrigated SE and SW zones were slightly warmer than the outside or control temperature (Fig. 4) prior to the increase in water temperature produced by the irrigation heater.

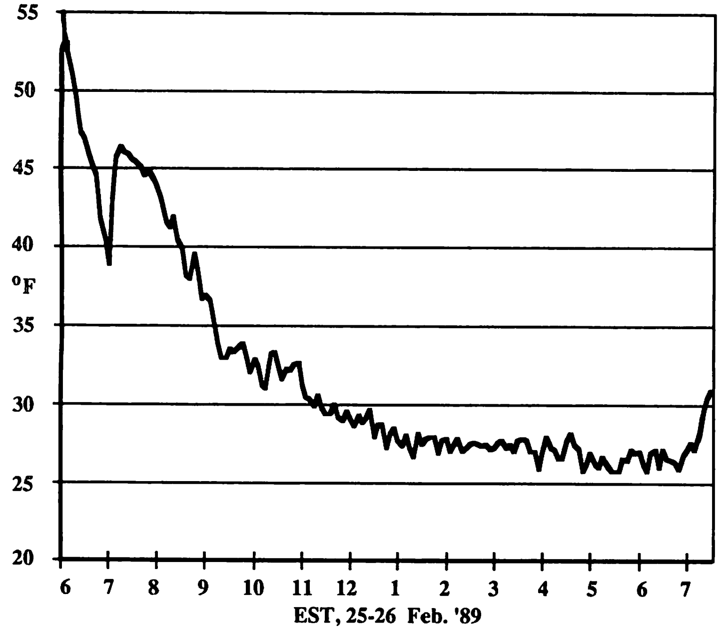

Fig. 3. Time series of 5 minute averages of leaf temperature at NW corner of the orhard exhibits typical cooling curve for a radiant frost. Averaging removed much of the rapid temperature fluctuation characteristic of the 1 minute data shown in Figures 4 and 6.

The pulse of heat in the irrigation water is shown on the same time scale as the leaf temperatures by plotting the temperature of the water as it flowed into the heater versus the water temperature at the output. The heater was operating effectively by 10:15 PM which became the start of the second hour in the analysis.

The leaf temperatures at the control and SW locations (T_c and T_s in Fig. 4) were fluctuating making it difficult to see the difference. A modeling study of the energy budget of leaves during frosts leads one to expect temperatures to fluctuate in time and space (14, 28, 29). The temperature trace beneath the cover is much smoother and shows some reluctance to drop as rapidly as the outside temperature traces (T_k in Fig. 4). This tendency toward smooth and slightly elevated temperatures has been noted in other data sets and may be considered a characteristic of the effect that orchard covers have on leaf temperature (12, 13, 16). It can be noted that the turbulent fluctuations increased in T_k during the period in which heat was added to irrigation water as might be expected from the added buoyancy to parcels of air near the sprinklers by sensible heating of the air and substitution of water vapor for other atmospheric gases. Both of these processes destabilize the layered atmosphere and result in mixing of the parcels making up the layers.

The difference in leaf temperature that may be attributed to the combination of sprinkling and elevation of the temperature of the irrigation water was sufficiently small that a summary of the average temperatures was required to evaluate it (Table 1). The average effect on the leaf temperature in the middle of Zone SW that can be attributed to the heated irrigation "pulse" was 0.8°F. This

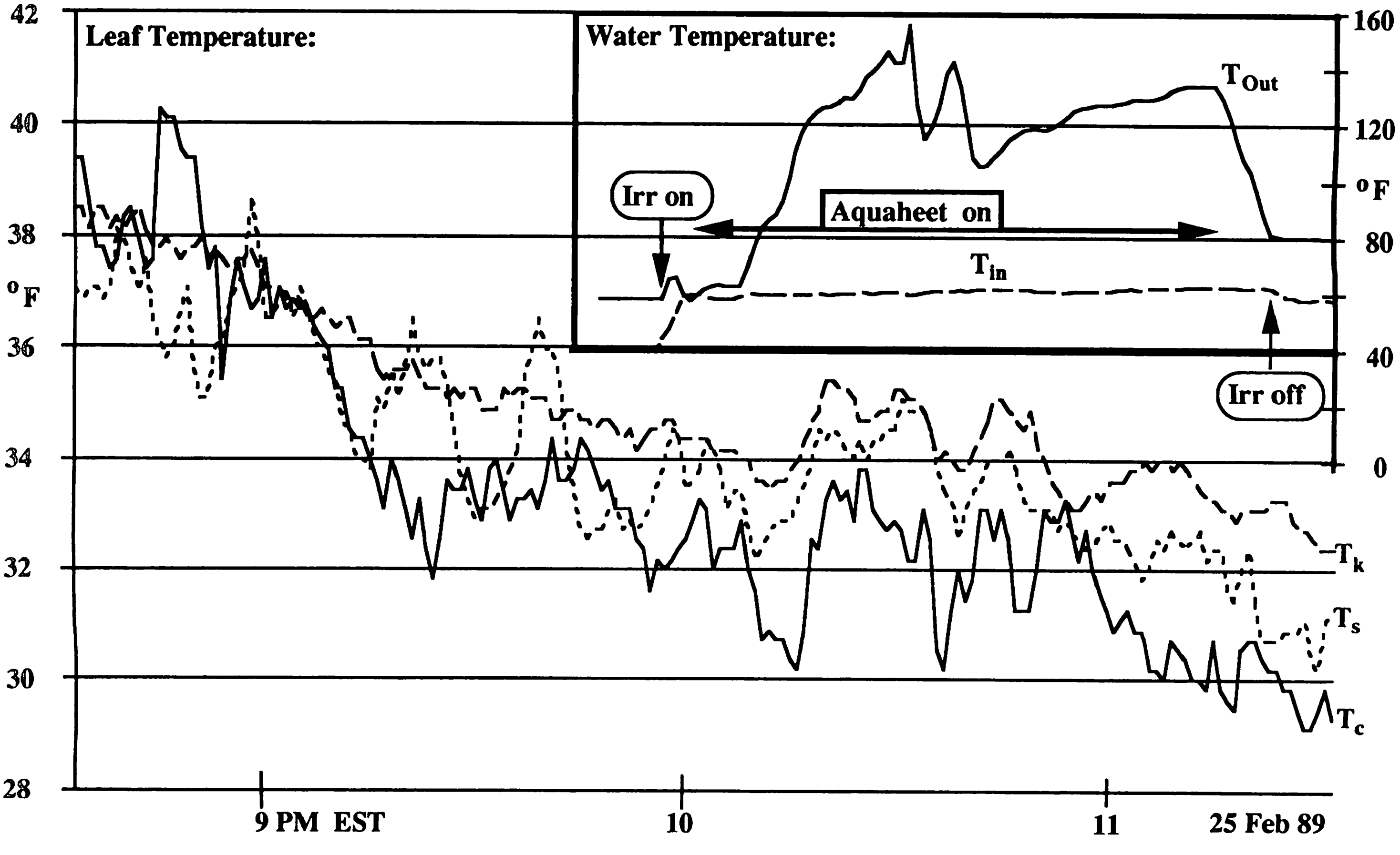

Fig. 4. The period during which irrigation was on and the irrigation heater was supplying heat to the irrigation stream are indicated in an insert which has the same time scale as the larger graph of the temperatures of two irrigated zones (T_k and T_s] in comparison to temperature in the control area, T_c. See Figure 1 for leaf temperature sensor location and Table 1 for computed differences between the temperature traces.

Table 1. Average temperatures and differences in temperature in °F. See Fig. 1 for relative locations. Diff stands for difference and Ave stands for average. Averages were of 61 one minute sensings. SD stands for standard deviation from the average.

[25 Feb. 89]	9 PM-10 PM		10:15-11:15 PM		EST
Locations	Ave T	SD	Ave T	SD	T diff
Outside [OS]	34.0	1.5	31.9	1.2	2.1
SW	34.7	1.4	33.4	0.9	1.3
T diff [SW-OS]	0.7		1.5		0.8
SE	35.4	0.9	34.2	0.7	1.2
T diff [SE-OS]	1.5		2.4		0.9
T diff [SE-SW]	0.7		0.9		0.1

value is less than the 1.5°F average difference that was noticed during the hour beginning at 10:15 PM because Zone SW was found to average 0.7°F above the control during the previous hour, i.e. from 9 to 10 PM. The effect under the orchard cover by the same analysis scheme was only 0.1°F higher, i.e. 0.9°F above the adjusted control temperature. The smoother temperature trace beneath the cover shows up in smaller standard deviations [SD]. Standard deviations of the outside temperatures are quite large, from 0.9°F to 1.5°F. These values were small relative to fluctuations as indicated by the standard deviations in Table 1 and the traces in Fig. 3 and may not indicate significant differences but they may provide estimates of the worst cases.

The leaf temperature, T_k or T_s, could be argued to be nearly a worst case scenario on the grounds that it represents a leaf, isolated from other leaves, oriented to maximize radiant exchange with the cold sky and to minimize convective exchange with the horizontal drift, as far from any sprinkler as possible. To provide a view of what was happening within the trees, four thermocouples were moved and placed in two trees as indicated in Figure 5 and their temperature traces are shown in Figure 6 for the period from when they were connected until midnight. There can be little doubt that the heated irrigation water caused heat transfer within the tree of much greater magnitude than that taking place at either the leaf in mid-row (T_s) or at the fence (T_c). Table 2 summarizes the differences and may be used in conjunction with Table 1 as an indication of the range of temperatures that may be expected under the test conditions.

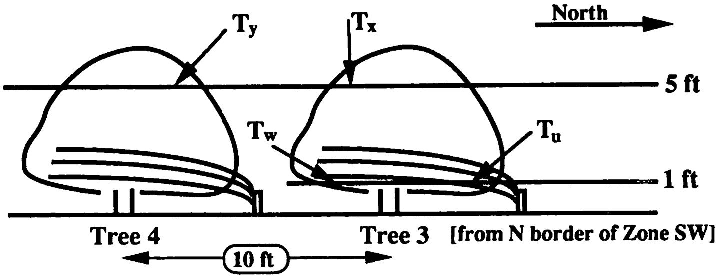

Fig. 5. Location of thermocouples taped to leaves on two tree [except for T_u which was placed in the spray and not taped to a leaf]. See Figure 1 for location of two trees within Zone SW.

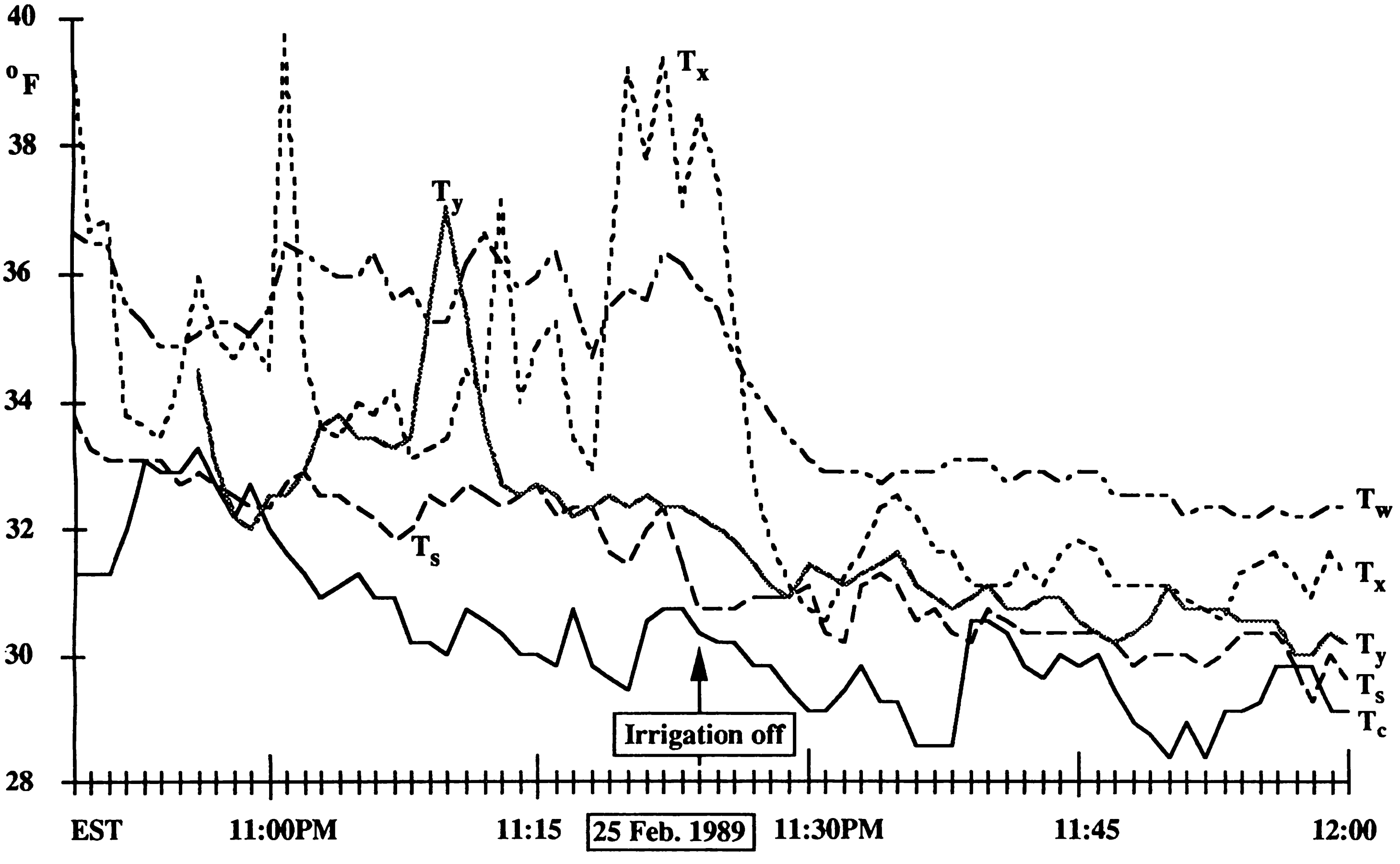

Fig. 6. Leaf temperature traces for the period from 10:48 PM till midnight [see Figures 1 and 5 for leaf locations and Table 2 for a summary of the differences in leaf temperatures when irrigation was occurring]. Notice periodic departures of leaf temperatures on the tree upward from what may be assumed to be ambient temperature traces exhibited after the irrigation discontinued at 11:24 PM.

Table 2. Leaf temperature differences in °F between locations plotted in Figures 1 and 5 for the period 10:48 PM through 11:25 PM EST, February 25, 1989. Ave indicates the average difference; Max the maximum difference; Min the minimum difference. SD stands for the standard deviation from the mean difference.

	Tx-Ts	Ty-Ts	Tw-Ts	Tx-Tc	Ty-Tc	Tw-Tc
Ave	3.0	1.0	3.4	4.3	2.4	4.7
Max	7.7	5.2	5.0	9.7	7.0	6.5
Min	0.4	–0.4	1.8	0.5	–0.7	1.8
SD	2.2	1.3	0.8	2.4	1.5	1.3

Other environmental observations. Wind speeds never exceeded 3 mph even at the 10 ft. level and included frequent periods during which the anemometers at the 5 ft. level were stalled (less than 0.3 mph). Wind drift varied from ENE to the WSW as observed by watching the plume from the water heater, with the most frequent drifts from the NW. Inversion strength ranged from 1.8 to 6.8°F, averaging 3.8°F with a standard deviation of 1.0°F from 9 PM to midnight, 25 February 1989. Dew points of 33°F and 29°F were measured in SE near 9:15 PM with a sling psychrometer and with the Bendix psychrometer respectfully.

Water flow rates were estimated to be 1344 gph flowing to both blocks. The average increase in water temperature flowing through the water heater during the period, 10:15 PM-11:15 PM, was 61.17°F. Heat supplied to the irrigation water was estimated to be almost 0.7 million Btu/hr. The total acreage for SW and SE is 1.65 acre permitting an estimate of the heat added per acre to be about 462,000 Btu/acre/hr for the SW zone and 367,000 Btu/acre/hr for the SE zone. For comparison, 35 orchard heaters burning 0.5 gph would have added 2 million Btu/acre/hr. So the temperature effects observed are with the addition of only 19% in the case of the SW zone and only 15% in the case of the SE zone of the heat typically applied with orchard heaters.

Condensation effect suggested. Water vapor is much lighter in weight than dry air. Moist air parcels are buoyant and tend to rise just as plumes from orchard heaters do except on a much smaller scale (14). The result is a mixing of parcels of moist air with drier air, an unstable flow. While the fluctuations of the vapor content of the passing air parcels was not viewed directly from data acquired, the fluctuations of temperature suggest that there are much larger fluctuations in characteristics of the air parcels affecting the leaf temperatures during the period when the heated irrigation water was being applied than during the adjustment period following the cutoff of the heater and the irrigation. The turbulent nature of the leaf temperature traces shown in Figure 6 suggest unstable transport of heat from the sprinkler to the leaves by a process which seems likely to involve enhanced evaporation near the nozzle, i.e. at the surface of the warm sprinkler droplets and later condensation of the resulting invisible water vapor. This process is diagramed in Figure 7.

The implication of the scenario described above is that the mechanism through which undertree sprinklers provide protection for fruit trees is revealing itself. Attention can be focused on the effect that water temperature has on evaportaion rates from sprinkler droplets and then onward to the effect of enhanced humidity on vertical transport upward into the tree. Ultimately the likelihood that water vapor will condense on leaves and twigs can be estimated from observations of leaf and twig temperature in the tree canopy. Ability to vary the irrigation water temperature is a welcomed tool in the design of undertree irrigation protection experiments.

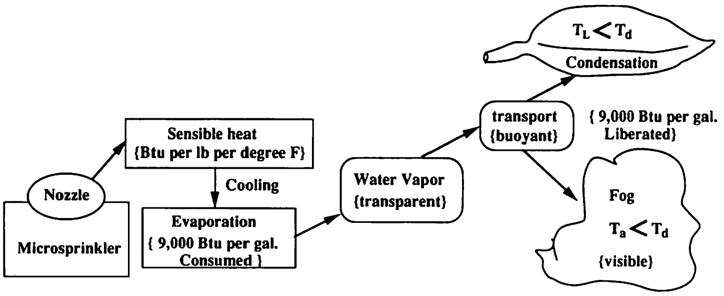

Fig. 7. Diagrammatic concept: hot water warms the air through which it is sprayed. Evaporative cooling takes place where heat is available to support it, i.e. near the microsprinkler nozzle, and this evaporation cools the sprayed droplets as well as the adjacent air. Evaporated water replaces air parcels with water vapor which tends to rise up into the canopy. This invisible plume leans with the drift. The water vapor remains in motion until it either condenses to a fog droplet or finds a surface, such as a leaf, below the dewpoint temperature on which it condenses to water droplets [dew]. Condensation liberates the heat of evaporation either to the air [adding to its buoyancy] or to the leaf [adding to its temperature]. When the temperature of the leaf is below freezing the heat of fusion is also liberated as frost is formed. Heat added to irrigation water may be envisioned as enhancing these mechanisms.

Summary. The presence of a microsprinkler system and associated irrigation water heater in a small orchard on the main campus of the University of Florida provides an opportunity to observe the results of operating such a system during frequent freezing periods that characterize Gainesville's climate. One such period is analyzed during which the temperatures were at or just above freezing so that the effect can be isolated to condensation without the complication of heat liberated by ice formation. Leaf temperature modification near the sprinklers [one per tree] were on the order of those experienced when using 5 or even 10 times the amount of oil in orchard heaters [ignoring in this simple comparison the energy used in pumping the water]. This is not unexpected since it has been accepted for some time that a larger number of smaller fires would improve the efficiency of orchard heating. This is but the first of a series of observations that may be expected from the described facility.

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TENSIOMETERS FOR IRRIGATION SCHEDULING IN A FLORIDA CITRUS GROVE

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Abstract. **Many growers have expressed distrust in the use of tensiometers for irrigation scheduling in citrus [Citrus sinensis (L.) Osb.] groves. Our observations, however, show that tensiometers are reliable indicators of soil moisture conditions within the citrus root zone and are an accurate method for scheduling irrigation. Observations were made at six tensiometers stations on an eight year old orange grove with a spray emitter type trickle irrigation system and a uniform soil type. Six, eighteen and thirty-six inch (15, 46 and 91cm, respectively) length tensiometers were used. With few exceptions, the tensiometer data from all six stations revealed similar information. Under the conditions found at this grove, the 6 inch depth tensiometer provided the best information for irrigation scheduling. It was necessary to have tensiometers both inside and outside the wetted area of the irrigation system in order to assess the effects of rainfall.**

The two key questions about irrigation which every grower must answer are: "When is it time to start irrigation?" and "When is it time to stop irrigation?" These are difficult questions to answer in a precise way. Crop water budgets, evapotranspiration estimates and other scheduling methods are good planning tools which give the growers valuable information. However, these methods fail to give clues as to whether the schedule is working or not and rely on the grower being able to recognize when adjustments need to be made.

Citrus growers need a more precise way of determining when to start and stop their irrigation systems. The ethics and economics of water conservation convince most growers that over-irrigating is not desirable. On the other hand, the purpose of having supplemental irrigation is to ensure good yields by applying sufficient water to the crop when needed.

Soil moisture availability has been a common way of assessing the crop water status in many crops for many years. Several reliable scientific tools exist to measure soil moisture (2), however, many require a high degree of skill to operate and are time consuming to set up and read. In

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