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Project No. 87-07 - Tree and Crop Research
Freeze Protection - Irrigation

Project Leaders: Dr. Richard L. Snyder
(On Sabbatical)
Cooperative Extension
Land, Air and Water Resources Department
University of California
Davis, CA 95616
(916) 752-1130

Mr. Joseph H. Connell
Butte County
Cooperative Extension
2279 Del Oro Avenue, Suite B
Oroville, CA 95965
(916) 538-7201

Personnel/Cooperators: W. Asai, J. Carroll

Objectives: (1) Study the effects of various under-tree sprinkler operation schemes on the environment within an almond orchard under a variety of freezing weather conditions. (2) Determine the effects of frost damage timing on crop yield. (3) Study methods of improving the effectiveness of frost protection with under-tree sprinklers.

Interpretive Summary: The experiments were as follows:

1) Evaluate optimal placement of hand move sprinkler lines for frost protection.
2) Study the effects of ground cover on orchard temperature during frost.
3) Attempt to artificially induce freezing conditions to develop and test a frost computer model.
4) Monitor weather during frost conditions to develop and test a frost computer model.

In experiment 1, four treatments were tested, a control with no sprinklers, and three different sprinkler spacings. Minimum temperatures were measured on a cold night in January. Air temperatures in the sprinkled areas were all 1-2° higher than in the control plots but there were no appreciable differences between spacing treatments. Soil temperatures responded more directly to treatment. The surface temperatures were colder as distances from the sprinklers increased. Plot size restrictions may have lessened differences compared to a whole orchard condition.

In experiment 2, four treatments were monitored as follows: 1) Fallow 2) 2-inch mowing height 3) 4-inch mowing height 4) uncut. The most significant observation is that the fallow treatment had the coldest surface temperature of any treatment when the soil surface had been dried by winds. To be warmer, bare ground must be firm and moist at the surface. There was actually little difference in height between the 2 inch and 4 inch treatments and there was little temperature difference between them and the uncut treatment in this experiment.

Experiment 3, the attempt to artificially frost a whole tree, was unsuccessful. Chamber design did not successfully prevent mixing of cold air with external ambient air and hence when temperatures were monitored inside and outside the chamber, minimal differences were observed. Improvements in chamber design will be necessary before this can be successful.

In experiment 4, temperatures were monitored on a frost night in a Chico, CA orchard. When sprinklers were turned on, the temperature in the sprinkled orchard increased relative to the control station outside the orchard. As light winds stopped, the temperature at the control station began to drop slightly. A 6° drop occurred within half an hour--a much greater sudden drop than expected due to cold air intrusion from an accumulation area near the nearby mountains. Benefits from sprinklers were overwhelmed by cold, dry air intruding, and temperatures along the orchard edge dropped considerably. No current freezing-temperature computer model would have predicted the observed temperature change. Unfortunately, since a combination physical-climatological model would be needed to accurately predict frost under these conditions, a separate model may be needed for individual orchards everywhere in California.

FROST PROTECTION OF ALMONDS WITH UNDER-TREE SPRINKLERS

Tree and Crop Research
Freeze Protection-Irrigation
Project No. 86-06

April 1, 1987

Project Leaders:

Dr. Richard L. Snyder
Cooperative Extension
Land, Air and Water Resources Dept.
University of California
Davis, CA 95616
(916) 752-1130

Mr. Joseph H. Connell
Butte County
Cooperative Extension
2279 Del Oro Ave., Suite B
Oroville, CA 95965
(916) 538-7201

Personnel/Cooperators: W. Asai, R. H. Shaw, K.T. Paw U, J. J. Carroll, W. Micke

Objectives:

(1) Study the effects of various under-tree sprinkler operation schemes on the environment within an almond orchard under a variety of freezing weather conditions. (2) Determine the effects of frost damage timing on field crop yield. (3) Study methods of improving the effectiveness of frost protection with under-tree sprinklers.

Progress:

The physical mechanisms that are involved in the effective use of under-tree sprinklers for frost protection are not well understood, and consequently advice on the optimal use of the method is not available. When to start and stop sprinkler operation, needed precipitation rates, and sprinkler spacing all affect the environment within an orchard. Recommendations on the best management cannot be given without information on how operation physically affects this environment.

Methods:

Four separate experiments were conducted during the 1986-87 winter and spring frost season. Experiment 1 was conducted to study the optimal placement of hand-move sprinkler lines for frost protection. The second experiment was designed to study the effects of ground cover on orchard temperatures during frost conditions. The third experiment was to attempt to artificially induce freezing conditions. The fourth experiment was to monitor the weather during frost conditions to develop and test a frost computer model.

In experiment 1, four treatments were used (see figure 1). One treatment was a control where no sprinklers were operated. The second was a permanent buried sprinkler system on a diamond spacing with one row of trees between heads. Tree spacing was 26 x 26 feet and sprinklers were located as shown in the attached plot diagram. In the third treatment, every other line of sprinklers was removed leaving two rows of trees (52 feet) between lines and 52 feet between heads in the lines. In the fourth treatment, three lines of sprinklers were removed between each pair of operating sprinkler lines leaving 104 feet between lines and 52 feet between heads in the lines. Impact sprinklers with 5/16 inch orifices were substituted for the non-impact sprinklers in treatments 3 and 4. Minimum temperatures were measured in several locations in each treatment using frost minimum shelters in the locations shown in the plot diagram (figure 1).

In experiment 2, a plot was set up in an orchard near Chico and an infrared thermometer was used to monitor the effective emitting temperature of ground covers of differing heights. The plots were arranged in a Latin square design (figure 2) with four treatments.

Number	Treatment
1	Fallow
2	2-inch height
3	4-inch height
4	uncut

Experiment 3 was conducted to determine if we could artificially create freezing conditions for a whole tree. A chamber was built large enough to surround a tree up to approximately 12 feet tall. It was constructed from PVC pipe and clear plastic. The purpose of the chamber was to reduce wind flow, which would normally remove any artificial frost conditions. Large tanks of liquid CO_2 were used to artificially reduce temperature within the chamber.

Experiment 4 was conducted in an orchard near Chico. An automatic weather station was set up inside and outside of the orchard. The control station was set up just north of the orchard on the upwind side. A second station was located well within the orchard, where sprinklers were operated for frost protection.

Results:

Experiment 1 was conducted only on the night of January 18-19, 1987. Most nights during January were windy or foggy and the test night was the only good night for the experiment. An infrared thermometer with the emissivity set to 0.98 was used to measure soil surface temperature directly in front of each temperature shelter. Actual measurements were taken at 3:35 a.m. and 7:30 a.m. The minimum temperatures for the night were also recorded. Air temperatures were measured at 5 feet height. Estimated precipitation rates were 0.08, 0.18, and 0.09 inches per hour for the 26 x 26 diamond, 52 x 52, and 104 x 52 spacings, respectively.

Air temperatures in the sprinkled areas were all 1°F to 2°F higher than the control plots, but there was no appreciable difference between spacing treatments. The lack of difference can be partially explained by the light winds during the night which tended to distribute heat supplied by the sprinklers regardless of spacing. The effect of wind is obvious in table 1 where the air temperatures showed a considerable increase from 3:35 a.m. to 7:30 a.m. The minimum readings were lower than the 3:35 or the 7:30 measurements, so temperature dropped after 3:35 until the wind speed increased again raising the air temperatures.

Soil surface temperatures showed a more dependent relationship to the treatments. Surface measurements at 3:35 a.m. in the 104 x 52 spacing treatment were clearly colder in areas away from the sprinklers (stations 7 and 8). Surface temperature near stations 11 and 12 were essentially as cold as those measured in the control area. Even in the 52 x 52 spacing treatment, the soil surface temperature was lower as distance from the sprinklers increased (stations 3 and 4). Station 1 surface temperature at 3:35 a.m. was colder than expected. Based on the 7:30 a.m. measurement, the -2.9°C reading was probably a bad measurement.

In conclusion, sprinkler spacing does have an effect on soil surface temperatures, but in this experiment it had little effect on air temperature. Wind between 3:35 a.m. and 7:30 a.m. probably helped to even out the benefits of sprinkler operation, making the 104 x 52 spacing treatment more effective than it would be in no-wind conditions. Also, plot size restrictions probably somewhat affected results. The wider spacing treatments may not have been as effective if a whole orchard, rather than a small plot, was protected. Another consideration is the observed air temperatures at 3:35 a.m. and 7:30 a.m. were above the melting point. There was very little ice formation during the experiment because temperatures warmed up as wind speed increased. The results may have been different if more of the sprinkler water had frozen, releasing more latent heat.

Experiment 2 was conducted on several nights mainly during January. Inclement weather or sprinkler operation during February prevented further measurements. An infrared thermometer set to and emissivity of 0.98 was used to make surface temperature measurements on the various ground cover heights. The plots were located in the northwest corner of the orchard and were set up in a Latin square design (see figure 2). Each experimental unit was located within a 26 x 26 foot square of 4 trees. Mean surface temperature observations on several dates are given in table 3 for the various treatments. Statistics are not reported because the cutting heights were not clearly established during January and it was quite windy during the one February observation date.

The most significant observation is that the fallow treatment had the coldest emitting surface temperature on all but January 9 and 10. The soil surface was still moist on January 9 and 10 and there was little wind. On January 14 and 17, measurements were made during windy conditions following several days of high winds. Most likely the winds dried the fallow soil surface reducing thermal conductivity and hence the soils ability to conduct daytime solar heat for storage in the more moist lower depths. Thus, there was probably a greater temperature range at the soil surface for the fallow soil.

February 18 was also a windy morning following a relatively dry period and those conditions may explain the colder fallow surface. There was little difference between heights of the 2-inch and 4-inch treatments (table 4) and there was little temperature difference between them and the uncut treatment.

In conclusion, our results tend to contradict the normal recommendation to have a fallow soil. This should be interpreted with caution, however, because we feel the fallow soil would have been warmer if the observations had not followed windy dry periods that dried the fallow surface. We still would recommend a fallow surface if it is moist. Thus, a few days of dry windy conditions should be followed by a light surface irrigation to obtain benefit from having a fallow orchard floor. It appears that there is little difference in effective emitting temperatures when the ground cover exceeded about 4 inches height. However, this needs further study.

Experiment 3 was to design, build, and test a chamber, and test the procedure to artificially induce frost damage to a whole tree. A chamber was built out of PVC pipe and clear plastic. It was built in an octagonal shape and the clear plastic could be raised and lowered for testing. When raised, the plastic reduced wind to a height of 12 feet.

Two tanks of liquid CO_2 were released inside the chamber on a morning in early spring, 1987. Unfortunately, the wind was blowing at 5 meters per second and raising the plastic was extremely difficult. We monitored temperature inside and outside of the chamber and observed minimal differences. Clearly, this method will not work under moderately windy conditions. Evidently, wind blowing over the opening draws the cold air out of the chamber.

Experiment 4 was conducted in an orchard near Chico. The weather inside of an orchard during sprinkler operation for frost protection was compared with the weather immediately upwind from the orchard. Data were gathered to determine if a predictive computer model can be developed and to study the effects of the sprinkler operation of the weather. The sprinkler system has an application rate of 0.08 inches per hour and the sprinklers are spaced with 26 feet between lines and sprinklers spread 52 feet on a line. Alternate lines are staggered to give a diamond sprinkler pattern.

On the night of February 24-25, 1987 a potentially severe frost was predicted. The previous week was quite windy. The wind speed was forecasted to drop causing frost to occur in sheltered areas. Air temperatures in the sprinkler and control areas and wind speeds from 1800 hours to 0200 are plotted in figure 3. The wind was blowing from the north all day, but it stopped about 1830 hours. Temperatures dropped from approximately 44°F starting at 1830 hours until 2200 hours during the calm period. At 2230, the wind speed increased and slowed the temperature drop. After 2330 hours, the wind died again and the temperature began to drop. The sprinklers were turned on at midnight and the temperature in the sprinkled orchard increased relative to the control.

Figure 3 shows how the air temperatures and wind speeds changed from the time the sprinklers were turned on until 0730 hours. Sunrise occurred between 0630 and 0700 hours. After the sprinklers were turned on, wind speed varied between 1.0 and 3.0 meters per second until 0330 when it dropped. Air temperature in the control area began to drop slightly after the winds stopped at 0400 hours. Then a large drop of approximately 6°F occurred within half an hour from 0500 to 0530 hours. A temperature change of 6°F within half an hour is an extreme drop and it is much greater than we would have believed possible. To our knowledge, no freezing-temperature computer model would have come close to predicting the observed temperature change.

The only explanation we have for the temperature observations is that cold air accumulated in a depressed area to the northeast between the orchard and the mountains. While the wind was blowing from the north, the accumulated cold air was blocked from the orchard. When the wind stopped, cold air drainage from the mountains forced the accumulated cold air from the depressed area up into the orchard. Because computer models are mainly physical and the observed processes also involve site specific topography, this frost condition could not be predicted without considering climatology or meso-scale meteorology in addition to micro-scale physical processes.

The effects of cold air intrusion into the sprinkler protected orchard were dramatic. Basically, the benefits from sprinkler operation were overwhelmed by the cold, dry air and temperatures along the edge dropped considerably. Although temperatures were not measured just inside the edge of the orchard, ice formation told the story. There was ice formation on the ground at a distance of 10 tree rows in from the upwind edge. Ice was observed on the lower branches and blossoms of the trees to a distance of 15 tree rows in from the edge. Clearly, it was cold air intrusion rather than radiation that caused the ice formation. Ice on the ground would be more extensive if radiation was the culprit. The weather station inside the orchard was approximately 1/4 mile from the upwind edge of the orchard and it was relatively unaffected by the cold air intrusion on the night of February 24-25.

In conclusion, it is clear that a micro-scale physical computer model would not have predicted the observed temperature drop. Climatology or a meso-scale model must be included to accurately predict this frost occurrence. The set of physical conditions that caused the frost occurrence would be likely to cause a similar frost if they occurred again. Consequently, a combination physical-climatological model is needed. Unfortunately, this means that a separate model may be needed to accurately predict frost for individual orchards everywhere in California.

Figure 1. Layout of the 1987 almond frost experiment on sprinkler spacing. symbols based in the diagram are tree (o), sprinkler (x), and temperature (▣). Control stations 13 and 14 were located north of the sprinkler plots.

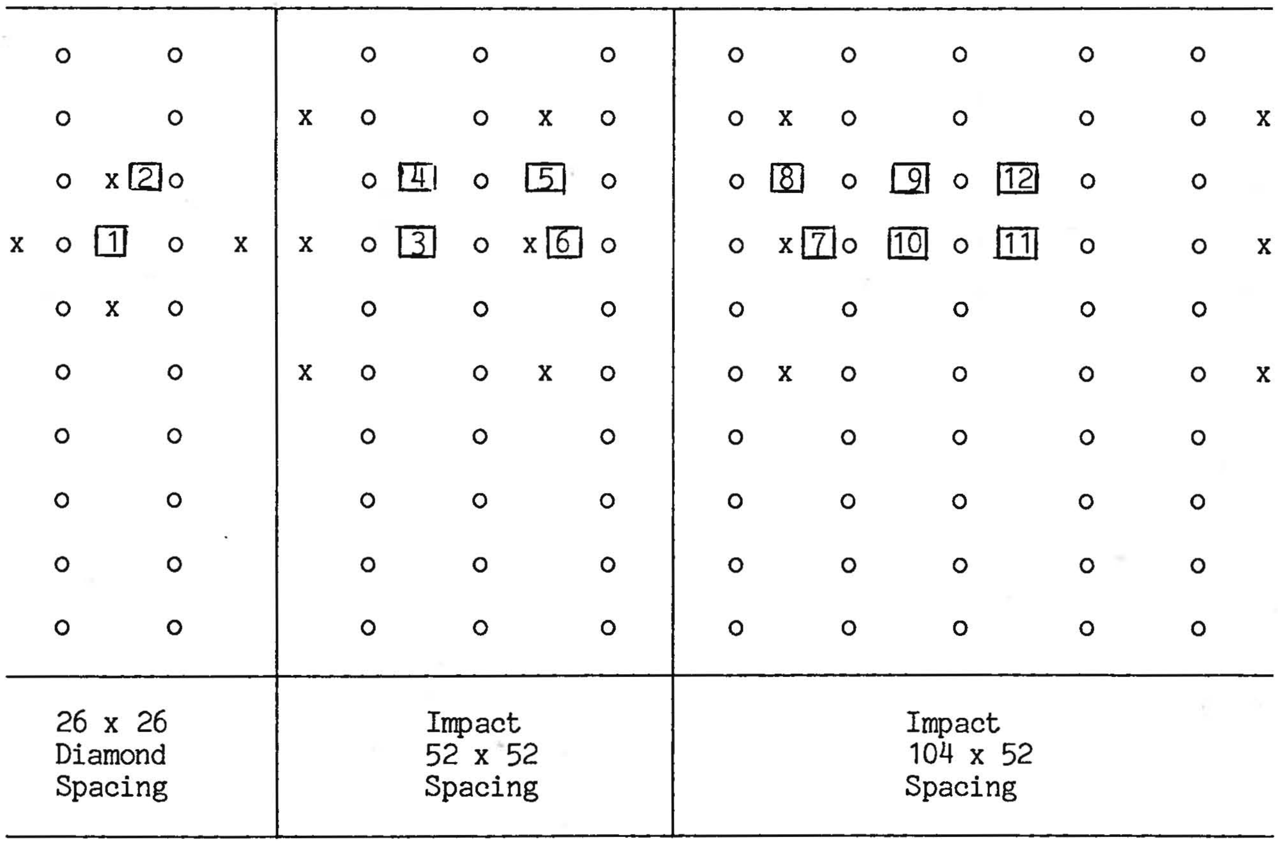

Figure 2. Plot layout for the 1987 experiment on the effects of ground cover cutting height on frost protection. Treatments are (1) uncut, (2) 4-inch tall, (3) 2-inch tall, and (4) fallow.

4	2	1	3
1	3	4	2
3	1	2	4
2	4	3	1

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Table 1. Observed temperature readings in the minimum temperature shelters and on the soil surface near the shelters on the night of January 18-19, 1987.[a]

Station	Ice Bath Calibration	3:35 a.m. Readings		7:30 a.m. Readings		Minimum Readings	
	°F	air °F	sfc °C	air °F	sfc °C	air °F	
1	32	33	-2.9	36	-1.7	32[b]	diamond
2	31	32	-2.1	35	-1.4	27	
3	32	34	-1.8	37	-1.5	28	52 x 52
4	32	33	-1.6	36	-1.5	28	
5[c]	31	32	-0.9	35	-0.8	27	
6	31	34	-1.2	36	-1.2	28	
7	33	34	-1.1	37	-1.4	26	104 x 52
8	32	32	-1.1	33	-1.0	28	
9	33	32	-2.8	37	-1.7	28	
10	32	33	-2.4	36	-1.3	27	
11	32	33	-2.8	37	-2.4	28	
12	32	32	-2.9	36	-2.9	27	
13	33	33	-3.0	36	-3.0	27	Control[d]
14	32	32	-2.7	35	-2.5	27	

[a]Sprinklers were turned on at midnight when the ground temperature was -3.5°C, the sky temperature was -48.5, the average temperature was 30°F. Sprinklers were turned off at 7:30 a.m., and sunrise occurred at 7:30 a.m. Stations 2, 6, and 7 were immediately adjacent to sprinklers.

[b]This thermometer was bumped and the reading changed.

[c]Water was ponding on the soil near the station.

[d]Sky temperatures were -46.5°C and -46.4°C at 3:35 and 7:30, respectively.

Table 2. Minimum air and soil surface[a] temperature readings corrected for ice calibration measured on the night of January 18-19, 1987.

Treatment Spacing	Station Number	Air Temperature		Surface Temperature		Surface Temperature	
		°F	°C	°F	°C	°F	°C
26 x 26	1	32[b]	0.0	26.8	-2.9		-1.7
diamond	2	28	-2.2	28.2	-2.1		-1.4
104 x 52	3	28	-2.2	28.8	-1.8		-1.5
	4	28	-2.2	29.1	-1.6		-1.5
	5	28	-2.2	30.4	-0.9		-0.8
	6	29	-1.7		-1.2		-1.2
104 x 52	7	25	-3.9	29.8	-1.1[c]		-1.4
	8	28	-2.2	30.0	-1.1		-1.0
	9	27	-2.8	27.0	-2.8		-1.7
	10	27	-2.8	27.7	-2.4		-1.3
	11	28	-2.2	27.0	-2.8		-2.4
	12	27	-2.8	26.8	-2.9		-2.9
control	13	26	-3.3	26.6	-3.0		-3.0
	14	27	-2.8	27.1	-2.7		-2.5

[a]Soil surface temperature was measured with an infrared thermometer with the emissivity = 0.98.

[b]Temperature reading was disturbed.

[c]All minimum soil surface temperatures were recorded at 3:35 a.m. except for station 7 which had its lowest temperature at 7:30 a.m.

Table 3. Mean temperature observations just before sunrise by date for various cutting heights.

Date	Fallow	2-inch	4-inch	Uncut
Jan. 9[a]	-2.6	-2.6	-2.8	-3.0
Jan. 10[b]	-3.8	-4.8	-5.1	-5.2
Jan. 14[c]	-2.6	-1.9	-1.8	-1.9
Jan. 17[d]	-3.9	-3.7	-3.7	-3.5
Feb. 18[e]	1.8	2.7	2.9	2.7

[a]Clear sky, dew on ground cover, air temperature = -1°C, sky temperature = 45.3°C.

[b]Scattered light cirrus clouds, moderate frost on grass, air temperature = -3°C, sky temperature ~ 46°C.

[c]Clear sky, winds 1-3 m s^{-1} but were much stronger during the night and previous days, air temperature = 3.5°C, dew-point 0°C, sky temperature = 47.8°C.

[d]Clear sky, winds 2-5 m s^{-1}, air temperature = 32°F, sky temperature = -45.5°C. Windy all night.

[e]Clear sky, winds about 3 m s^{-1} all night, air temperature = 6°C, sky temperature = -47.5°C.

Table 4. Ground cover heights (inches) on February 18, 1987. Treatment numbers are shown in the upper right corner.

4 fallow	2 3	1 10	3 6
1 3	3 2.5	4 fallow	2 5.5
3 4	1 5	2 5	4 fallow
2 4.5	4 fallow	3 4	1 10

Treatment		Mean Height
1	Uncut	7.0
2	4-inch	4.5
3	2-inch	4.1
4	fallow	0.0

February 25, 1987

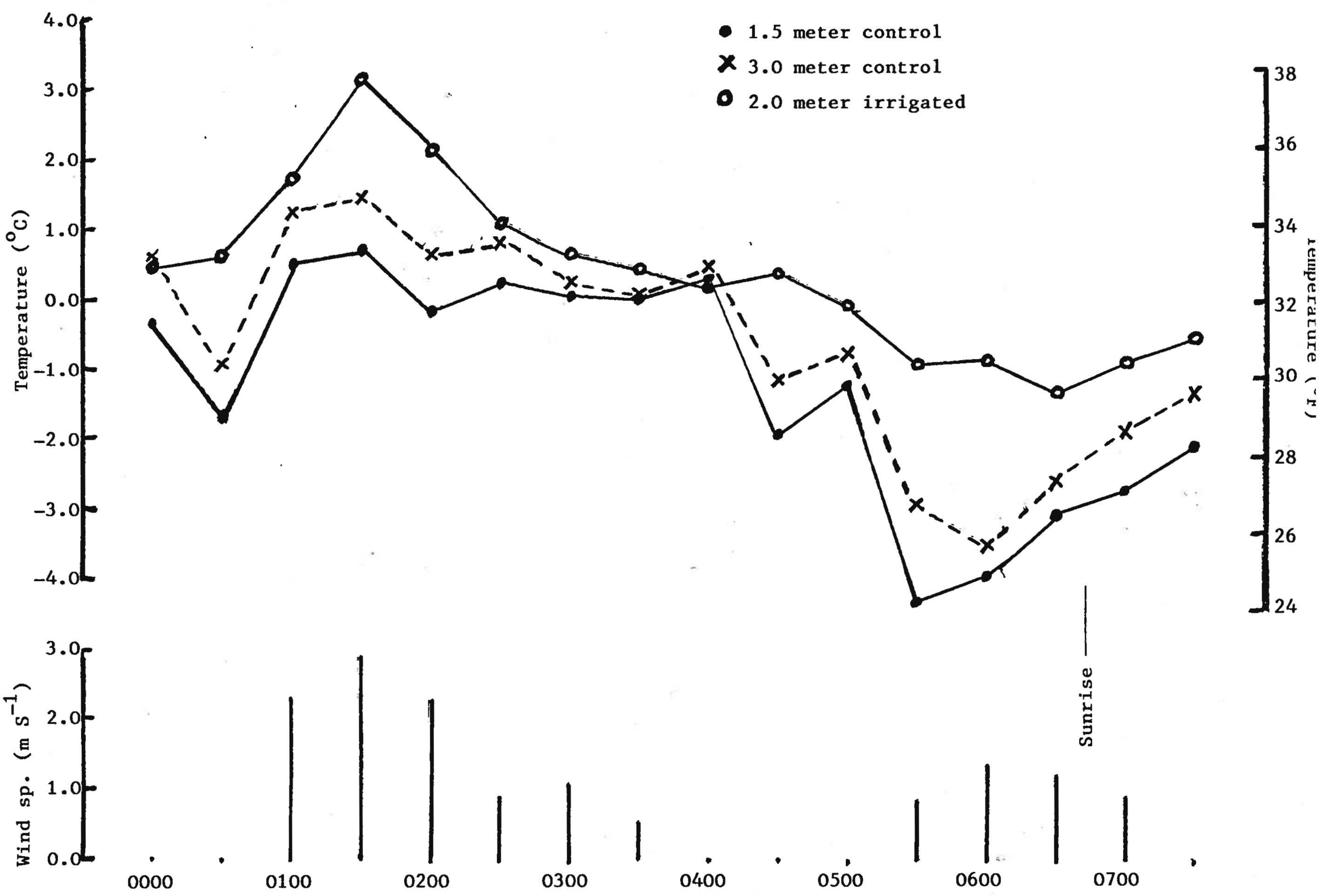

Figure 4. Temperatures and wind speeds r...orded on February 25, 1987 from 0000 hours to 730C ...ours in the almond frost experiment north of Chico.

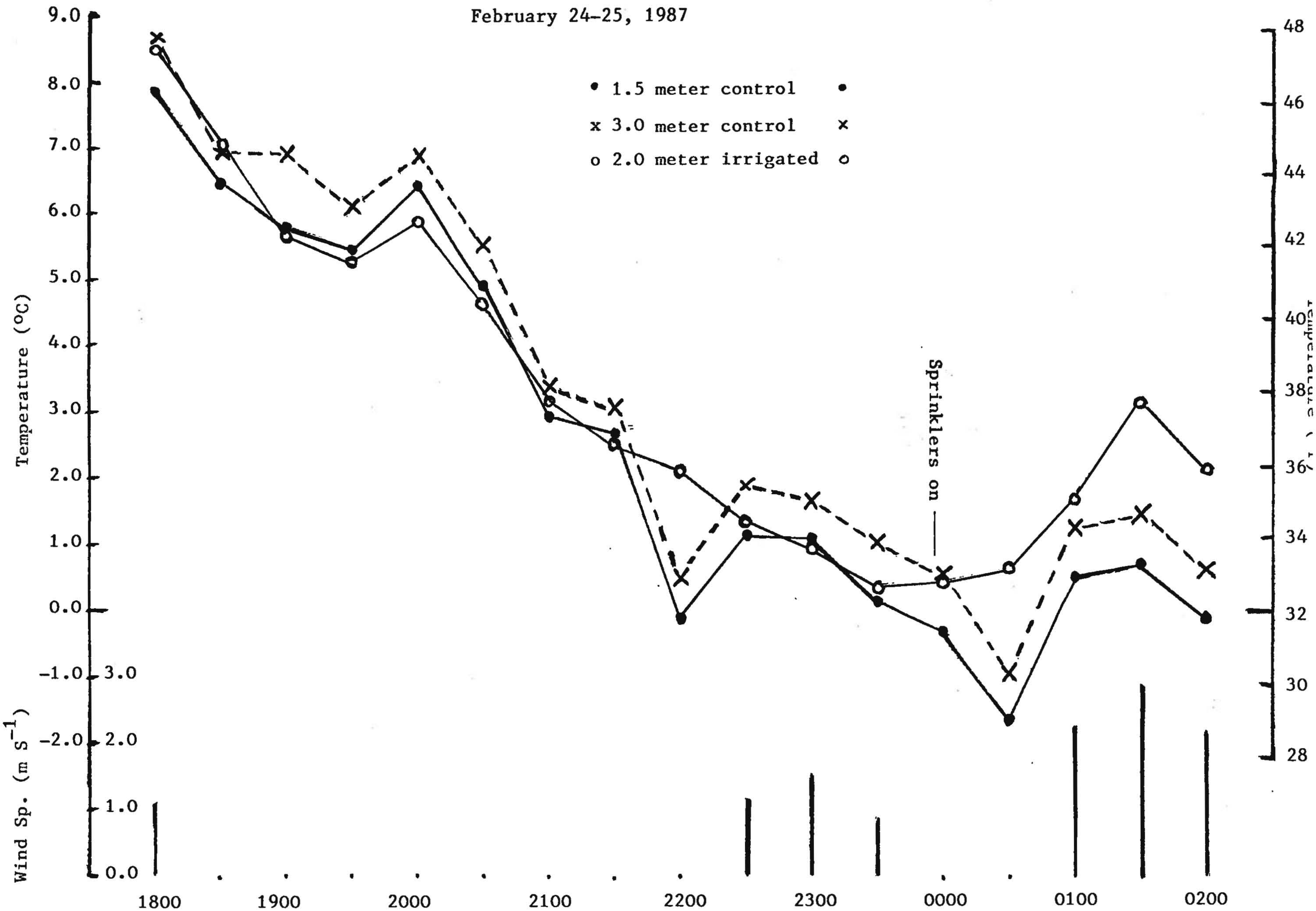

Figure 3. Temperatures and wind speeds recorded on February 24–25, 1987 from 1800 hours to 0200 hours in the almond frost experiment north of Chico.