Freeze and Frost Protection with Aqueous Foam—Field Experiments

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ADDITIONAL INDEX WORDS. freeze and frost damage, plant cold protection, radiation shield, biodegradable aqueous foam, and mulching.

SUMMARY. Newly formulated aqueous foam was tested in the field. The foam demonstrated the longevity necessary for practical field use. Soil temperatures beneath an insulation layer of aqueous foam were measured to determine the effectiveness of foam as soil mulch. Leaf temperature within a canopy was monitored to observe the modification of plant leaf temperature, and to evaluate the phytotoxic effects of foam applied directly to the leaf canopy. Leaves were not damaged after being covered with the foam for two weeks. The foam-protected soil was effectively insulated, and the aqueous foam proved to be an effective radiation shield against the cold night sky. Temperature differences as high as 5 °C (9 °F) were measured between the foam-covered and uncovered copper metal plates, which were used to simulate plant leaves. The foam covered plates were ≈80% as effective as the aluminum foil covered plates in reducing radiation heat transfer.

The development and evaluation of the gelatin-sugar-based aqueous foam was presented by Choi et al. (1999). Many possible applications of this long-lasting foam may be found if its effectiveness for cold protection is proven in the field. The foam can be used as soil mulch in a greenhouse or plastic tunnel, as an insulator for tree trunks, or as a cover for frost protection.

Protection from unsuitable air and leaf tissue temperatures is a major problem in the spring and fall of each growing season. In particular, potential losses of plant production follows seedling transplant for early season growth, even when utilizing plasticulture techniques of mulching the soil with plastic film, or employing row covers. Plasticulture techniques include the use of film mulches to cover the soil surface and to warm the plant root zone, or tunnels formed of transparent plastic film constructed above each row of highly valued crops throughout large fields, in an attempt to modify the aerial environment of the plant. Increased air temperature, humidity, and wind protection can be achieved with film-covered tunnels. The nursery industry uses white plastic film covered tunnel greenhouses to protect its nursery stock from harsh winter conditions, by preventing large fluctuations of diurnal air temperatures. In this way, premature cold season growth can be minimized, and damage to the plants reduced (Johnson and Roberts, 1983).

The long-lasting aqueous foam has the potential to act as a superior mulching material when applied directly over the soil. An experiment was conducted (for freeze–frost protection) to measure soil temperatures and determine the effectiveness of foam as a soil mulch (Choi et al., 1999). In addition, two trays of lettuce seedlings were monitored to observe the modification of plant leaf temperature resulting from an application of foam. The removal by water spray or rain and ultimate fate of the foam was also discussed. In a review of frost-freeze meteorology, Perry (1998) noted that foams have successfully averted plant damage, but they could not be removed easily.

A subsequent experiment (for frost protection) was planned to evaluate the effectiveness of the foam against climatic conditions that cause frost. Copper plate surfaces were painted black and instrumented to measure surface temperatures both with and without radiation shields. Three copper surfaces were established either with a thin foam layer, a thick foam layer, an aluminum foil cover, or unprotected (Fig. 1a). The radiation shields were supported slightly above the copper surface on wire mesh, in order to simulate protected and unprotected freestanding tree canopies, as well as low profile trees and plants. The aluminum foil replicate was designed to eliminate radiative heat exchange between the copper surface and the cold sky, and thus provide a relative comparison for the other three treatments.

Experimental design—Outdoor quantitative evaluations

In this paper, two experiments will be reported that were completed during January and February 1998 at the Campus Agricultural Research Center of University of Arizona, Tucson. The first, one determined the protection provided by foam against freeze and frost, and the second evaluated frost protection alone.

Freeze–frost protection

A polyethylene plastic film-covered, hoop-supported row tunnel [1 × 2 × 0.8 m (3.3 6.6 × 2.6 ft, length × width × height] was installed above a side-by-side test consisting of foam applied to the ground as a soil mulch and foam applied to a tray of lettuce plants as a plant insulator (Choi et al., 1999). The tunnel provided protection from rainfall, but not from radiative heat loss; i.e., longwave transmission through the polyethylene was ≈80% for a single, non-infrared barrier film (Giacomelli and Roberts, 1993). Thus, radiative heat loss at night could be significant under the clear, winter desert sky.

The soil was tilled and raked smooth, and thermocouples were installed with two replications each on three soil treatment areas [30 × 60 cm (11.8 × 23.6 inch)]. The treatments included two depths of applied foam over soil—thin foam [2.5 cm (1.0 inch)], thick foam [5 cm (2.0 inch)]—and bare ground as a control. At each of these six locations, three thermocouples were located to measure the temperature of the soil near the surface [0.25 cm (0.1 inch)] and at a depth of 2.5 cm (1 inch) (see Choi et al., 1999, for detail locations). The air temperature within the tunnel was measured at 12 cm (4.4 inch) above the bare soil. All thermocouple junctions in the air or within the foam layers were fitted with radiation shields.

Two trays [30 × 60 cm (11.8 × 23.6 inch)] of lettuce (*Lactuca sativa* L. 'Black Seeded Simpson'), containing 15 seedlings each, were placed side-by-side within the tunnel. At the time of field testing, a closed plant canopy ex-

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isted within the lettuce tray. Thermocouple junctions were attached to selected leaves by inserting the thermocouple within the midrib of the adaxial face of the leaf, about one-third the leaf distance up from the root zone, and well within the plant canopy. Foam was applied to cover one entire tray to a depth of ≈2 cm (0.8 inch). This test began on 29 Jan. 1998, and was terminated on 12 Feb. 1998.

Lettuce was chosen for this study because it grows quickly and can tolerate the cold night air and leaf temperatures common during desert winter nights. The lettuce was germinated and seeded (5 Dec. 1997), and transplanted into 25 mm (1 inch) foam cubes (10 Dec. 1997). The plants were grown in a greenhouse at 22/17 °C (72/63 °F) day/night air temperatures and natural photoperiod conditions, within a tray flood irrigated with nutrient solution to a depth of 2 cm (0.8 inch) at intervals of 4 d.

Frost protection

The plastic film tunnel and the lettuce were removed for this experiment, and the foam layers were exposed fully to daytime solar radiation and the cold night sky. Four sets of copper plates and radiation shields on insulators were placed on the soil (see Fig. 1a), and two of them were covered by 4 cm (1.6 inch) and 2 cm (0.8 inch) thick foam layers placed on the screens. A 1.6 mm (0.06 inch) thick, 10 × 10 cm (4 × 4 inch) copper plate with its upper and lower surfaces painted black was attached to a 25 × 25 × 2 cm (1 × 1 × 0.8 inch) insulator. The insulator and the copper plate were separated by a radiation shield (several layers of aluminum foil) to minimize radiative heat exchange and to create an air pocket for the reduction of conductive heat transfer. A 30 × 30 cm (12 × 12 inch) metal screen [mesh size: 1.25 × 1.25 cm, (0.5 × 0.5 inch)] was attached ≈3 cm (1.2 inch) above each of the four copper plate assemblies. The metal screens were covered with either 2 cm (0.8 inch, thin foam), 4 cm (1.6 inch, thick foam), or aluminum foil. One screen remained unprotected to serve as a control. Five thermocouples were located at the bottom surface of each copper plate, and their specific locations are shown in Fig. 1b.

During the test period, the nearby Arizona Meteorological Network weather station recorded min/max daily air temperatures as 0 and 26 °C (32 and 79 °F), respectively. Daily average wind speed ranged from 1.7 to 4.1 $m \cdot s^{-1}$ (5.6 to 13.5 ft/s), and the highest wind speed recorded was 15 $m \cdot s^{-1}$ (49.2 ft/s). Temperatures of the copper plates were recorded on clear nights to observe the effectiveness of the foam insulation to prevent sky radiation loss. There were 6 rainy days during the period, and the foam-covered screens were removed and sheltered. Thus, the foam layers were exposed to the dry outdoor environment for 8 d, with only a minor observed reduction in foam thickness (≈10%), while lateral (length and width) shrinkage was not evident. Its size and resilience were about the same as those of the foam observed in the laboratory (Choi et al., 1999).

Data acquisition

Air, soil and foam temperatures were measured with 24 gage type-T thermocouples. A thermister in each terminal block (National Instrument SCXI 1100 multiplexer, SCXI 1303 isothermal terminal block, and AT-MIO-16H-9 multifunction board, Austin, Texas) was used as a reference cold junction temperature, as presented by Choi et al. (1999). All the thermocouple junctions that measured air and foam temperatures were shielded from

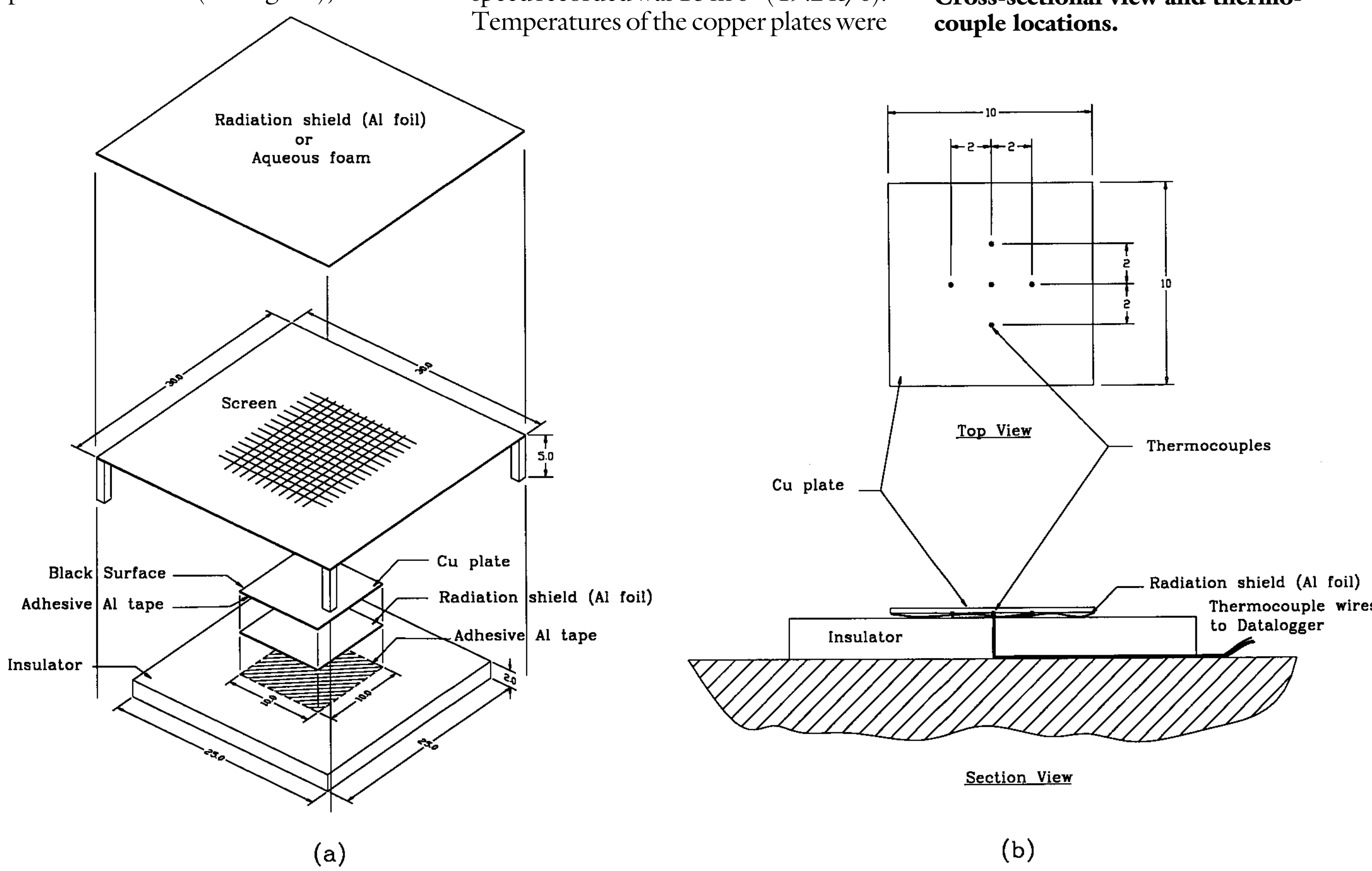


Fig. 1. Schematic of field experiments for frost protection. (a) Overall experimental setup. (b) Cross-sectional view and thermocouple locations.

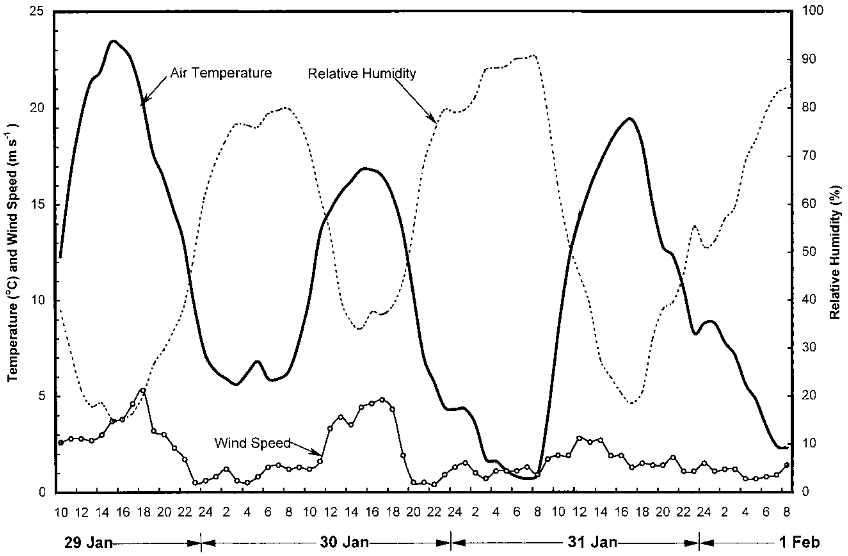


Fig. 2. Air temperature, relative humidity, and wind speed data during the freeze–frost experiments. °F = 1.8 (°C) + 32.

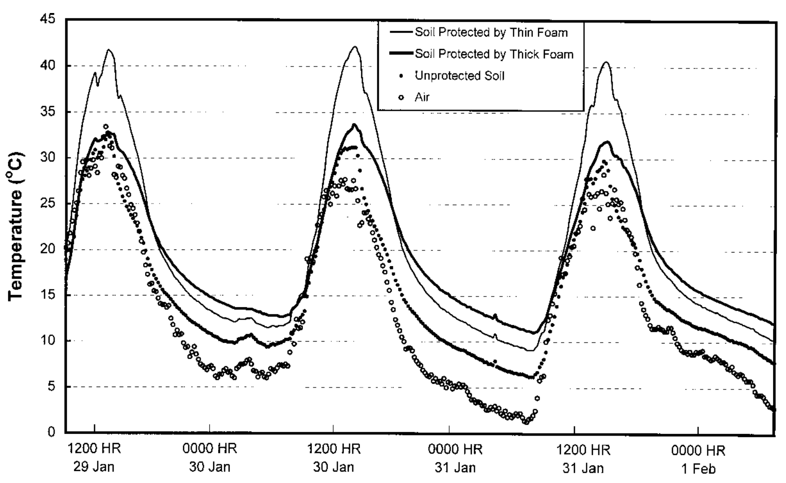


Fig. 3. Soil temperature at 2.5 cm (1 inch) deep; °F = 1.8 (°C)+32.

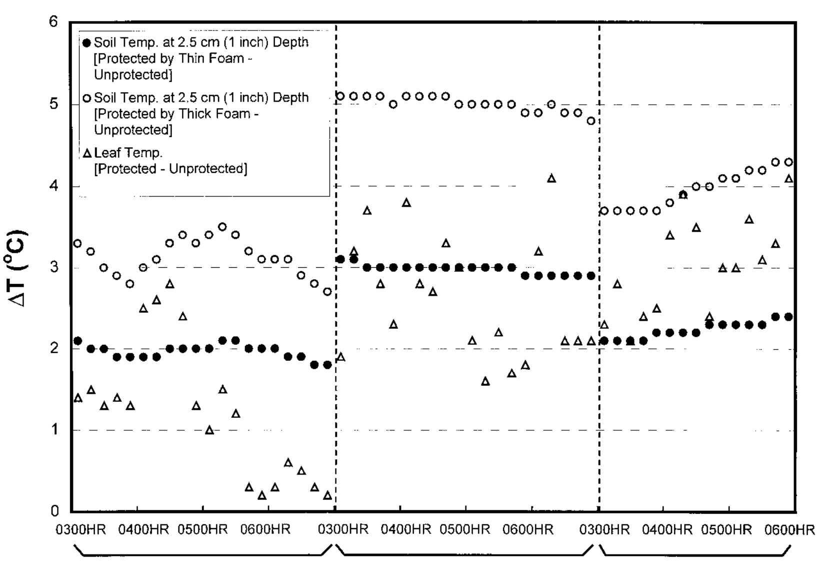


Fig. 4. Temperature differences (ΔT) between protected and unprotected soils and leaves during the early morning hours (0300 to 0600 HR); °F = 1.8 (°C) + 32.

radiation. Each experiment was preceded by a calibration test of the data acquisition system, with particular emphasis on the thermocouple sensors. Based on data from a series of calibration tests, the accuracy was determined to be ±0.15 °C (±0.27 °F) , and repeatability was ±0.05 °C (±0.09 °F).

The contacts between the thermocouple junctions and the copper plates were inspected before the experiment. To verify the consistency of experimental setup and the accuracy of thermocouple readings, a preliminary experiment was carried out without radiation shields (i.e., foam or aluminum foil covers) during a calm and clear night. Throughout the test period, the time-averaged temperature readings of each thermocouple remained within ±0.15 °C (±0.27 °F) of the average temperature of all four copper plates.

The changes in air temperature (inside and outside of the foam layers), soil temperature, and leaf temperature were simultaneously monitored in graphic form on the computer screen. Using the data acquisition system, the average values determined from 500 scans/s were automatically stored in a designated computer file every 8 min for later data analysis.

Results and discussion

During the 2-week test period, the treatments were continuously monitored, and four sets of data, including those registered on 29 Jan. 2, 5 and 9 Feb. 1998, were used for analysis, because they typified the pattern of winter weather in Arizona. Daily weather data during the period are available on an official Internet site (University of Arizona, 1999). An unusual amount of rainfall was recorded in Arizona due to the El Nino effect during the 1997–98 winter, and a total of 51 mm (2 inch) of rainfall was recorded during this experiment. As shown in Fig. 2 (the data collected from the nearby Arizona Meteorological Network weather station), the wind was usually calm through the night until early morning. It was partly cloudy or cloudy from the night of 29 Jan. until the mid-morning of 30 Jan. The early morning air temperature dropped near the freezing point on the cold, clear morning of 31 Jan. 1998. The daily minimum relative humidity ranged from 10% to 30%.

Freeze–frost protection. Figure 3 presents the temperature fluctuation of air and soil at a 2.5 cm (1 inch) depth. Each

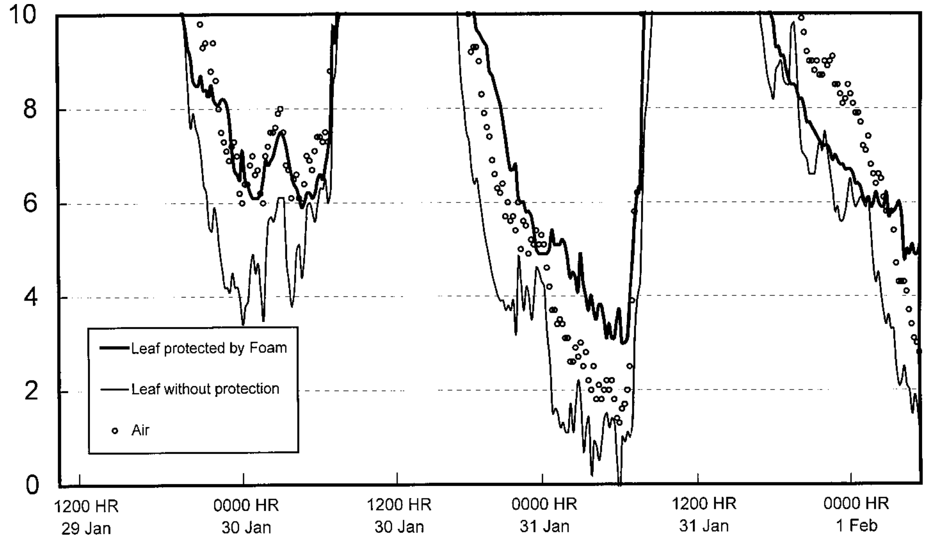


Fig. 5. Temperature of the midribs of foam-covered and uncovered lettuce leaves. °F = 1.8 (°C) + 32.

temperature reading represents the average value from two locations. The daily fluctuation pattern was nearly the same as the data collected at the weather station, and the temperature readings were 5 to 10 °C (9 to 18 °F) higher during the day than the weather station data due to a moderate greenhouse effect caused by the plastic film tunnel. The soil temperature protected by the thick foam maintained the highest temperature at night, and the thin foam maintained the highest temperature during the day.

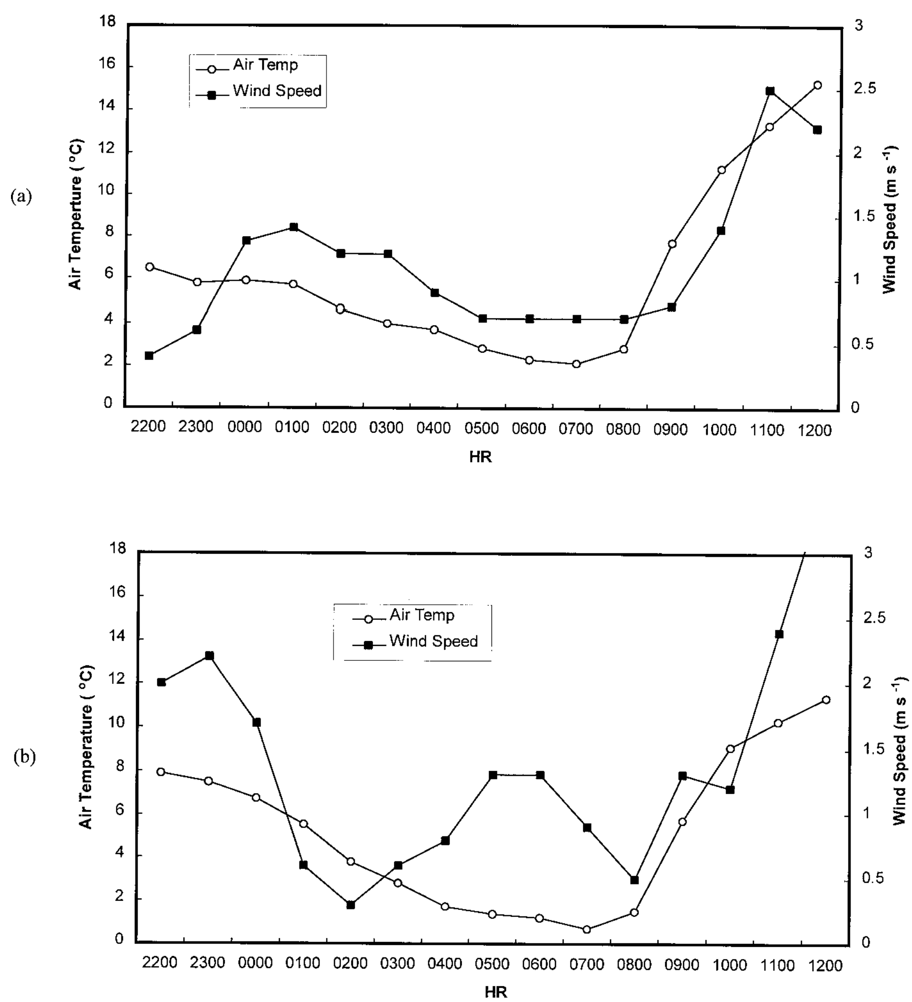
During the cold morning (from 0300 to 0700 HR) of 31 Jan. 1998, the soil temperature difference (ΔT) between the thick-foam protected soil and the unprotected soil was ≈5 °C (9 °F), and the difference between the thick foam treatment and the air was nearly 10 °C (18 °F), as shown in Figs. 3 and 4. The thin foam provided a reduced insulation effect during the same period, with about a 3 °C (5.4 °F) temperature difference. On the relatively mild morning of 30 Jan., the effectiveness of the foam as measured by the temperature difference was reduced. On 1 Feb. 1998, the temperature difference between the foam-protected soil and the unprotected soil gradually increased (Fig. 4) as the air temperature dropped early in the morning (Fig. 3). The differences were quite consistent during cold and clear nights.

The daytime soil temperatures under the thin foam were consistently higher than under the thick foam, reaching values between 8 to 9 °C (14 to 16 °F) greater (Fig. 3). The shortwave solar radiation apparently penetrated the thin foam and was absorbed at the soil surface, while the foam acted as a good insulator against convective heat loss. However, the stored thermal energy was quickly lost after sunset. Radiative loss from the soil surface to the cold clear sky could have contributed to the energy loss. The accumulation of thermal energy during the day, therefore, did not significantly alter the soil temperature during the following evening.

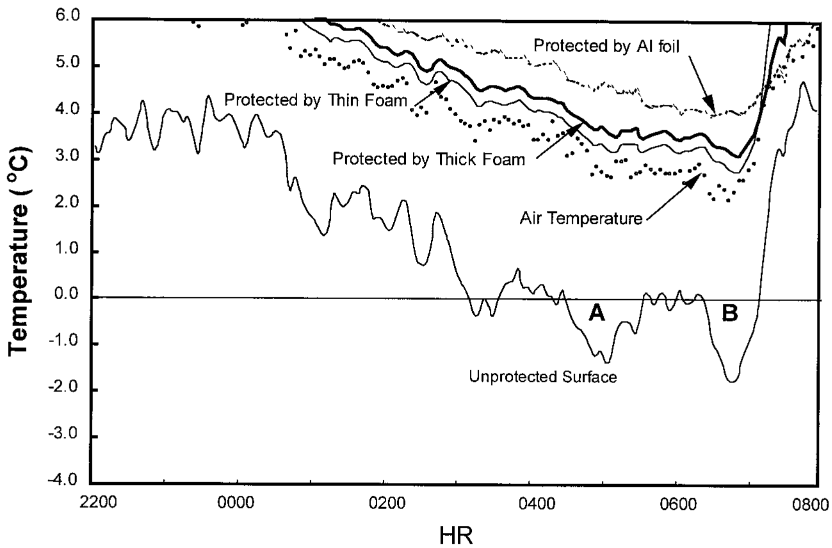
Temperature of the midribs of foam-covered and uncovered lettuce leaves is shown in Fig. 5. During the cloudy and warm morning of 30 Jan. 1998, the effect of the foam was not significant. The temperature difference between the protected and unprotected leaves was negligible (see Fig. 4) due to the cloud cover. On 31 Jan. 1998, the temperature differences for the leaf covered with foam were ≈3 °C (5.4 °F) on average and as high as 4 °C (7.2 °F) greater than the uncovered leaf. Figure 5 indicates that the leaf temperatures of the protected midrib were higher than the air temperature, because the foam layer protected the lettuce leaves from radiative loss to the cold and clear sky during the morning hours of 31 Jan. and 1 Feb. 1998. Such a trend was not evident on the cloudy morning of 30 Jan. 1998.

FROST PROTECTION. The frost protec-

Fig. 6. Air temperature and wind speed data during the frost experiments. °F = 1.8 (°C) + 32; 1 m·s⁻¹ = 3.3 ft/s; (a) 21 Feb.; (b) 25 Feb.



(a)



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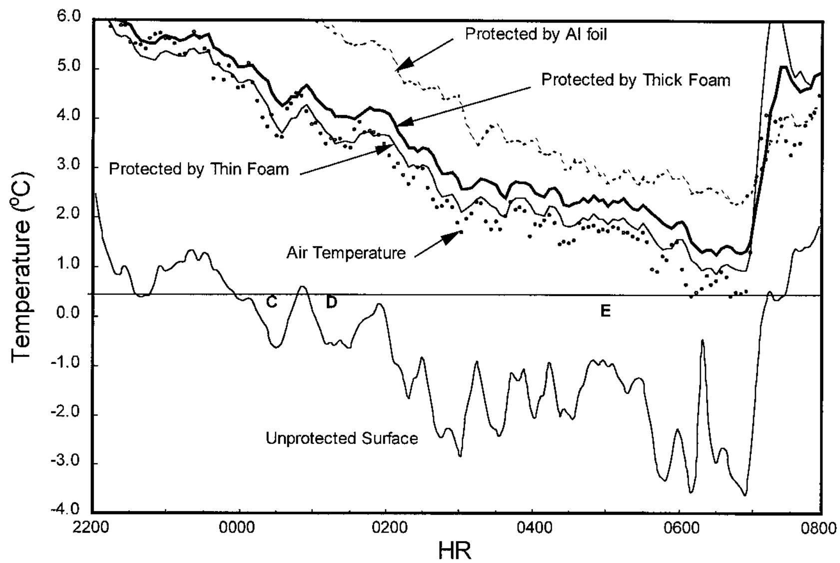


Fig. 7. Temperature of protected and unprotected copper plates. °F = 1.8 (°C)+32; (a) 21 Feb.; (b) 25 Feb.

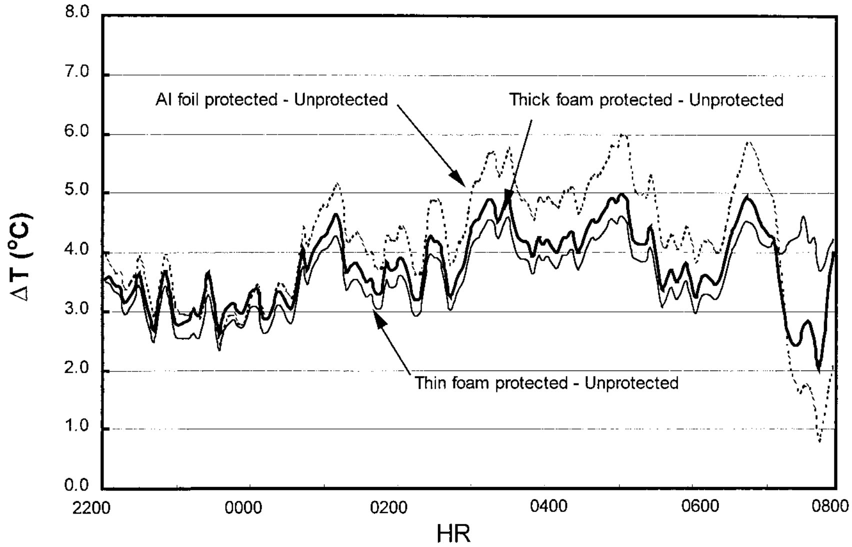
tion experiments were conducted during 6 nights (12, 14, 18, 21, 23, and 25 Feb. 1998), as determined by the appropriate weather conditions (wind, temperature, and cloud cover) from the nearby weather station. The weather conditions of 21 and 25 Feb. were particularly favorable to observe the effectiveness of foam to prevent frost. On 21 Feb., there was little wind [generally under 1 $m \cdot s^{-1}$ (3.3 ft/s) in the morning] and the average air temperature between 0600 to 0700 HR. was ≈2 °C (35.6 °F), as presented in Fig. 6a. Only a thin cloud cover remained through the evening until the early morning. On 25 to 26 Feb. (see Fig. 6b), the average wind speed was over 1 $m \cdot s^{-1}$ (3.3 ft/s) from 0400 to 0600 HR, while the minimum air temperature dropped nearly to the freezing point, and the sky was almost clear.

Temperatures of the copper plates and the air shown in Fig. 7a and b demonstrate that the copper plates protected by thick or thin foam layers maintained consistently higher temperatures than the unprotected plate. Therefore, it is obvious that the aqueous foam could be used as a radiation shield against the cold night sky. The temperature differences were as high as 5 °C (9 °F), as shown in Fig. 8a and b. As expected, aluminum foil minimized the radiation loss, and the plate protected by the foil maintained the highest temperature for both nights. The plate protected by thick foam maintained a slightly higher temperature than the plate protected by thin foam. It should be noted that the foam was prepared on 12 Feb., and the water content must have reached the minimum asymptote before the experiment, as described by Choi et al. (1999). Nevertheless, both thick and thin foam acted as good radiation shields.

In Fig. 7b, the unprotected (no foam covering) plate exhibited significant temperature fluctuations during the early morning period (0300 to 0700 HR) in comparison with the data in Fig. 7a. In particular, the temperature increased significantly [more than 3 °C (5.4 °F)] at 0630 HR, while the temperature of the other plates remained nearly steady. These fluctuations were probably due to continuously changing wind and cloud conditions. Cloud cover changes would more directly affect the unprotected plate, which was fully exposed to longwave radiation losses and thus more sensitive to the changing environment, than the other plates that were protected either by a foam layer or by aluminum foil. If there were a gust of wind, the unprotected plate should have readily gained thermal energy by convection. On the other hand, the convective heat transfer on the protected (foam covered) copper surface must have been negligible, because the plate temperatures were nearly equal to the air temperature. It should be noted that the temperature readings of protected plates were generally higher than the air temperature, probably a result of heat transfer from the insulator under each plate, although both conductive and radiative energy losses were minimized by several layers of aluminum foil between each plate and the insulation.

In an effort to quantify the effectiveness of the foam as an insulator, the following equation was developed, $\eta = T_{Foam\ protected} - T_{Unprotected} / T_{Al\ protected} - T_{Unprotected}$, where η and T represent the effectiveness of the foam and the temperature of the various copper plates, respectively. In the above equation, the temperature difference, $T_{Al\ protected} - T_{Unprotected}$, represents the maximum potential difference of temperatures due to radiation heat loss for the given weather conditions and is used as a reference base. The effectiveness (η) ranges from 66% to 80% for the thin foam and from 74% to 86% for the thick foam, as shown in Table 1, when the temperature of the unprotected plate surface drops under the freezing point (regions A–E in Fig. 7a and b). Overall, the effectiveness of the thick foam was only ≈6% to 8% higher than that of thin foam. The average effectiveness of the foam on 26 Feb. decreased ≈5% compared with results on 22 Feb., due, in part, to the degradation of the foam.

a)



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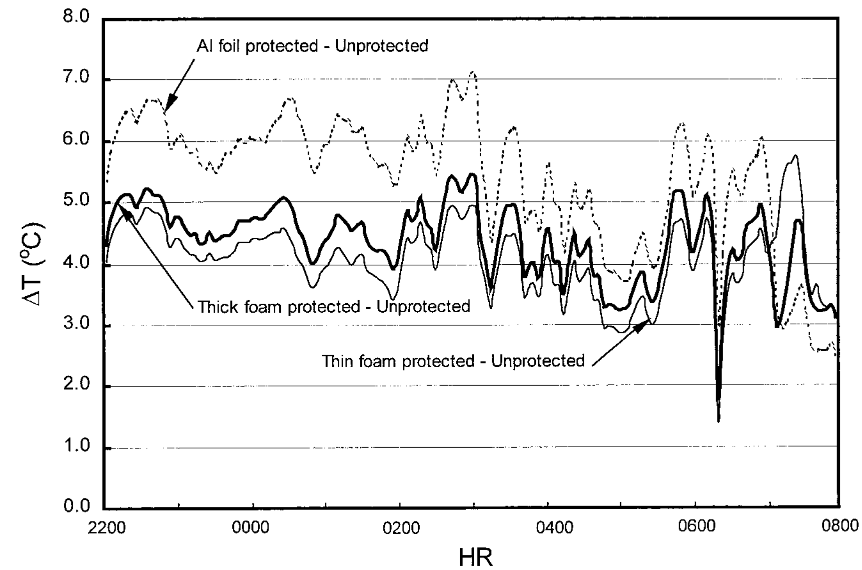

Fig. 8. Temperature differences (ΔT) of protected and unprotected copper plates. °F = 1.8 (°C) + 32; (a) 21 Feb.; (b) 25 Feb.

Conclusions

The foam protected soil was effectively insulated and generally exhibited temperatures that were 3 and 5 °C (5.4 and 9 °F) above that of the bare soil for the thin and thick foam covers, respectively. When compared to air temperature, these values increased to 10 and 8 °C (18.0 and 16.2 °F), respectively. Radiation heat losses from the plant leaf canopy were reduced on clear nights by an application of foam directly to the leaf. Temperatures were from 3 to 4 °C (5.4 and 7.2 °F) higher than the air temperature. Leaves were not damaged after being covered with the foam for 14 d.

Thermocouples on the copper plates effectively measured radiation heat losses under clear sky and cloud covered conditions. The aqueous foam proved to be an effective radiation shield against the cold night sky, and temperature differences as high as 5 °C (9 °F) were measured between the covered and uncovered plates. The foam covered plates were ≈80% as effective as the aluminum foil covered plates in reducing radiation heat transfer. The foam maintained its integrity under dry weather conditions for a total of 8 d and nights of exposure.

In conclusion, the gelatin-based, aqueous foam can be used as biodegradable soil mulch. The foam can potentially protect the aerial portion of both low and high profile crops from damage by below freezing air temperature, and from frost caused by radiation heat loss under clear sky night conditions. The foam can easily adhere to plant canopies, branches and trunks of freestanding tall trees, and unless washed away by water spray, the foam structure will be maintained in typical outdoor environments.

Table 1. Effectiveness (η) of foam as insulator for specific time periods on 21 and 25 Feb. T_{Al}, $T_{Thin\ foam}$, and $T_{Thick\ foam}$ denote the temperature readings of copper plates protected by aluminum (Al) foil, thin foam, and thick foam, respectively.

Region in Figs. 7a and b where $T_{Unprotected}$ < 0 °C (32 °F)	$\eta_{Thin\ foam}$[z]	$\eta_{Thick\ foam}$[y]
A	78.0%	84.0%
B	80.2%	85.7%
C	67.7%	75.4%
D	66.2%	74.2%
E	75.1%	81.8%

[z] $\eta_{Thin\ foam} = (T_{Thin\ foam} - T_{Unprotected})/(T_{Al} - T_{Unprotected})$
[y] $\eta_{Thick\ foam} = (T_{Thick\ foam} - T_{Unprotected})/(T_{Al} - T_{Unprotected})$

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