Infrared Radiation Shields for Cold Protection of Young Citrus Trees[1]

J. David Martsolf[2,3] and John F. Gerber,[2]
University of Florida, Gainesville

Abstract. Aluminum-foil-surfaced shields were evaluated with individual citrus trees. These shields, highly reflective in the infrared, moderated leaf temperatures by interrupting their radiant heat loss. A horizontal shield over an individual tree provided about 1° F of cold protection on clear and relatively calm nights. Temperatures of shielded and unshielded leaves were not affected by moderate wind drift or position on the tree. Radiant cooling may induce air flow over the tree that tends to convectively equalize leaf and air temperature. Large differences did not occur between leaf temperatures on adjacent trees. Neither position nor replication produced large temperature differences between leaves at night. Analysis of the heat balance in quasi-steady state indicated that 1° differences were reasonable and that small radiation shields cannot be expected to provide more protection than the amount that leaves are radiantly cooled below air temperature.

INTRODUCTION

RADIANT heat loss cools exposed surfaces on clear nights. Blocking this radiation by a shield should increase the heat loss and moderate leaf temperature. Clouds are examples of natural shielding from a cold night sky (1).

Data from California indicate that a small shield (40 cm × 50 cm) placed 50 cm above the tree caused citrus leaf temperatures to change from about 1.8°F below air temperature to near air temperature (2). The use of "brushing" materials as radiation shields on vegetables has provided frost protection (7). Experiments with plastic enclosure (7 ft sq) with 6 ft plastic sides, revealed that the condensation of water on the film rendered it virtually opaque to infrared radiation (14). These shelters provided 2 to 7° of protection by moderating both radiative and convective heat loss. An opaque paper tent of similar size over small citrus trees provided only 2° of protection in California (1). A 4-ft-wide plastic strip rolled out over a horizontal trellis resulted in a 3° protection to grape vines on clear nights (10).

Banking small citrus trees with soil is the only widely used practice for non-bearing citrus in Florida (6). This practice provides protection below the soil line from death only. Small citrus trees were observed to be more susceptible to frost damage than mature trees (13). There is a need for an economically feasible method that will protect small trees.

MATERIALS AND METHODS

Two experiments were conducted to determine the effects of infrared shielding upon the microclimate of small citrus trees. The first experiment was conducted in Highlands County, Florida, in a grove of 4-year-old 'Valencia' oranges, *Citrus sinensis* Osbeck, budded on rough lemon, *C. jambhiri* Lush set 25 by 25 ft. The soil was Lakeland fine sand, cleanly cultivated. The site was practically flat with a slight slope toward the east, and was bordered by older groves on the north and west, and by open fields on the east and south.

The second experiment was conducted in a grove on the campus of the University of Florida at Gainesville. The trees were 5-year-old 'Owari' satsumas, *C. reticulata* Blanco, budded onto *Poncirus trifoliata* (Lynn.) Raf., set 15 by 30 ft on Arredonda loamy sand. The grove was cleanly cultivated. Both sites were rather typical of young groves in the surrounding area.

Temperatures were measured with 24 gauge copper-constantan thermocouples and a 20-point potentiometer with automatic reference junction compensation. Thermocouples for measuring leaf temperatures have been reviewed by Waggoner and Shaw 15. They have been criticized because of radiation errors (2, 3); however, the nocturnal radiant flux density is an order of magnitude smaller than the daytime densities, thus radiation errors at night are small. The thermocouples used are shown in Fig. 1. Leaf temperatures were measured by taping the thermocouple to the underside of the leaf. This method was found to be more satisfactory than those of Lorenzen (8) and Eggert (4).

Air temperatures were measured with thermocouples mounted vertically below a cardboard shield, 4½ ft above bare soil in the middles between trees. Twig temperatures were measured by pressing a sharpened thermocouple beneath the bark next to the cambium on the upper surface; soil temperatures were measured by pressing thermocouples into the soil to a depth of 1 inch; fruit temperatures were measured by inserting a sharpened thermocouple ½ inch into the fruit. In the second experiment, only leaf temperatures were measured.

The experiment was designed so that the positions of the thermocouples on each tree were chosen from 4 adjacent trees at random by dividing each tree into 5 sections (Fig. 2). The position of the thermocouple and the recorder sequence were chosen randomly.

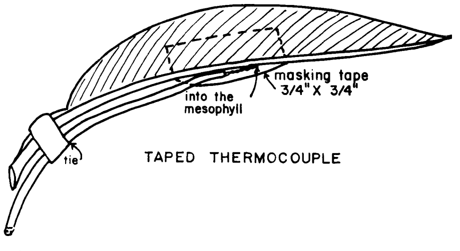


Fig. 1. Cross sections of citrus leaves with the thermocouple and leaf prepared for nocturnal leaf temperature measurement.

8. Schmidt, B. L., and Triplett, G. B., Jr. 1967. Controlling wind erosion. *Ohio Rep. Res. Develop.* 52:35–37.
9. Skidmore, E. L. 1966. Wind and sandblast injury to seedling green beans. *Agron. J.* 58:311–315.
10. Whitehead, F. H. 1963. Experimental studies of the effect of wind on plant growth and anatomy. III. Soil moisture relations (*Helianthus annuus*). *New Phytol.* 62:80–85.
11. Woodruff, N. P. 1956. Wind-blown soil abrasive injuries to winter wheat plants. *Agron. J.* 48:499–504.
12. Zingg, A. W. 1950. The intensity-frequency of Kansas winds. *USDA, SCS-TP* 88.

---

[1] Received for publication October 14, 1968. Florida Agricultural Experiment Stations Journal Series No. 3078.

[2] Research Assistant, and Associate Professor of Climatology, respectively, Department of Fruit Crops. Research completed in partial fulfillment of requirements for the MSA degree at the University of Florida.

[3] Currently Associate Professor of Agricultural Climatology, Department of Horticulture, The Pennsylvania State University, University Park.

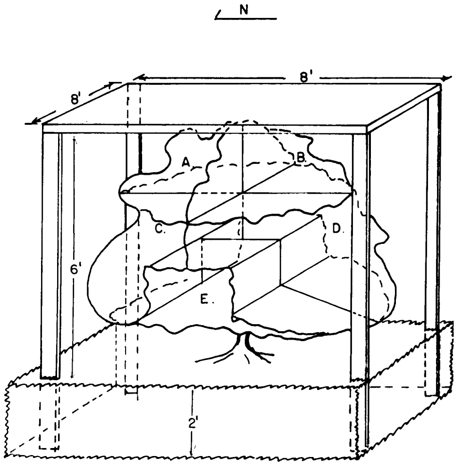
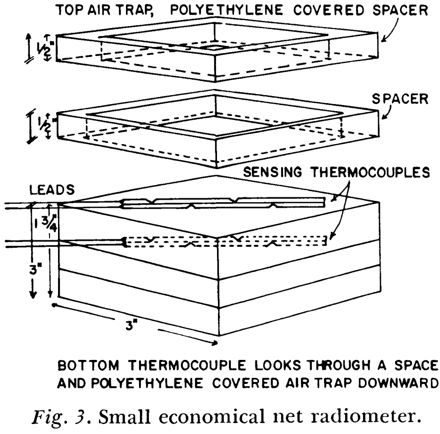


Fig. 2. Diagram of the radiation shield resting on four posts over a tree. The tree is subdivided into sections for randomized leaf temperature measurement.

The shields could be placed over either 2 of the 4 trees, and could be alternated from night to night. The radiation shields were constructed of heavy duty, highly reflective (12) aluminum-foil cemented to one side of hardboard sheets. They were 8 ft square and supported above the trees by means of posts with the foil covered surface facing downward (Fig. 2). In the first experiment, the shields were 8 ft above the ground, but in second, only 6 ft. The shields were installed at sunset and removed at sunrise.

Comparisons were made of leaf temperatures of 2 trees, 1 shielded and 1 unshielded in the first experiment, and in the leaves of 4 trees, 2 of which were shielded and 2 unshielded in the second experiment.

The differences in radiant heat loss were measured by 2 net radiometers (11) constructed with styrofoam bodies. The radiometers construction is shown in Fig. 3. A small, fan-driven heater blew warm air across the top of the unshielded radiometers to prevent dew and frost formation on the polyethylene film. The temperature of the sensors in the 2 radiometers agreed to within ½° when exposed simultaneously over a homogeneous surface.



BOTTOM THERMOCOUPLE LOOKS THROUGH A SPACER AND POLYETHYLENE COVERED AIR TRAP DOWNWARD.

Fig. 3. Small economical net radiometer.

Results and Discussion

Cold protection value. The difference in leaf temperatures between shielded and unshielded trees was referred to as the cold protection value. The magnitude of the protection provided when leaf temperatures were near minimum temperatures was of greatest interest (Table 1). Approximately 1° of protection was provided by the 8 ft square shields. The night of March 6, 1967 was an exception in which the value was decreased approximately 50% by wind. The mean differences for DeSoto City in Table 2 are differences between 4 sets of leaf temperatures in 2 trees, one shielded and one unshielded. Those for Gainesville are differences from 10 sets of leaf temperatures in 4 trees, 2 shielded and 2 unshielded.

Table 1. Cold protection value averaged over the coldest hour of the night.

Location	Date 1962	For hour beginning at[a]	Wind observed during hour	Cold protection value[b] (°F)
DeSoto City.	Jan 3	0230	Calm	1.1**
DeSoto City.	Jan 4	0240	Calm	1.0**
DeSoto City.	Jan 13	0300	Calm	1.0**
Gainesville...	Mar 6	0610	Gusty	0.6**
Gainesville...	Mar 7	0630	Light	0.9**
Gainesville...	Mar 8	0640	Calm	1.0**

**The cold protection values are significant at the .01 level.

[a] The minimum temperature for the night occurred during the last quarter of this hour.

[b] Cold protection value ≡ leaf temperature difference ($\bar{T}_s - \bar{T}_u$), where $\bar{T}_s$ = the shielded-leaf temperatures averaged overtime (1 hr) and $\bar{T}_u$ = the unshielded-leaf temperatures averaged over the same period as was $\bar{T}_s$.

Shielded fruit temperatures averaged 1.5° warmer than unshielded fruit. During the coldest hours, these differences were smaller, about 1.2°. Twig temperatures followed air temperature closely in both the shielded and unshielded trees. The shielded twigs averaged only 0.1° higher than the unshielded twigs. Air temperature fluctuated more than the shielded leaf temperature but averaged nearly the same over periods of an hour or more. During the coldest hour, leaf temperatures were 1 to 2° below air temperature. Earlier in the night, this difference was often greater than 2°. The soil temperatures at points ½ inch beneath the surface differed by 24°; being 10° below air temperature in the unshielded plot and 14° above air temperature in the shielded plot. The loss of heat from the soil surface beneath the tree was greatly modified by the shields. This was consistent with the radiometer measurements (Table 2). The leaf temperature response to this reduction in radiant heat loss was much smaller than that of the radiometer or the soil surface (both having little convection affect) which implies that the leaf temperature must be strongly influenced by convective heat flow even with light winds.

Table 2. Ratio of the net radiant energy loss from the unshielded tree to that from the shielded tree in Experiment 1.

Date 1962	Ratios	
	For entire night	During hour of most rapid temperature fall
Jan 2–3.........	17	20
Jan 3–4.........	4	15
Jan 12–13.......	100	50

Comparisons of leaf cooling rates for shielded and unshielded trees. Fig. 4a, b, and c, describe time-temperature relations for one set of leaves every 10 min. The vertical distance between the curves decreased from about 2° to approximately 1° as the night progressed. The minimum leaf temperatures occurred just prior to sunrise on radiation nights. In Fig. 4a, the effect of fog formation which moved into the plot about 4:30 AM is in evidence. In Fig. 4b, a thin mist that gradually grew into a ground fog arrested the temperature fall during an otherwise clear night. A breeze that suddenly developed turbulent mixing of the stratified morning air was responsible for the temperature rise at 4:00 AM in Fig 4c. Air temperature was not plotted in these figures since it overlies the shielded leaf values.

Regardless of differences between nights the 1 or 2° temperature differences persisted, Fig. 4. In over 1,700 leaf temperature comparisons made in 2 locations there was not a single instance in which the shielded leaves were colder than the unshielded leaves.

Leaf temperature differences. During the coldest hour of the first 3 nights 6 temperatures for each leaf were averaged over the hour (Table 1), the resulting 24 averages were subjected to an analysis of variance. A highly significant F ratio, i.e., less than .005 probability of a larger F, was indicated for both treatments and night differences and replication means were nonsignificant. The 1° cold protection value persisted through all 3 nights even though the

Table 3. Average leaf temperature (°F) for the coldest hour Experiment 1.

Treatment	Jan. 2–3	Jan. 3–4	Jan. 12–13	X̄
Shielded.........	36.9	31.3	28.1	32.10
Unshielded......	35.7	30.3	27.1	31.03
Difference.......	1.2	1.0	1.0	1.07
X̄..............	36.3	30.8	27.6	31.58

Treatments lsd (.01) = 0.45°F.

Table 4. Analyses of variance indicating significant differences in leaf temperature due to shielding.

Date	Variant	DF	F
Mar 5–6	Treatments	1	28.54*
	Positions	4	2.30
	Replications	1	8.36**
Mar 6–7	Treatments	1	37.23**
	Positions	4	1.46
	Replications	1	1.37
Mar 7–8	Treatments	1	144.51**
	Positions	4	6.45**
	Replications	1	11.15**

* = significance (0.05 level).
** = high significance (0.01 level).

Table 5. Influence of position on tree upon leaf temperature during 2 calm and clear nights.

Positions	Mean Temperatures	
	February 27–28	March 7–8
a...........	66.38 ab	39.89 a
b...........	66.45 a	39.42 ab
c...........	66.16 b	39.04 b
d...........	66.31 ab	39.22 b
e...........	66.24 ab	39.26 b

hourly mean temperatures were progressively colder (Table 3). The F ratio for the interaction mean squares for nights versus treatments is only 0.16. The least significant leaf temperature difference was 0.45° while the average effect for the coldest hour for 3 nights was slightly more than 1°. Three consecutive nights, March 5–8, were used to test the effect of the shields on leaf temperature (Table 4). During the first and third nights, trees 1 and 3 were shielded; trees 2 and 4 were shielded on the second night. Although all 3 nights were clear, the first night the wind speed varied from high on March 5–6, to moderate on March 6–7, to light (calm) on March 7–8.

Very little variation was noted between the 4 replicated trees in the second experiment except for positions. There was a significant difference between positions within the trees (Fig. 2). Results of Duncan's test for positional differences on the radiantly cooled night of February 27–28 indicate that position "b" differed from position "c" (Table 5). This result was expected since the first position was the southern top of the tree while the latter was the northern skirt of the tree. On the cooler night of March 7–8, position "a", the northern top of the tree, was significantly warmer than skirt positions "c" and "d" and than the interior position "e". The magnitudes of these differences average less than 1°. Air density differences created by radiational cooling of leaves near the top of the tree would increase air motion and thus convective heat exchange with the air, warming them to near ambient air temperature. Thus, radiational exchange sets in motion other transfer mechanisms which tend to destroy the differences caused by radiational cooling.

Nocturnal density flow theory. The results support a theory of the interaction of convective and radiative heat exchanges in calm, clear nights. Surfaces of exposed leaves lose heat by radiation and tend to drop below the ambient air temperature. The density differences of air cooled by the leaf surfaces develop eddies which sink, sliding off the top surfaces of exposed leaves, over leaves beneath them until they are dissipated by entrainment of surrounding air or exchange of heat with leaves and twigs. This may be a continuous process but more likely has a pulsating nature. As the velocity of this density flow increases, the shear between the sinking eddies with their environment creates turbulence which in turn destroys the density gradients which had initiated the flow. The net result of the eddies cascading from radiatively cooled leaves may be to partially destroy the stratification of temperature that would exist above bare ground. This disruption of the nocturnal inversion has been borne out by temperature profiles in orchards (9).

The leaf temperature differences obtained are not great and while significant may at first glance appear trivial. Certainly if the 1° differences

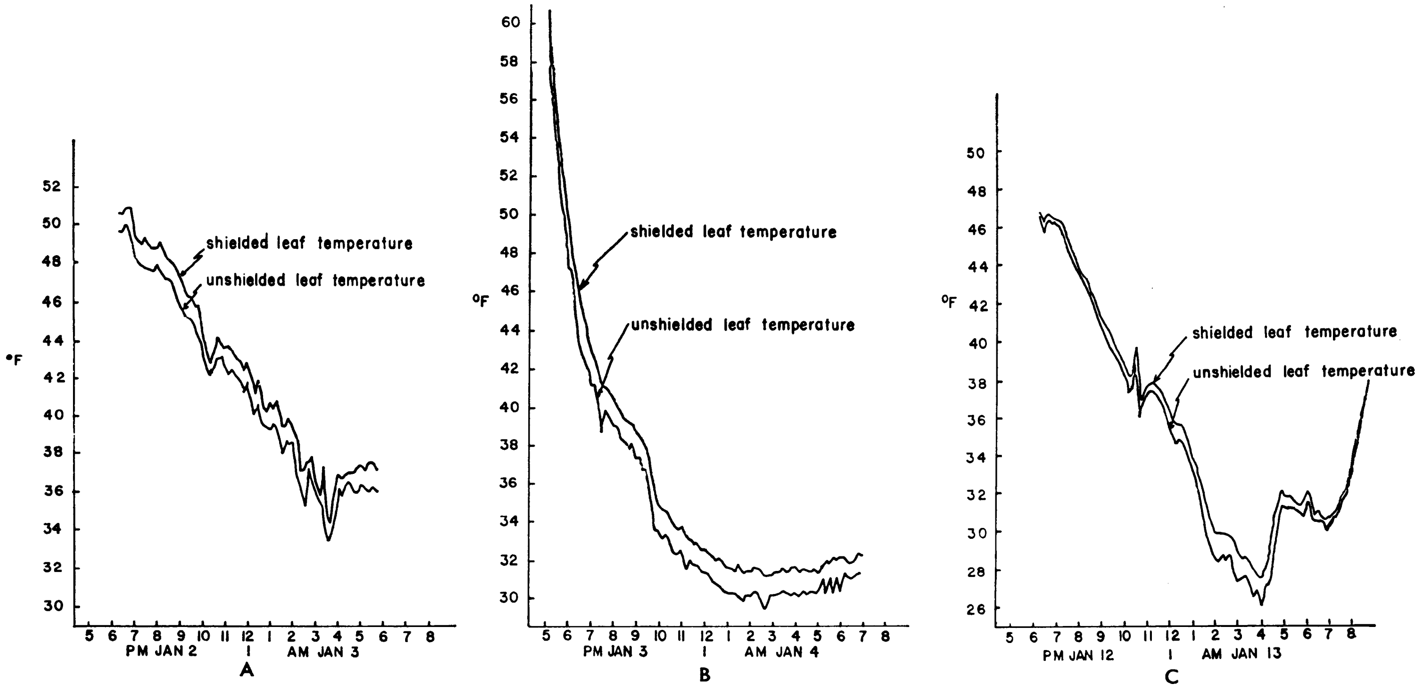


Fig. 4. Temperature-time plots for shielded and unshielded leaves.

were the only result obtained they could be dismissed.

The density flow theory may be used for an explanation on the relatively small differences between air temperature (T_a) and unshielded leaf temperature (T_u), observed to be about 2° in the early evening and 1° near dawn. The dependence of shielded leaf temperature (T_s) upon the temperature difference, ($T_a - T_u$), may be developed by considering the convective heat exchange (Q) between the unshielded leaf and the air:

$$Q = 2h_c(T_a - T_u) \qquad (1)$$

and the convective heat exchange between the shielded leaf and the air:

$$Q' = 2h_c'(T_a - T_s) \qquad (2)$$

where: Q and Q′ are the convective heat transfers between the unshielded and shielded leaf and the air respectively,

and h_c and h_c' are the coefficents of convection for the unshielded and shielded leaves respectively. The constant, 2, describes both sides of the leaf.

Assuming steady state, negligible latent heat transfer, negligible heat storage, i.e. quasi-stable leaf temperature, the energy balances for the leaves can be indicated as:

$$R_n = Q \quad \text{and} \quad R_n' = Q' \qquad (3)$$

for the unshielded and shielded leaves respectively,

where: R_n and R_n' are the net radiant energy fluxes at the locations of the unshielded and shielded leaves in that order.

By defining $\alpha = R_n/R_n'$, and $\beta = h_c/h_c'$ *(4) (5)*

and by substituting *(1)*, *(2)*, *(3)* and *(5)* into Equation *(4)*, one may solve for the shielded leaf temperature.

$$T_s = T_a - \frac{\beta}{\alpha}(T_a - T_u). \qquad (6)$$

If α approaches infinity, while β takes on any reasonable value, the last term in Equation (6) goes to zero and the shielded leaf temperature (T_s) approaches the air temperature (T_a). Another test is to let α go to unity indicating that there is no shielding from radiant loss. There are no reasons to expect β to differ from near unity under these conditions resulting in T_s equal to T_a. The reasonableness of these limits suggests that Equation *(6)* may adequately describe the observed temperatures when observed values of α, T_a and T_u are substituted. Assuming $\beta = 1$, $T_a = 30°$ and letting α range from 4 to 100 (Table 2) results in T_s ranging from 29.75° to 29.99°. The protection due to shielding, ($T_s - T_u$), ranges from 0.75 to 0.99. The close agreement between this and the observed protection of 1° is submitted as support for the theory of convective destruction of temperature gradients between the leaf and air.

For the case, $\alpha > \beta$ Equation *(6)* can can be used to predict that the protection provided by shielding, ($T_s - T_u$), would be limited to a magnitude no greater than ($T_a - T_u$) or about 1° near dawn in this study. The case in which α becomes a negative, indicating that the shielded leaf is experiencing a net gain in radiant energy while the unshielded leaf is losing energy by radiation, would admit a T_s greater than T_a. However, as a ($T_a - T_s$) gradient developed the convective exchange would be expected to limit it also. It would be difficult to envision ($\alpha < 0$) unless the reflective shield was mirroring a heater or shielded warm soil between the trees.

Thus, small shields alone cannot be expected to provide much more protection than the amount that leaves are radiantly cooled below air temperature. In the cases studied this protection was observed to be 1°F near dawn.

LITERATURE CITED

1. BROOKS, F. A. 1959. An introduction to physical climatology, University of California. Davis, California, pp. 133–146.
2. CURTIS, O. F. 1936. Leaf temperatures and the cooling of leaves by radiation. *Plant Physiol.* 11:343–346.
3. ————. 1938. Wallace and Clum "Leaf temperatures" a critical analysis with additional data. *Amer. J. Bot.* 25:761–771.
4. EGGERT, R. 1946. The construction and installation of thermocouples for biological research. *J. Agr. Res.* 72:341–355.
5. GATES, D. M., and C. M. BENEDICT. 1963. Convective phenomena from plants in still air. *Amer. J. Bot.* 50: 563–573.
6. GERBER, J. F., and J. D. MARTSOLF. 1965. Protecting citrus from cold damage. *Univ. of Fla. Agr. Ext. Cir.* 287,29 pp.
7. HART, S. A., and F. W. ZINK. 1957. Brushing and brushing materials for frost protection. *Proc. Amer. Soc. Hort. Sci.* 69:475–479.
8. LORENZEN, C. 1949. The thermocouple in agricultural research. *Agr. Engr.* 30:275-279.
9. REESE, R. L., and J. F. GERBER. 1963. Field trials with a wind-machine in a citrus grove. *Proc. Fla. State Hort. Soc.* 76:81–86.
10. SCHULTZ, H. B. 1961 .Microclimates on spring frost nights in Napa valley vineyards. *Amer. J. Enology & Viticul.* 12(2):81–87.
11. SUOMI, V. E., and P. M. KUHN. 1958. An economical net radiometer. *Tellus* 10: 160–163.
12. TANNER, C. B. 1963. Basic instrumentation and measurements for plant environment and micrometeorology. *Univ. of Wisc. Dept. of Soils Bul.* 6, p. A 15.
13. TURRELL, F. M., and S. W. AUSTIN. 1965. Comparative nocturnal thermal budgets of large and small trees. *Ecology* 46(1 & 2):25–34.
14. WAGGONER, P. E. 1948. Protecting plants from the cold, the principles and benefits of plastic shelters. *Conn. Agr. Exp. Sta. Bul.* 614:1–36.
15. ————, and R. H. SHAW. 1952. Temperature of potato and tomato leaves. *Plant Physiol.* 27:710–724.