Heat Transfer in Citrus Groves

frost protection studies of effectiveness of wind machines alone and in combination with heaters

F. A. Brooks, C. F. Kelly, D. G. Rhoades, and H. B. Schultz

The economic value of frost protection directly depends upon the productivity of the orchard—in quantity and quality. No close averages are available but it can be assumed that the citrus grower who has to heat more than six or seven nights a year probably is losing money on frost protection.

The use of wind machines for frost protection—economical by virtue of drawing on the warm air usually found above tree tops in typical radiation frosts—has greatly expanded since World War II largely because the operating cost is about one fifth that for heaters. Field studies of actual expenditures for frost protection using heaters and using wind machines in Los Angeles County show heating to cost about $3.60 per acre hour; wind machines alone $0.55; and a combination of wind machines plus heaters about $0.67 per acre hour.

When the 2° F or 3° F temperature rise obtained by machine under ordinary conditions is insufficient, the firing of 8 to 15 heaters per acre—instead of 25 to 50—usually supplies an extra degree or two. Thus the combination of machine plus heaters meets the usual radiation frost conditions in California so well it is now the accepted system for economical frost protection.

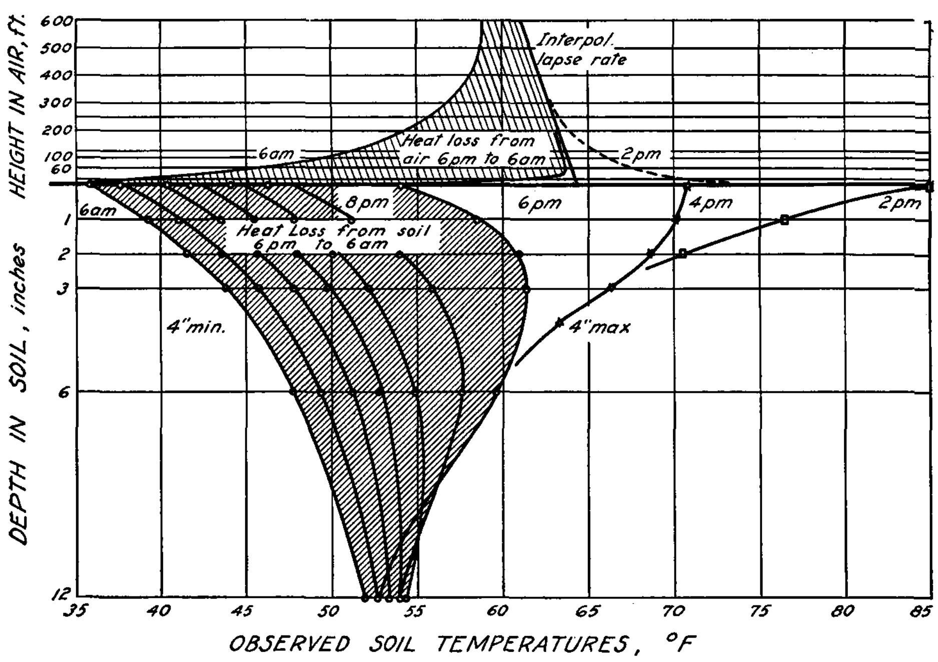
Radiation Cooling to the Sky

The earth's atmosphere as a heat source radiating back to the ground restricts typical radiation frosts in citrus areas to those few calm nights having cold dry atmosphere aloft.

The frost warnings are always qualified with a proviso of no cloudiness—other than thin high clouds—because a water-droplet cloud if present acts as a radiation shield and when at low level, itself radiates at a temperature not much colder than the daytime air temperature. With the arrival of low clouds the ground surface temperature rises because the previous chilling due to full radiation loss is too much for the lessened net radiation demand of the sky.

One of the oldest proposals for reducing frost is by area-wide cloud screening to reduce long-wave radiation loss. This would be of direct effect, but the necessary large-particle fog generators are not yet available.

Bi-hourly sweep of soil temperature profiles observed at Riverside, February 24, 1939, during typical nocturnal radiation cooling. Corresponding air temperatures are shown at a scale reduction 1500 to 1 to indicate the same heat capacity per unit area on the graph. The shaded areas show that about four times as much heat comes from the ground as from the air. If the soil were covered with snow or a mulch blanket insulating the stored heat, most of heat lost by radiation would come from the air, and the surface would be much colder.



Conduction from the Ground

Next in importance for heat balance in the orchard is the heat flow from the ground, as the ground is the major source of supply for heat radiated to the sky.

Since in average February weather the soil temperature at one-foot depth is at least 20° F above freezing, there can be no frost until the surface soil temperature is about 20° F lower than the average in the soil, that is, when the gradient exceeds about 20° F per foot. The illustration on this page shows how temperature gradients establish themselves to the degree necessary to meet the heat demand. The progressive cooling is indicated by the two-hour lines. After a spell of clear cold, windy weather, the deep soil temperature may be only 10° F above freezing, and then frost could occur with half the average gradient.

Convection from Overhead

The heat flow from overhead air by eddy-convection downward follows much the same pattern as heat flow from the ground. Because of daytime heating, the air from 100 feet above ground to a few thousand feet is usually more than 20° F above freezing. Thus if there is powerful eddy-convection, as in a wind, heat is available from such a huge depth of air that there is no frost hazard except in major freezes when the air itself is down to freezing. And, conversely, on very calm nights of excessive stability, there is very little eddy-convection, and a thin layer of air near the ground quickly drops in temperature because of the inherently small heat capacity of air. How the air heat supplements the ground heat in meeting the net sky radiation demand can be seen in columns 1 and 2. The decrease in surface temperature applies to both soil and air so a high thermal conduc-

Continued on page 14

TRANSFER

Continued from page 5

tivity for one automatically decreases the temperature gradient needed in the other. Ordinarily, in sheltered southern California citrus areas during radiation frosts the air by convection and short range radiation will furnish only 20% to 25% as much heat to the cold sky as the ground does. If wind machines could change the natural eddy-convection rates overhead, the air heat contribution might be increased artificially, but their effect on downward eddy thermal convection from overhead air has yet to be calculated.

The heat capacity of the trees is limited by such a small average size of branch that there is very little time lag in the diurnal temperature waves. The main effect of tree material is the heat made available hour by hour which saves the soil heat a little. While cooling 1° F per hour a nine-year old orchard provides about 10% of the radiation demand, and since this will increase with tree weight, it may be a significant reason for older orchards being less susceptible to frost damage.

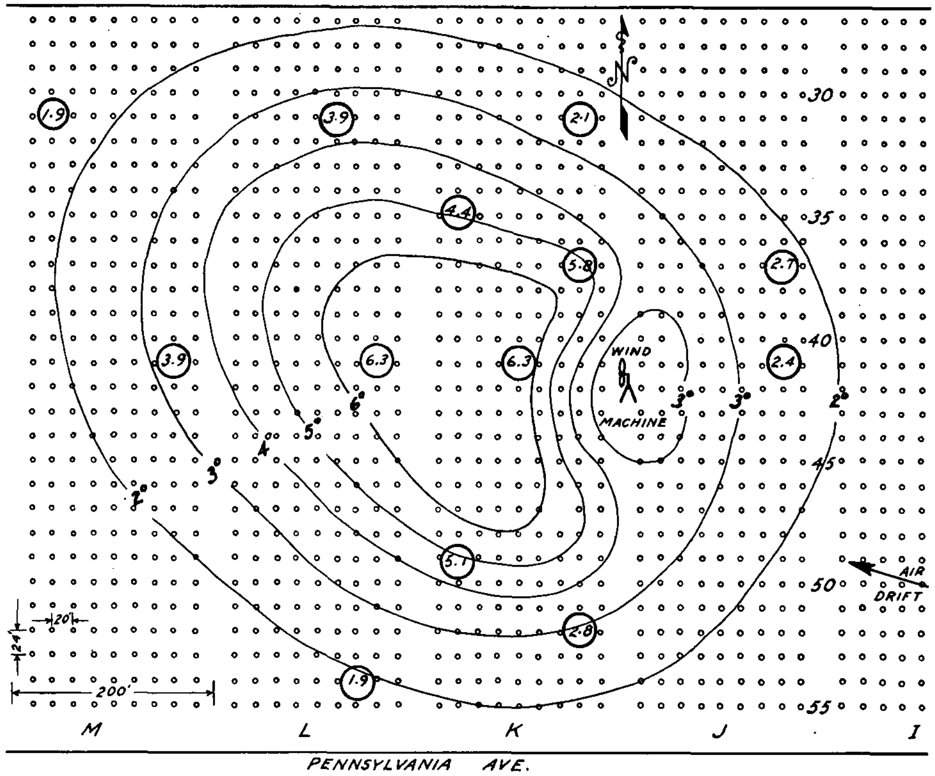
Condensation and Freezing

Change of phase of moisture is often a noticeable source of nocturnal heat. The rate of hourly cooling is usually slow and steady on a night of high dew-point, and there is often a dwell of a half hour or more at 32° F, while in a black frost the temperatures usually drop rapidly and are unsteady. The slower cooling is due mostly to increased back radiation from the more moist atmosphere. The temperature steadiness in the moist air is largely due to stronger water-vapor radiation exchange over short distances.

The heat evolved by formation of dew in lowering the dew-point from 40° F to 32° F—for example—is only about 8 Btu per square foot for an air layer 60 feet thick. If this takes four hours it is only about one tenth the sky radiation rate. This may mean, however, a 2° F or 3° F higher minimum temperature because of the usual 20° F to 30° F temperature gradient. When the dew turns to frost the latent heat of freezing this quantity of dew is about 1 Btu per horizontal square foot, which is equivalent to 1° F in a total of 20° F gradient. If this occurs in one hour it counteracts the usual 1° F drop and explains the expected dwell.

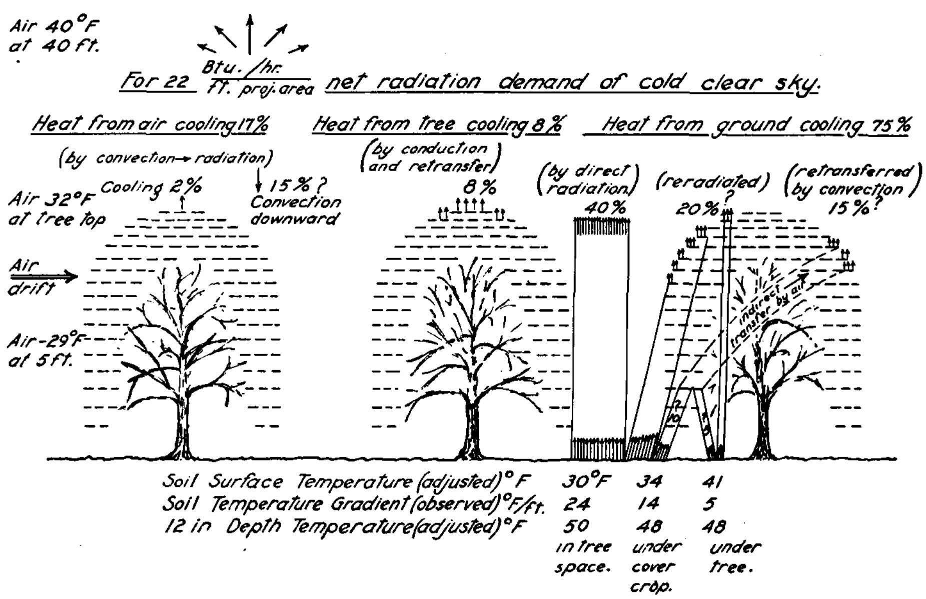
Wind Machine and Heaters

Wind machines pumping warm air downward deliver more heat into isolated tracts than comes by natural eddy-convection. But by the square mile, unless multiple wind machines bring down heat from higher in the air than natural eddy-



AREA RESPONSE TO WIND MACHINE, Deg. F

The area response single wind machine alone on a 14° F inversion night shows a 2° F protection of 9½ acres. The acreage protected 3° F is substantially reduced because of the cold area around the base of the wind machine but down drift there is strong protection—4° F—for 3.3 acres.



Estimation of heat flow inside a citrus orchard. The average outgoing radiation lost is assumed at 22 Btu/hr/ft²—British thermal units per hour per square foot. Of the total heat some 75%—*right*—would come from ground cooling. About 40% of this would go directly from the exposed soil surface to the sky, 20% by indirect radiation, and 15% indirectly by convection currents to the tree tops. Some 17% of the heat—*left*—would come from air cooling. About 15% of this comes by eddy-convection downward from above the orchard and 2% by cooling orchard air. The cooling of the trees as solids would account for the remaining 8%—*center*.

convection does—which is not yet determined—the machines are a heat source only to the extent of the heat generated by the power plant. Thus it seems likely that the main benefit of area-wide use of wind machines is modification of the natural profile and more uniformity in orchard temperatures.

Significant responses from wind machines depend more directly on temperature inversion than do heaters, and are probably more sensitive to variation in air drift velocity.

Riverside Tests

Test field No. 2 at Riverside—where the 1951 tests were made—is in a region of moderate-to-fast air drift, so a continuous record of temperature profiles and of air-drift velocities and directions was needed.

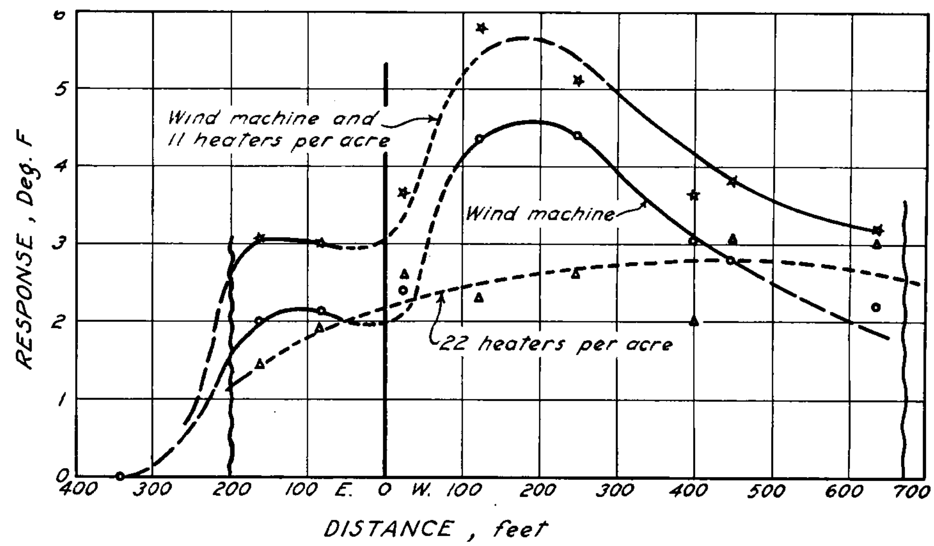
Air temperature observation levels were at 20″, 80″, 16′, 26′, 40′, and 65½′. Soil temperatures were measured at –⅜″, –4″, –20″ and about –60″. Six heat-flow plates were at –⅜″; the radiometers were at 20 feet; and the sensitive cup anemometers were at 80″, 26′, 45′, and hot wire anemometer at 60′. All these stations covered about 10 acres. Outside reference stations also were essential so the installation was about 1400 by 1800 feet.

The major reference station, A-1, is 950 feet farther east of A2 a little north, has the same elements excepting the radiometers. Two reference stations, B1 and B3, 700 feet north and 625 east have 40-foot masts for air temperatures and velocity.

To get an average measure of orchard response five additional 40-foot masts were installed and 22 trees were equipped with four couples at 80″ and two in the tree tops at 16 feet. All the tree thermocouples were mounted approximately one third the distance through the foliage from outside toward the hollow center. To avoid servicing 30-odd ice-baths the reference junctions were buried in the ground about 60 inches deep. Then with several miles of multiple-conductor cable, 116 pairs of leads were brought to nine automatic recorders in the field house.

Conditions at Riverside on calm, clear nights were typical for radiation frosts, but rarely were steady. The most significant disturbance was due to an erratic gravity flow of cold air.

The outside station, B-2, 700 feet south in an open field proved unusable, because the air-flow was so much freer there that the 80-inch temperatures were sometimes 10° F warmer than the 80″ temperature in the orchard. Such erratic conditions at the outside station could not properly be considered as representing natural orchard conditions, so interpretation during operations were compared with the three stations in the orchard as previously described, up-drift or 250 feet to the side of the operations area. Sometimes there seemed to be pulse flow with peak velocities as large as the operation responses to be measured.



Three response curves for (1) single 90 bhp wind machine, (2) same machine supported by 11 heaters per acre, and (3) 22 heaters per acre alone. In this orchard with a strong inversion (9.8° F) the single wind machine does about as well within 450 feet as 22 heaters per acre. The combined response of machine plus 11 heaters per acre equals about 29 heaters per acre.

Two modern wind machines erected side by side for comparative tests. The whole tower top rotates slowly bringing a blast to a given direction every four or five minutes. The propellers are mounted 32 feet above ground and directed slightly downward so that the air blast penetrates the orchard about 80 feet away and produces strong low-level gusts from about 150 to 300 feet. The single electric 90 bhp machine is specially designed for down-drift operation, taking four minutes to sweep the lower 180° but skipping around the up-drift 180° in 1⅓ minutes. The dual engine machine, each operating at 65 bhp turns 40° per minute as is usual for square 15-acre tracts.

Tests were run only under typical radiation frost conditions, namely: clear sky; temperatures below 40° F at midnight; and air drift in the natural direction for gravity flow. Altogether 30 nights of tests were completed in the 1950–51 investigations.

The main differences from modification by heating is that the wind machine lowers the air temperature at the 40-foot level instead of raising it. The general effect is that successive temperature profiles tend with distance to revert to the original up-drift inversion. It is necessary, therefore, in area protection to have a machine every 600 or 800 feet to keep mixing the air as fast as the cold-stratification tends to form.

One factor needs further investigation, namely the carry-over of the chilling at the 40-foot level. This lowering does increase the temperature gradient tending to bring more heat down by eddy-convection from overhead, but unless this plus engine heat completely makes up for the heat not drawn from ground the wind machine farthest up-drift will make conditions less favorable for machine down-drift.

F. A. Brooks is Professor of Agricultural Engineering, University of California College of Agriculture, Davis.

C. F. Kelly is Associate Agricultural Engineer, University of California College of Agriculture, Davis.

D. G. Rhoades is Assistant Specialist, Agricultural Engineering, University of California College of Agriculture, Davis.

H. B. Schultz is Assistant Specialist in Agricultural Engineering, University of California College of Agriculture, Davis.

The above progress report is based on Research Project No. 400-V.