Protecting Plants From the Cold

The Principles and Benefits of Plastic Shelters

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Summary

The desire for plants out of season spurs the invention of shelters for plants. In this Bulletin, shelters, frost protectors in the field, and heated frames or houses, are examined with particular attention to plastics.

The frost protection provided by an unheated covering was moderate, about 3°F. Surprisingly, the degree of protection was the same for shelters of diverse abilities to produce a "greenhouse" effect through the absorption of long-wave, outgoing radiation. Heating shelters 20° above the average minimum temperature outside required about 5 kilowatt-hours or 17,000 B.T.U. per square foot per month; once again, large differences in ability to absorb outgoing radiation caused only tiny differences in heat loss.

The film of dew deposited on the covering film in a field or in a "greenhouse" is nearly opaque to long-wave radiation; thus, films of different absorptivities became equally opaque to outgoing radiation when they were used for shelters. Other items in the energy budget also were examined: conduction of heat from the soil, convective exchange with the air outside, condensation and evaporation, and heat from fuel. When the budget was balanced, we found that the 2 to 5 degrees of protection offered by an unheated shelter represented an equilibrium which was difficult to change. The budget revealed, however, that a moderate expenditure of fuel could provide considerable warmth.

Shelters of plastic and waxed paper protected plants from frost until the minimum temperature reached 25° in a Weather Bureau shelter. Exposed plants had survived a minimum of 31°.

The yield of early tomatoes was increased by shelters in a cool spring, decreased by shelters in a warm spring.

The maximum probability of shelters providing needed frost protection is about 4 out of 10, the corresponding probability of their failing is about 1 out of 10 and of their being unnecessary is about 5 out of 10. This maximum probability of benefit is obtained if the plants are transplanted near the mean date of last occurrence of 30°.

Springs as cool as in 1956 are rare and the associated spectacular increases in yield of early tomatoes also must be rare. Springs as warm as 1957 are common and the need for ventilating or removing shelters also must be common.

Acknowledgments

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Protecting Plants From the Cold

The Principles and Benefits of Plastic Shelters

Paul E. Waggoner

Man perennially pushes his favorite plants into more frigid climates, risking a possible loss to frost in the hope of gaining beauty, a choice food, a premium for an early crop, or the envy of his neighbor. Plants are set out ever earlier and ever nearer the poles in the annual lottery with frost.

No gardening loss is more sudden, dramatic, and melancholy than that caused by frost.

> "Seldom does the opportunity occur to observe such pronounced changes in nature as after a sudden frost. Plants that were previously bursting with life now offer a picture of complete destruction; everywhere are leaves and young shoots limp and blackened as though burnt by the frost. Tender shoots lie on the ground robbed of their turgor. Flowers have become wilted, their lively colors replaced by brown and dirty shades" (Maximov, 1914).

Naturally, man has devised schemes for protecting his plants from the cold.

Frost protection is always possible, but it is only occasionally practical. Heated shelters such as greenhouses and hot beds will always protect, but the cost of fuel and construction must be borne. Unheated shelters such as cold frames and caps or cloches over plants in the field require no fuel and are cheap to construct, but the degree of protection is limited. Thus, the probability of benefit must be compared to the cost. The probability of benefit depends, for one thing, upon the probability of frost.

A plant protector must admit the short-wave radiation from the sun that is needed for photosynthesis and warming, and, at the same time, the protector must prevent the loss of heat by long-wave radiation as well as by convection.

The short-wave solar radiation that reaches the earth and the plants on it is partly reflected, partly used in evaporation, and partly used in warming everything on which it falls. The energy of the earth and plants is lost by convection and long-wave radiation (Fig. 1). Any closed structure will decrease the loss of energy by convection, but those made of glass are peculiar: they allow some 90 per cent of the energy from the sun to enter, but hardly any of the outgoing long-wave radiation to escape. This peculiarity makes them valuable for greenhouses and cold frames and produces a "greenhouse" effect. Whether the glass shelter is a greenhouse heated by steam or a cap heated by the warm soil, the principal is the same. Thus, a covering of glass helps protect plants from cold winds in the day time and from frosts at night.

Gardeners have long sought a less costly, lighter material than glass from which to build protectors. They have used paper and early plastic films (Conin and Sherman, 1930; Hibbard, 1932, and Ware, 1936) and, more recently, newer plastic films (Uehara and Isozaki, 1953, and Emmert, 1955). Polyethylene has found wide use in the construction of greenhouses and row covers. However, the high transparency of polyethylene to the long-wave radiation that cools the earth suggests that this film will not produce the same greenhouse effect as does glass.

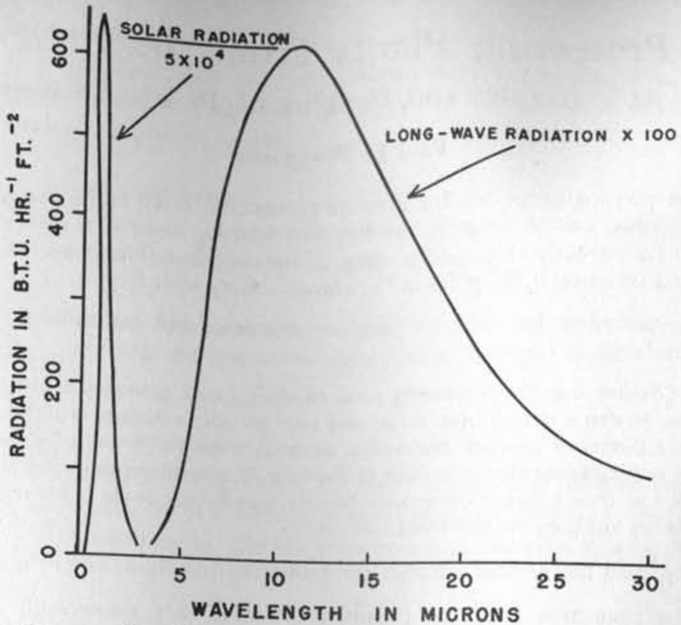

Figure 1. Energy radiated by the sun (short-wave) and by the earth (long-wave) at different wavelengths.

If this is true, then a plastic that absorbs long-wave radiation would be markedly better.

In this Bulletin we report measurements of the degree of frost protection provided by unheated shelters or row coverings made of a variety of plastic films with contrasting abilities to absorb long-wave radiation. The energy loss from heated shelters covered with several materials has also been measured. Following these practical observations, the principle of operation or the energy budget of the plastic shelters is examined. Finally, we examine the effects of unheated shelters upon a model, frost-sensitive plant, the tomato, and estimate the probability of a benefit from this practice in four climates: southern New England, New Jersey, northern Iowa, and southern Missouri.

Protection From the Cold by Unheated Shelters Covered With Films of Diverse Absorptivities

The daily minimum temperature in a shelter will exceed that in the open by a number of degrees. This number is a measure of the degree of frost protection provided. If we concern ourselves only with that important type of frost that occurs on clear mornings, we can estimate the degree of frost protection by taking temperature observations inside and outside of the shelter on a clear morning whether or not plants are present or frost occurs. Several investigators have already made such observations; we shall express their results in the familiar Fahrenheit degrees (in which all temperature measurements in this publication are expressed). A ventilated cap provided 3° of protection at a height of 4 inches and 8° of protection at a height of 1 inch (Schmidt, 1929). Waxed paper caps and continuous paper row coverings gave 4 to 5 degrees of protection in the center of the enclosed air (Hibbard, 1932). Polyethylene row coverings were said to protect crops against temperatures of 25°, i.e. they provided 7° of protection (Emmert, 1955). A glass cloche or bell gave 9° of protection (Franklin, 1955). Evidently we can expect 3 to 7 degrees of protection near the center of protectors. Does the exact degree depend upon the ability of the various films to absorb the long-wave radiation that cools the soil and plant?

Three plastics of contrasting abilities to absorb long-wave radiation were chosen to test the effect of this characteristic upon the degree of frost protection. Polyethylene is notorious for its inability to absorb long-wave radiation. This characteristic can be estimated: the per cent absorption in 0.002 inch of the film at each unit wavelength from 3 to 15 microns is multiplied by the intensity of long-wave radiation from the earth (black body, 32°); the products are added; and this sum is divided by the sum for perfect transmission. Polyethylene absorbs one-eighth of this important portion of the long-wave radiation from the earth.

The second plastic, an acrylonitrile-styrene copolymer marketed as "Sisalglaze," "Polyflex II," and "Polyflex 230," was chosen because its transmission is in sharp contrast to polyethylene. A 0.005-inch film of what we shall call Sisalglaze absorbs fully two-thirds of the long-wave radiation defined above.

The third plastic was polyvinyl chloride with a dioctyl phthalate plasticizer. A film of this material 0.002 inch thick absorbs one-half of the long-wave radiation we are considering.

As a reference we can add glass which will be found by the same method to absorb 99 per cent in a plate 0.125 inch thick. This gives a point of reference for the one-eighth absorption by polyethylene, two-thirds by Sisalglaze, and one-half by polyvinyl chloride.

The foregoing estimates of the fraction of the outgoing radiation which the films absorb have limitations. First, the visual averaging of percentage absorption from the absorption spectra introduces some small errors. Second, and more important, we have no information regarding the absorption at the wavelengths greater than 15 microns, wavelengths where nearly half of the radiation from the earth is emitted. We shall proceed on the assumption that the order of the absorptive abilities determined above would not be changed if their characteristics above 15 microns were known. That is, Sisalglaze absorbs more of the outgoing radiation from the earth than does polyethylene, and polyvinyl chloride is intermediate. Later we shall present some confirmation of this statement.

Assuming the importance of the greenhouse effect or the absorption of long-wave radiation, we predicted that the degree of frost protection should be greater from Sisalglaze than from polyethylene, with polyvinyl chloride being intermediate. This prediction was tested by constructing continuous row coverings of the three plastics, and then measuring the difference in minimum temperature between inside and outside.

The coverings or shelters were erected on Gloucester sandy loam 100 feet from the nearest trees or buildings. The area was level, the soil bare and wet to field capacity. The rows covered by the shelters ran north-south and were 48 inches long. The films were supported at 12-inch intervals by wire wickets 18 inches tall and 18 inches wide at the soil line. The film was secured at the soil line by burial in a trench. The rows covered by the shelters were 48 inches apart, leaving 30 inches between the sides of the shelters. Similar shelters have been constructed by Emmert (1955).

The temperatures were measured by copper-constantan thermocouples made of 30-gauge wire. An ice-water mixture was used as a reference. The potentials were measured by a Leeds and Northrup recording potentiometer; a distance of 1.43 inches on the chart corresponded to 1 millivolt or 45°. The temperatures were read from the chart to the nearest one-quarter degree.

A thermocouple was suspended 25 inches above the bare soil plot; three other thermocouples were suspended at the same height but above the shelters. Four other thermocouples were suspended 0.4 inch above the bare and the sheltered soil surfaces. The temperatures of all eight thermocouples were observed in 32 seconds, and the temperatures of the pair of thermocouples, one 25 and one 0.4 inches, above each plot were observed within 4 seconds.

The temperature of the air as measured by 30-gauge thermocouples changes rapidly with time; these temporal fluctuations should be minimized in our comparisons or estimates of degree of protection. This was accomplished by first referring each 0.4-inch temperature to the 25-inch temperature above it, which was taken only 4 seconds before. Having thus eliminated much of the time-change from the observations, the degree of protection was estimated by comparing these corrected temperatures for the shelters to those for the open surface. The adjustments can be summarized:

> Degree of protection = (Temperature at 0.4 inch in the shelter – Temperature observed above the shelter and 4 seconds before) – (Temperature at 0.4 inch in the open – Temperature observed above the open surface and 4 seconds before).

We have discussed the plastic films in terms of the ability to absorb radiant heat. Therefore, for reference we required a measure of the radiation of all wavelengths striking and leaving the soil surface. This was provided by a net radiometer (Gier and Dunkle, 1951) which measured the difference between incoming and outgoing radiation received on a level surface 36 inches above the soil. The net flow of radiation is conveniently expressed in B.T.U./hr.ft.^{2} and assigned a positive sign when the earth is gaining heat, a negative sign when the earth is losing heat. The net radiation for October 2-3 is presented in Table 1. The maxima reached during the 2 days are about half of the maxima reached on clear days in June. The minimum is typical of a clear night.

Table 1. Net flow of radiation in B.T.U./hr.ft.^{2} over bare soil, October 2-3, 1956, Guilford, Connecticut

2 P.M.	4	6	8	10	M.D.T.	2 A.M.	4	6	8	10	Noon	2 P.M.
175	20	−15	−18	−13	−13	−13	−13	−9	35	128	103	97

The protection provided by the shelters on October 2-3, 1956 is presented in Figure 2. The results are typical of those obtained on the three preceding days. The days and nights were mostly cloudless and the films were wet with dew on the inside. The important features of these observations are obvious: the increase in temperature and in heat storage in the soil caused by the shelters may be large in the daytime, but the protection is a modest 2 to 4 degrees at night; and the protection under all materials, day or night, is about equal, regardless of the varying abilities of the films to absorb the 3 to 15 micron wavelengths of the long-wave radiation that accomplishes much of the cooling of the surface of the soil. The "protection" of about 15° during the day may well prove too hot for plants.

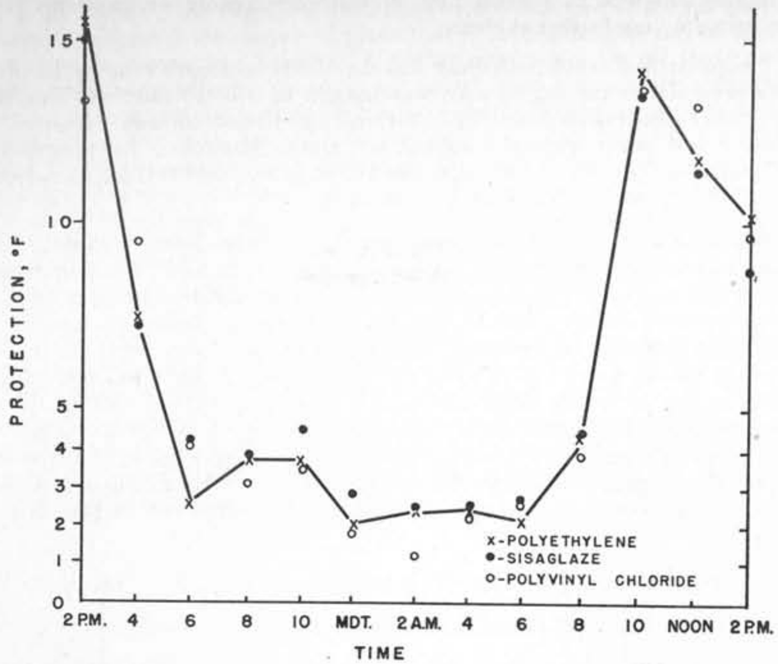

Figure 2. The degree of protection provided by films used as row coverings. Zero protection indicates that the adjusted temperatures at a height of 0.4 inch in a shelter and in the open are equal. Oct. 2-3, 1956.

Some variation in the degree of protection will occur from day to day and season to season as the heat coming from the nighttime source—the soil—is changed. An increase will occur in April and May when the sun is more nearly overhead than it is in October; then the net flow of radiation will be doubled, approaching 200 B.T.U./hr.ft.^{2} at midday, and more heat will be stored in the soil during the daylight hours. The temperature within the shelters at midday will be torrid. Also, an increase will occur whenever the porosity of the soil is decreased by compaction, thus increasing the transfer of heat from the soil to the air. The addition of water to dry soil also will increase the diffusivity and, hence, the protection (van Duin, 1956). A mineral soil will provide more protection than an organic soil.

The observation that a covering of a film that absorbs more longwave radiation will produce no more protection seems firmly established when a film that absorbs two-thirds of important radiation provides no more protection than a film that absorbs only one-eighth of this radiation with wavelength of 3 to 15 microns. The evidence of Figure 2 is consistent with observations made in Japan (Kaneseki and Miyagawa (1954). Variations in the absolute degree of protection provided by shelters should not affect the protection one film will provide relative to that provided by another film. Nevertheless, before we leave this point, let us bring to bear further evidence.

Neoprene film 0.005 inch thick has the ability to absorb nine-tenths of the earth's radiation in the region with wavelengths of 3 to 15 microns. This is an even greater proportion than the two-thirds absorbtion already estimated for Sisalglaze and much greater than the one-eighth absorbtion by polyethylene 0.002 inch thick. Therefore, a comparison of the protection provided by polyethylene and neoprene films was most informative.

Row covers similar to the ones already described were erected on bare Cheshire sandy loam on the clear night of August 22-23, 1956. The polyethylene covering ran 144 inches, the neoprene ran 48 inches north-south. The neoprene covering was 24 inches south of the polyethylene one. Because neoprene deteriorates in sunlight, the coverings were not installed until 8:30 P.M., thus the protection provided was entirely due to the trapping of heat and not partially due—as in the preceding experiment—to a greater storage of heat in the soil during the preceding day. Temperatures were measured by thermocouples and a portable potentiometer; with this instrument about 8 minutes were required to observe the temperatures of all 32 thermocouples; temporal fluctuations were minimized by averaging four sets of observations completed in less than 40 minutes.

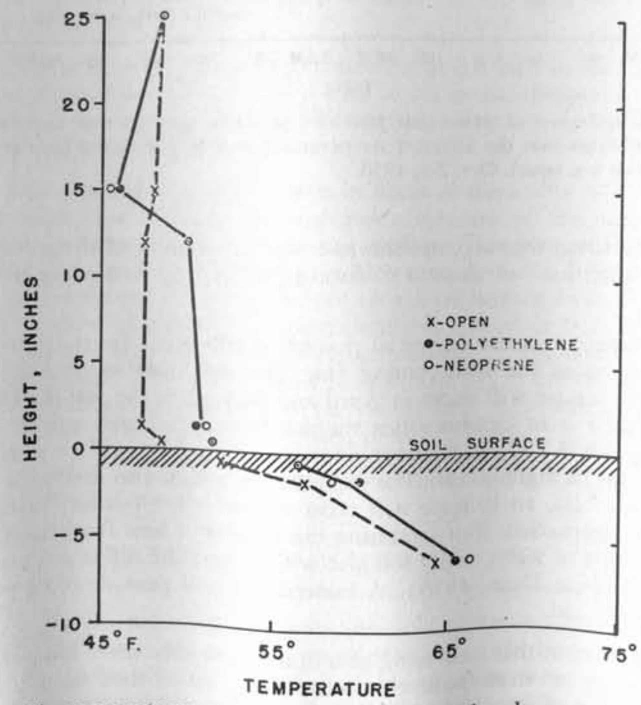

Figure 3. The temperatures at 5:30 a.m. in the open and under row coverings erected the preceding evening.

The observations taken at 5:30 A.M., which was near the time of minimum temperature, are presented in Figure 3. Different devices are used in Figures 2 and 3. In Figure 2 the degree of protection at 0.4 inch and at several hours can be seen, in Figure 3 the degree of protection at several heights can be seen at a given time. Beginning at a height of 25 inches, which is in the air above the two shelters and above adjacent bare soil, we found equal temperatures (Figure 3). The tops of the two shelters, 15 inches, were both cooler than the adjacent air; the films were wet with dew. Within the shelter at heights of 12, 1.6, and 0.4 inches, 3° of protection were provided. The soil at shallow depths cooled measurably less when a shelter was in place. The estimate of 3° of protection is of practical importance: this is that proportion of protection due to protection from cooling as opposed to the proportion due to the additional heating of soil beneath the tent on the previous day; therefore, 3° must be the lower limit of protection provided by the tents.

This second experiment (Figure 3) clearly verifies the first (Figure 2): although plastic films may range from one-eighth to nine-tenths in the proportion of important long-wave radiation which they absorb, the degree of protection they provide is nearly equal. Certainly, the importance of the greenhouse effect is not predominant or we have measured it in the wrong way. Before we seek a solution to this problem, let us present a further comparison of the films, a comparison of heat losses from heated shelters.

Heat Loss From Heated Shelters Covered by Materials of Diverse Absorptivities

Whether a shelter against the cold is warmed by the heat in the soil or in steam or electricity, the principle is the same. In the preceding chapter we measured the degree of protection provided when equal or nearly equal amounts of heat were applied. Now we shall consider the amounts of heat required for equal protection, as in a greenhouse. Once again we shall determine the importance of the absorption of long-wave radiation in the covering material by comparing materials of diverse absorptivities.

Three frames of Celotex three-quarters of an inch thick were erected on Cheshire sandy loam in mid-March, 1957. The frames were 12 inches high at the north end and tapered to 8 inches at the south end; their lower edge was buried in the soil 1 to 2 inches. The frames were covered by conventional cold-frame sash measuring 36 by 72 inches. One sash was glazed with glass, 0.125 inch thick; one with Sisalglaze, 0.005 inch thick; and one with polyethylene, 0.005 inch thick. The sash were sealed to the frames with adhesive tape, and the glass was sealed to the sash by transparent tape. We have estimated that one-eighth inch of glass absorbs 99 per cent of the important radiation of wavelengths between 3 and 15 microns whereas 0.005 inch of Sisalglaze absorbs two-thirds and 0.005 inch of polyethylene absorbs only one-fourth.

The minimum temperature of the air inside all three shelters was maintained at 44 to 52° by electrical heating cables lying on the soil. The minimum air temperature within each shelter was determined by an exposed minimum thermometer, and data for all days when the range of the three minima exceeded 4° were discarded. Electrical energy used was measured by three watthour meters. The sash were moved three times during the course of the experiment, each material used several days with each frame and meter to cancel out differences in equipment.

The frames were heated from March 14 to April 18, 1957, and satisfactory observations for 30 days were accumulated. During these weeks the oats within the frames grew until they pressed against the glass and film which were constantly wet with dew. The sun shone 57 per cent of the possible hours; the minimum daily temperature was below 50° a total of 596 degree-days during the 30 days. The consumption of energy is presented in Table 2.

Table 2. The consumption of energy in heating a frame to about 50° F for 30 days in March and April, 1957

Covering material	Thickness	Energy consumed for each square foot of sash	
	Inches	*Kilowatt hours*	*B.T.U. (thousands)*
Glass	0.125	4.6	15.9
Sisalglaze	0.005	4.8	16.3
Polyethelene	0.005	5.2	17.8

The findings presented in Table 2 provide a ready answer to the practical question: "How much does it cost to heat a frame for the protection of early plants?" More heat will be lost if the frame is kept warmer than 50° or if the outside temperature is lower. More or less fuel will be required if clouds cover the sun more or less than the 57 per cent we encountered.

The energy losses through the films and glass can also be estimated from these data because the losses through the soil and the frame are negligible. The relative losses by conduction through the known areas and thicknesses of glass, film, and Celotex are presented in Table 3; a thickness of 2 inches is assumed for the soil because the constant minimum temperature in the frame undoubtedly raised soil temperature above 50° to a considerable depth.

Table 3. The relative possible heat losses by conduction through the tops, sides, and bottoms of the heated shelters as calculated from thicknesses and thermal conductivities

Glass	Sisalglaze	Polyethylene	Celotex	Soil
		Relative heat losses		
100	230	880	6	6
		*Thermal conductivities**		
1.3	0.16	0.64	0.08	1.6

* Thousandths of a B.T.U. conducted per square foot per second for each degree difference through an inch thickness.

Clearly, losses other than through the glass and film are negligible. This was demonstrated dramatically during an ice storm: the ice clung to the sides of the frames but quickly melted when it struck the glass or film.

We can now estimate the relative losses by radiation and conduction through three materials of diverse absorptivities for long-wave radiation by referring to Table 2. The relative heat losses have a range equal to only one-fifth of the smallest loss; this is strikingly different from the range in abilities to transmit radiation of 3 to 15 micron wave length, a range some 75 times as great as the smallest loss. In this last experiment with heated shelters, we can see some difference, one-tenth, between a film, on one hand, that is a good absorber of radiation and a good insulator and a film, on the other hand, that is not. In the larger view, however, the results of the experiments with heated and unheated shelters are the same: large differences in absorptivities cause only small or negligible differences in heat loss or degree of protection.

The first phases of our presentation are now completed: the degree of protection from plastic row coverings has been estimated as modest, but greater than 2°. The heat losses through plastic-glazed sash over heated shelters has been estimated as 10 to 20 per cent more than through sash glazed with 0.125-inch glass (25 times as thick as the plastic sash). The differences in protection and heat loss among plastic shelters has been found to be dramatically less than the differences among the absorptivities of the films for 3 to 15 micron, long-wave radiation.

Heat Budget of Shelters

The gains and losses of heat by a shelter, its energy budget, determine the degree of protection provided by an unheated shelter or the cost of operating a heated one. The budget should permit us to understand the behavior of our present shelters and predict the behavior of others. Primarily, the exchange of energy we consider is that at the shelter's boundaries: the film and the soil line. This exchange is compared between shelters of different plastics and between shelters and the exposed soil.

A shelter exchanges energy with its surroundings by several means:

R_I = incoming radiation,
R_o = outgoing radiation,
S = conduction from the soil,
A_v = vertical exchange with the air by conduction and convection,
A_h = horizontal exchange with the air,
W = change of state of water, such as condensation,
H = heat from fuel.

When the temperatures inside and outside the shelters have reached equilibrium, the sum of the gains and losses must be equal to zero:

$$R_I + R_o + S + A_v + A_h + W + H = 0.$$

This is approximately the state reached during the important early morning hours when the temperatures are low and changing very slowly.

Radiation. The incoming and outgoing radiation of all wavelengths, R_I and R_o, should differ between unsheltered and sheltered locations as well as between, say, polyethylene and Sisalglaze. An equal thickness (0.005 inch) of polyethylene absorbs only one-fourth and Sisalglaze absorbs two-thirds of an important portion of the outgoing, long-wave radiation, as has already been noted. Observations of the actual radiation in the field improve our understanding of the failure of plastics of high and low absorptivities to produce different degrees of protection.

Plastic films, 0.005 inch polyethylene and Sisalglaze, were supported at a height of 72 inches by the framework pictured in Figure 4. The level Cheshire sandy loam was wet to field capacity and supported a sparse growth of closely-mown grass. The temperatures of the films or of the air at the same height were measured by 30-gauge copper-constantan thermocouples and a recording potentio-

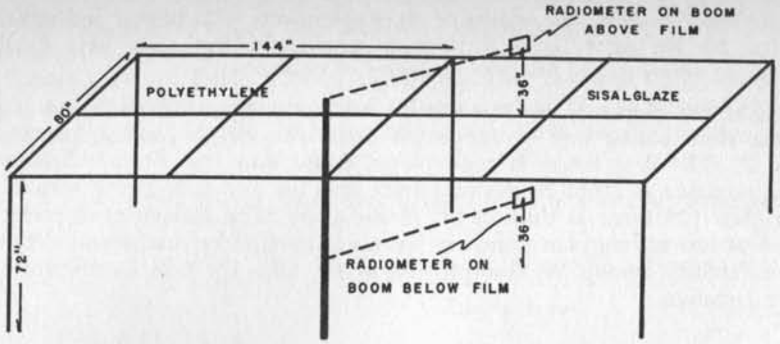

Figure 4. Plastic shelter and radiometer used in estimating radiation budget.

meter; the temperature of the soil was measured by thermocouples resting on its surface in grass-free spots 4 inches in diameter. The net radiation, $R_I - R_o$, and hemispherical radiation, R_I or R_o, received on horizontal surfaces were measured by the potentiometer and radiometers (Gier and Dunckle) at distances of 36 inches below and above the plastic and at the same level above open soil. The potentiometer had a response of 1 inch on the chart for 10° or for about 4.4 B.T.U./hr.ft.^{2}. The net radiometer was calibrated against the hemispherical, providing that the same net radiation would be indicated by the former and by the difference between the latter facing the sky and then the earth. The same meters were used for all positions, and temporal changes were eliminated by referring the meter under the plastic to the one in the open.

The effect of the shelters upon the outgoing radiation, R_o, from the soil was determined by an inverted hemispherical radiometer moved from the shelter to the open. Near 2 P.M. on September 18, a clear day, the R_o from the soil and grass beneath the polyethylene was 98.0 per cent of that in the open; at the same time the R_o beneath the Sisalglaze was 96.2 per cent of that in the open. R_o can be estimated from soil line temperatures by Stefan's law, ignoring the grass. The temperatures of the soil lines led to estimates of 96.7 and 98.2 per cent for R_o beneath polyethylene and Sisalglaze relative to R_o in the open. In our subsequent calculations we assumed R_o beneath the shelters was 97 per cent of that outside.

Similar estimates of the R_o were made near 7:30 P.M. The observations with the radiometer showed that the R_o's beneath the polyethylene and Sisalglaze were 101 and 102 per cent of R_o in the open. The temperature observations led to estimates of 101 and 103 per cent for polyethylene- and Sisalglaze-sheltered surface. The percentages observed with the radiometer were used in subsequent calculations.

The daytime radiation beneath the shelters was measured between 12:01 and 12:12 P.M. on a day with scattered clouds. Hemispherical radiation in the open and net radiation in the open or under a shelter were observed at 3-second intervals, continuous records of both were easily interpolated, and the data of Figure 5 were obtained at maxima, i.e. nearly steady states. Calculations were made as follows, assuming no variation in R_o during the 12 minutes required for the series:

$$R_{I\ \mathrm{open}} - R_{o\ \mathrm{open}} = R_{\mathrm{net\ open}}$$
$$R_{I\ \mathrm{shelter}} - 0.97\,R_{o\ \mathrm{open}} = R_{\mathrm{net\ shelter.}}$$

These results are presented in Figure 5 along with the temperatures of the films and air.

The radiation above the shelters was measured between 12:45 and 12:52 P.M. or within the same hour as the measurements beneath the shelters. Data were obtained from the charts as described above. Calculations were made as follows:

$$R_{I\ \mathrm{open}} - R_{o\ \mathrm{open}} = R_{\mathrm{net\ open}}$$
$$R_{I\ \mathrm{open}} - R_{o\ \mathrm{shelter}} = R_{\mathrm{net\ shelter}}$$

These results also are presented in Figure 5.

The temperatures of film and air were measured within a 30-second period near 12:32 P.M. and are given in Figure 5. The shadows of the framework confused temperature measurement at the soil surface, and these data are omitted.

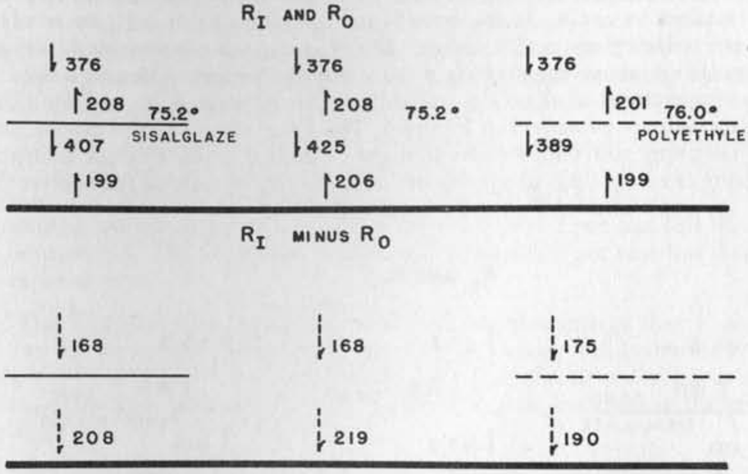

Figure 5. The radiation flux in B.T.U./hr.ft.^{2} above and below a polyethylene and a Sisalglaze film 0.005 inch thick and at the same heights in the open. Observed at 12:01-12:52 p.m., Sept. 18. Temperatures are in degrees Fahrenheit. R_I is directed downward, R_o upward.

The polyethylene decreased the incoming radiation beneath it by 8 per cent, the Sisalglaze by 4 per cent. Consequently, the soil beneath them was somewhat cooler and the outgoing radiation was 3 per cent less than in the open. Nevertheless, the net radiation was decreased 13 and 5 per cent beneath the polyethylene and Sisalglaze.

Sisalglaze had no effect upon the radiation above it. The outgoing radiation above polyethylene was decreased by 3 per cent.

The sum of transmitted and emitted radiation on both sides of the polyethylene film was less than that of the Sisalglaze because the polyethylene had both a lower transmission of short-wave and emission of long-wave radiation than the Sisalglaze. Both films surely had equal abilities to conduct heat to the air. Therefore, the greater gain in energy by polyethylene was manifested in a higher temperature as compared to Sisalglaze.

These estimates of decreased radiation are conservative because the shelters have finite dimensions and the radiometer beneath or above a shelter "sees" the open sky or the exposed soil at low angles above or below the horizon. However, the magnitude of the underestimation is small because the sun's radiation—which the radiometer sees only through the film—is much greater than sky radiation and because only the open sky or exposed soil radiation from less than 42° above or below the horizon reaches the radiometer without passing through the film.

We turn next to the nighttime. The twilight hours are the time of greatest net loss of energy by radiation and permit a clear view of the process. Accordingly, observations were taken above and below the plastic coverings at about a half hour after sunset on a clear evening. A light "fog" of dew was just appearing on the films. The observations below the shelters were completed between 6:30 and 6:37 P.M.; the changes in the radiation were slow and orderly; and the data were obtained by interpolating between duplicate observations to the center time at 6:33 P.M. Incoming, outgoing, and net radiation were calculated as they were for the daytime except R_o in the open is multiplied by 1.01 and 1.02 to obtain R_o beneath polyethylene and Sisalglaze. The observations are presented in Figure 6. The radiation above the shelters was measured between 6:38 and 6:44 P.M. and the temperatures of film, air, and soil surface between 6:47 and 6:52 P.M. These data also are presented in Figure 6. The lesser temporal and spatial variation in radiation and temperature at night permitted more efficient estimation than during the day. Comparisons at the same height, because of the shorter time elapsed, are more efficient than those between heights.

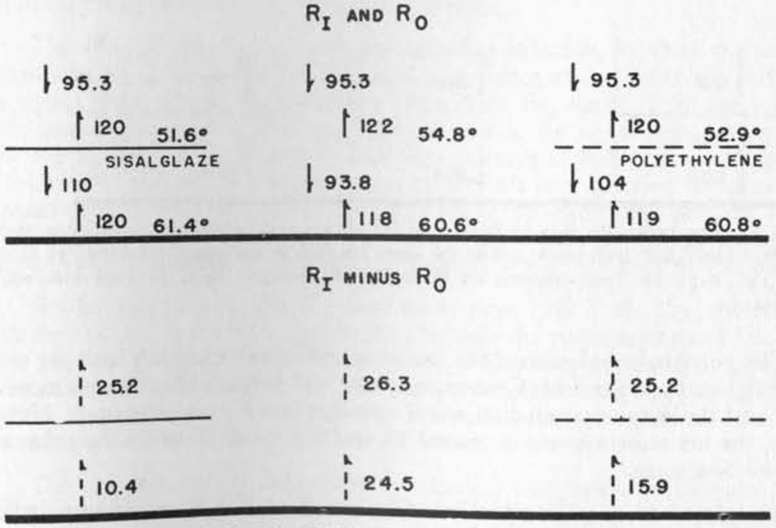

Figure 6. The radiation flux in B.T.U./hr.ft.² above and below a polyethylene and a Sisalglaze film 0.005 inch thick and at the same heights in the open. Observed at 6:30-6:52 p.m., Sept. 19. Temperatures are in degrees Fahrenheit. Dew had just begun to form on the films.

In the center of Figure 6 lies the unsheltered soil surface facing the clear, cold sky. Only 93.8 B.T.U./hr.ft.² from the sky reached this surface and it had cooled to 60.6°.

On the left is the surface sheltered by the Sisalglaze. This soil surface received the fraction of the sky radiation that the film did not absorb. In addition, this film—which is a fairly good absorber and, hence, emitter of long-wave radiation—sent radiation downward to the soil. The sum of the sky radiation not absorbed and the radiation emitted by the film was 17 per cent greater than the total sky radiation, greater because the film was effectively warmer than the gases in the sky. Hence, this soil surface was 0.8° warmer than the unsheltered surface. Although the sheltered surface was warmer than the unsheltered one and, hence, outgoing radiation was somewhat greater, the net radiation lost by the sheltered surface was only 42 per cent of that lost by the unsheltered one.

On the right of Figure 6 is the surface sheltered by polyethylene film. This soil surface received the fraction of the sky radiation that the film did not absorb. In addition, it received from the polyethylene a small amount of radiation, small because the film is a relatively poor absorber and, hence, a poor emitter. The sum of the sky radiation not absorbed and the radiation emitted by the film was 11 per cent greater than the total sky radiation because—once again—the film was effectively warmer than the gases in the sky. Although the sheltered surface was slightly warmer than the exposed one, the net radiation lost by the sheltered surface was only 65 per cent of that lost by the unsheltered one.

The radiation above the films was measured between 6:38 and 6:44 P.M. The incoming radiation at this new time and height was 95.3 B.T.U./hr.ft.². The outgoing radiation above unsheltered soil was 122 B.T.U./hr.ft.². The sum of transmitted and emitted radiation above both films was 2 per cent less than above the exposed soil. The net radiation above the films was 4 per cent less than above the exposed soil.

The Sisalglaze film transmitted and emitted more energy than it absorbed; this can be seen from the net radiation, $R_I - R_o$, above and below it, Figure 6. Thus, the observation that this film was cooler than the air about it was not surprising. The same phenomenon but to a lesser degree, occurred in the polyethylene film.

The net radiation was decreased by the shelters in the way that our calculations from absorption spectra led us to expect: Sisalglaze produced a greater decrease than did polyethylene. The contribution of that portion of the earth's long-wave radiation beyond 15 microns, a portion whose absorption is unknown to us, did not alter the assumed relative absorptivities of the two films. These facts happily confirmed our calculations; unhappily, they did not explain why Sisalglaze and neoprene had provided little if any more protection than polyethylene (Figure 2 and 3).

As the evening passed and the air cooled, a change in the shelters was apparent: the dew that was a light "fog" on the films at 6:30 became large drops of water on both the top and bottom of the films by 7:40 P.M. The shelters were no longer covered solely by the films of plastic that we had considered in theory; they were now covered by films of plastic and water. New observations of radiation and temperature were required.

The radiation beneath the shelters was measured between 7:36 and 7:43 P.M. The results, observed and calculated as before, are presented in Figure 7. The surface temperatures were measured within 30 seconds of 7:35 P.M. The incoming radiation measured at a height of 36 inches in the open was 96.4 B.T.U./hr.ft.². The exposed soil had cooled to 58.1°.

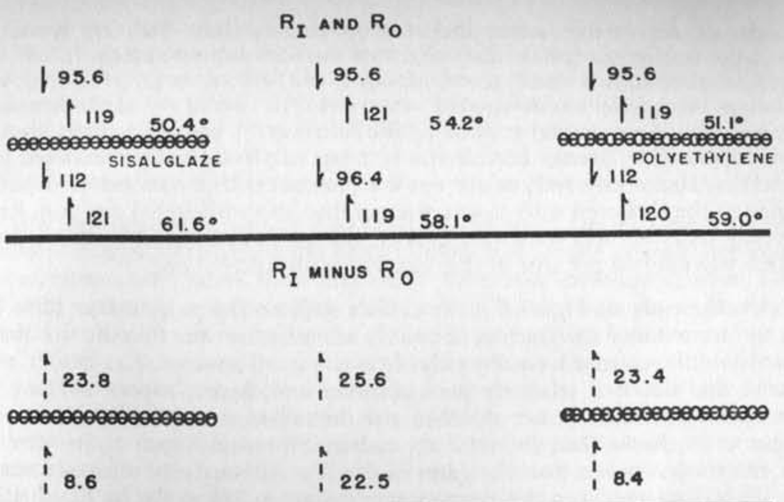

Figure 7. The radiation flux in B.T.U./hr.ft.^{2} above and below a polyethylene and a Sisalglaze film 0.005 inch thick and at the same heights in the open. Observed at 7:36-7:55 p.m., Sept. 19. Temperatures are in degrees Fahrenheit. Droplets of dew covered the films.

On the left and right of the unsheltered surface in Figure 7 stand the two shelters, shelters beneath which the net radiation varied from 10.4 to 15.9 only 70 minutes before. After these 70 minutes, the incoming radiation beneath them had increased, especially beneath the polyethylene, and the net radiation now varied by a negligible amount. The excess of the temperatures of the two sheltered soil surfaces above the temperature of the exposed soil was greater than it was 70 minutes before.

The radiation above the films was measured between 7:47 and 7:53 P.M., the temperature of the films within 30 seconds of 7:55 P.M. The incoming radiation measured at a level of 3 feet above that of the shelters, but over exposed soil, was 95.6 B.T.U./hr.ft.^{2}. The air at the level of the shelters was 54.2°.

Above the shelters, as below, the difference between the materials had largely disappeared. The sum of transmitted and emitted radiation above the two films was nearly equal. Consequently, both films were losing energy at the same rate and their temperatures had become more nearly equal. The films were net losers, and they were colder than the air about them.

The conservative nature of our estimates of differences has already been mentioned. However, the differences observed between the wet films are so small that they remain negligible even if they are doubled.

At last we can solve the mystery of how films of contrasting absorptivities are nearly equal in the protection they provide. On this final evening, we have seen how the divergence in radiational characteristics of two films disappeared as dew collected upon them. When the absorptivity of a film of water 0.002 inches thick is estimated for wavelengths of 3 to 15 microns, it is found to be over 99 per cent. Thus, a deposit of dew such as is generally found inside plastic row coverings and heated shelters or greenhouses increases the absorption and

emission of long-wave radiation. All plastics, when covered by dew, are capable of producing a "greenhouse" effect regardless of their absorption spectra; and differences among them in degree of protection disappear. Here, in the film of water on the plastic, is a large portion of the solution to the problem, "Why do plastics of diverse absorptivities produce nearly equal degrees of protection?" Because this dew is highly effective in absorbing long-wave radiation, only a slight increase in absorption can be expected from the addition of a second layer of plastic, a common practice among greenhouse operators.

In concluding this discussion of the radiation factor in the energy economy of plastic shelters, the decrease in net daytime gain can be set at about 10 per cent for dry film, 25 per cent for wet film (Kaneseki and Miyagawa, 1954). Significant decreases in light intensity are caused by a second layer of plastic, especially if excessive moisture accumulates between the layers and if the sunlight is dim. The decrease in net nighttime loss can be set at roughly two-thirds. The net loss beneath the shelters is less when the difference between the temperatures of the soil or plant and the film is less, more when the difference is more. The loss is much the same for all plastics so long as they are wet with dew.

Conduction of heat from the soil. The heat stored in the soil during the day is an important and economical source of heat for any shelter, particularly an unheated shelter on a cold night. This source of heat, called S, contributes some 10 B.T.U./hr.ft.^{2}. "Unheated" means that no fuel is being used, and only the warm soil is furnishing heat. Certainly the nature of this important storehouse must be examined.

The thermal properties of the soil are its conductivity, k, its specific heat, c, its density, d. These can all be related to the composition of the solid phase of the soil and the proportion of air and water in the soil (van Duin, 1956).

The amplitude S_o of the daily course of conduction in and out of the soil surface has been related to the amplitude T_o of the temperature course and to the thermal properties of the soil (van Duin, 1956, following Schmidt).

$$S_o = T_o\ (kcdf)^{1/2}$$

The f is the frequency of the periodic course of conduction and temperature and is a constant in our discussion.

First, the importance of the daily temperature variation T_o is obvious. If we set the permissible minimum temperature at 32° F, then doubling the excess of daytime temperature above 32 will double the conduction from the soil and, hence, assist in preventing freezing. The warmth of the daytime temperatures in a transparent shelter is largely a function of the brilliance of the sun. Smith (1951) has shown how the degree of protection is increased by increasing sunlight on the previous day.

The thermal properties $(kcd)^{1/2}$ are the other controlling factor. Table 4, based upon van Duin's nomographs provides a basis for discussion. Field capacities and wilting percentages of soils typified by the data of Table 4 provide a frame of reference for considering the water concentrations. The sand had a field capacity of 12.5 per cent, dry weight basis, and undoubtedly had a wilting percentage in the neighborhood of 4 per cent. The clay undoubtedly had a field capacity near 30 per cent and had a wilting percentage of 21.6 per cent. The peat was 90 per cent pore space. As a reference for the possible changes one can produce in bulk density, we have the evidence of Klute and Jacob (1949):

cultivation with a tractor increased bulk density from 1.25 to 1.32; a tractor and potato sprayer increased it to 1.46.

Table 4. The thermal properties $(kcd)^{1/2}$ of sand and clay based upon van Duin's calculations

Solid material	Bulk density	Water concentration % by dry weight	$(kcd)^{1/2}$, $\frac{\text{B.T.U.}}{\text{hr.}^{1/2}\text{ft.}^2\text{F}^\circ}$
Sand	1.25	4	1.7
		16	4.3
	1.50	3	2.2
		13	5.2
	1.75	3	3.2
		11	6.4
Clay	1.25	16	4.1
		24	5.0
		30	5.3
	1.50	20	5.7
		27	6.2
	1.75	17	6.5
Peaty soil*	about 0.2	about 300	1.4

* From Pessi (1956).

The properties $(kcd)^{1/2}$ and, hence, the conduction S are greater in sand and clay than they are in peat (Table 4). The frost hazard of peat is well known. The conduction also is seen to be significantly increased by increasing the density or compaction and by increasing the water concentration in the soil. Important increases in the conduction S from sand could be produced by increasing the water concentration from the wilting percentage to field capacity; the corresponding changes for clay are modest. Supporting flats of plants by dry gravel or by racks obviously decreases heat transfer and increases frost hazard. The increase in conduction S due to the compaction of either sand or clay is modest in view of the subsequent effects upon root physiology (de Roo, 1957).

The magnitude of the conduction S from bare Cheshire sandy loam was observed on two nights and provides an estimate for our discussion. This is the same soil used for the experiments of Figures 3 to 7. The flow of heat at a depth of 2.7 inches was measured at two locations by means of a heat flow unit inserted into a profile. The unit is basically the same as that in the radiometer (Gier and Dunkle, 1951). On the first night, July 27, the moisture concentration 1 inch above the heat flow units was estimated by fiberglass moisture units to be 5 to 8 per cent. Following this night, 1.16 inches of rain fell in 4 days. The second night of observations began 24 hours after these rains ceased, and the moisture concentration was estimated by fiberglass units and gravimetrically to be 17 to 19 per cent. The bulk density between 1.6 and 4.0 inches was estimated to be 1.27 to 1.28.

The flow of heat from the soil, S, and from the sky, $R_I - R_o$, are presented in Figure 8. Three features are important. First, the magnitude of S is 4 to 10 B.T.U./hr.ft.². Second, the rate is fairly constant during the hours of dark. Third, the addition of an inch of rain to the dry soil increased S by an important amount. On other soils, S has been estimated to be 4 to 18 B.T.U./hr.ft.² (Sutton, 1953). The contribution of S toward frost protection can be increased significantly by higher daytime temperatures, that is, by increased storage; by avoiding peaty soils; and by watering soils—especially sandy ones. This energy from the soil is carried to the air and plants within the shelter by means of radiation as shown beneath the films in Figures 6 and 7 and by means of convection in the air.

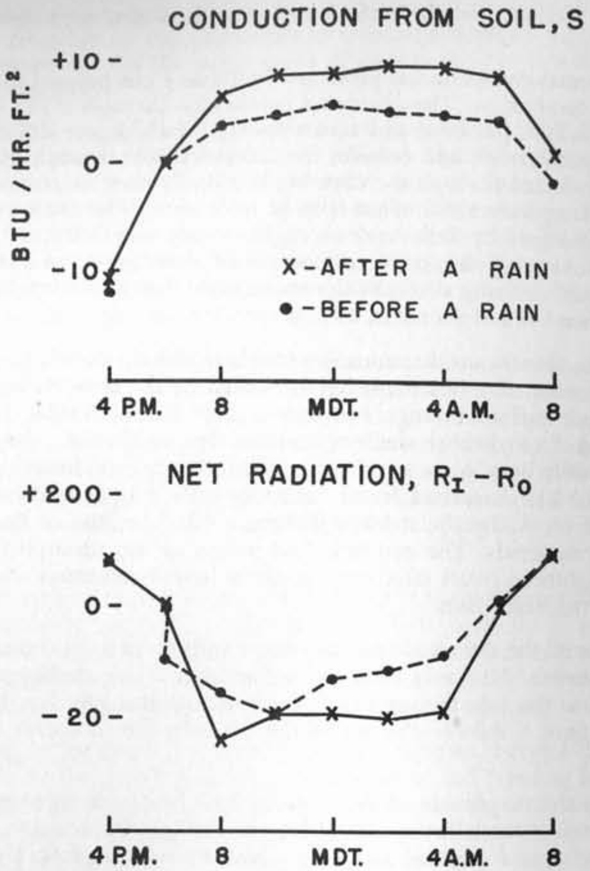

Figure 8. The flow of heat from the soil S as measured at a depth of 2.7 inches and the flow of radiation from the sky on bare Cheshire sandy loam before and after a rain. Note that scale of B.T.U./hr.ft.² for positive net radiation is compressed.

Convective exchange of heat with the air outside. Heat is exchanged between a shelter and the air outside by means of conduction in the layer of air immediately next to the film and by convection as well in the layers further away. The direction and amount of this net gain or loss of energy by the shelter depends upon whether the sheltering film is warmer or colder than the air about it.

The heated shelters, such as the covered frames of Celotex we examined in a preceding chapter, present a relatively simple case. The sides of the shelter conduct much less heat than the covering, and horizontal exchange A_h can be ignored. During the important nighttime hours the covering film always will be warmer than the air, and the vertical exchange A_v will always be a net loss for the shelter.

The thermal conductivities presented in Table 3 can be used to calculate the rate of heat conduction. The calculated conduction through 0.125 inch of glass is about 40 B.T.U. per hour and square foot for each degree difference in temperature between inside and outside; the calculated loss through film is greater. This heat conducted through the covering eventually must be removed by turbulence if the temperature difference is to be maintained. But the quantity of heat generally exchanged by turbulence at night is only one-fourth of the 40 units calculated above; and this one-fourth is passed down, not up. Free convection from the heated covering also fails to remove more than a relatively small amount of heat (Fishenden and Saunders, 1932).

From the above considerations, we conclude that the conductive loss of heat through the cover of a heated shelter is limited by the slow removal of energy from its upper surface through convection. The data of Tables 2 and 3, concerning losses from heated shelters, confirm this conclusion: despite a 7-fold range in possible heat losses as calculated from thermal conductivities and thicknesses (Table 2), the actual losses varied by only 12 per cent because of the limitation set on A_v by the stable nighttime air and because of the presence of water on all materials. The non-turbulent nature of the atmosphere during the important nighttime hours effectively insulates heated structures and sets an upper limit on the heat losses.

The case of the unheated row covering stands in striking contrast to that of the heated shelter. Not only does the unheated covering exchange heat at the sides as well as the top, the net exchange at the top is a gain for the shelter because—as Figure 3 shows—the top of the covering film is cooler than the surrounding air.

What is the magnitude of this gain of heat by a row covering? The sides of the shelter face the horizon, should have no net loss by radiation, should have a temperature equal to the air, and, hence, have no net gain from conduction A_h. The 2 to 5° difference between inside and outside temperatures will produce only a negligible loss.

The top of the covering faces the cold sky, becomes cooler than the surrounding air soon after sundown (Figures 3, 5, 6) and will have a net gain A_v from the air above it. Since the film is cooler than the air, the net gain from conduction is less than the net loss by radiation, about $(24 - 8) = 16$ B.T.U./hr.ft.^{2} in Figure 7. Therefore, the gain of energy A_v must be about the same as the gain experienced by the soil surface at night, $4 < A_v < 16$ B.T.U./hr.ft.^{2} according to Sutton (1953), Swinbank (1955), and our own measurements on Merrimac sandy loam. Stirring the air about the shelters will increase this gain and, thus, increase the degree of protection.

This energy A_v is transferred first to the film; then it is carried to the air, plants, and soil within the shelter by means of radiation, as shown beneath the films in Figures 6 and 7, and by means of convection in the air. Because a net loss upward occurs within the shelter through radiation and convection, the effect of A_v is felt in terms of a decreased net loss.

Evaporation and condensation. The formation of dew on the outside of the sheltering film will release energy which will be shared by the film and the air above. The evaporation of the dew will require an equal amount. Dew formation is frequent on the cool roofs of unheated shelters, Figures 3 and 7, and needs discussion. On the warm roofs of heated shelters it will rarely form and can be disregarded.

When in the evening a film of dew 0.010 inch thick forms on the roof of a plastic shelter, about 50 B.T.U./ft.^{2} are released. Hourly observations of condensation on soil have shown that about 0.020 inch of water per night can be deposited and that the deposition is largely in the early evening (Harrold and Dreibelbis, 1951). We shall assume that one-third of the heat, W, passes toward the warmth inside of the shelter and that dewfall occurs from 6 P.M. to midnight. Accordingly, 6 B.T.U./hr.ft.^{2} are added to the shelter by condensation from 6 P.M. to midnight, none thereafter.

This energy W is transferred to the film, a portion warming it, a portion passing through. The W decreases the net radiation beneath the shelter (Figures 6 and 7) and decreases the net loss of heat by convection within the shelter. Unfortunately, this source of energy is absent in the early morning hours when it is most sorely needed. Because the film is growing cooler at 8 P.M. (Figure 7), the gain of energy from W and from A_v from above and below must be less than the net loss by radiation. This upper limit on A_v plus W is 24 B.T.U./hr.ft.^{2} in Figure 7.

If in the early morning the film of dew on the shelter freezes, a new supply of energy suddenly appears. A film of water 0.01 inch thick will supply 7 B.T.U./ft.^{2} and about one-third should pass into the shelter in the form of decreased net radiational and convectional losses. Because of the small magnitude and the temporary nature of this supply of energy, it is relatively unimportant.

The melting of ice and the evaporation of dew subtract energy from the budget of the shelter in the same manner that condensation and freezing added energy. When the sun rises, the 0.01 to 0.02 inch deposit of ice or water on the film will melt and evaporate, delaying the warming process until the sun has added some 50 to 100 B.T.U./ft.^{2}. This will require at least an hour when the sun is low, and, hence, the duration of low temperatures within the shelter will be considerably longer than a dry thermometer indicates. Thus, the changes of state of water are on balance a detriment to the shelter: they add heat in the evening when the need is moderate and subtract it in the early morning when the need is severe.

Heat from fuel. The amount of heat required to maintain a warm temperature in a plastic-covered shelter has already been estimated (Table 2): about 5 kilowatt hours or 16 B.T.U. per square foot of sash were required to maintain a shelter about 20° warmer than the minimum outside temperature for one month (Table 2). In a preceding section, we have pointed out how the nighttime's atmosphere limited ability to carry away heat and the ability of water to absorb long-wave radiation prevent ruinous losses through the transparent covers of the shelters and minimize differences amongst plastics and glass. Thus the gardener who wishes to maintain a hot bed at about 50° for the two important months of March and April can count on spending in the neighborhood of 5 kilowatt-hours for each square foot of bed in a climate similar to that of Mt. Carmel, Connecticut.

Balancing the energy budget. The radiation gains and losses of a shelter have been examined closely and the other exchanges of energy have been estimated from the literature. Now an attempt will be made to set down the budget of a shelter in the important case of a clear night. Plastic shelters are commonly wet with water on the inside; therefore, we shall speak only of water-covered polyethylene such as that examined near 8 P.M. on September 19, 1957 and depicted in Figure 7.

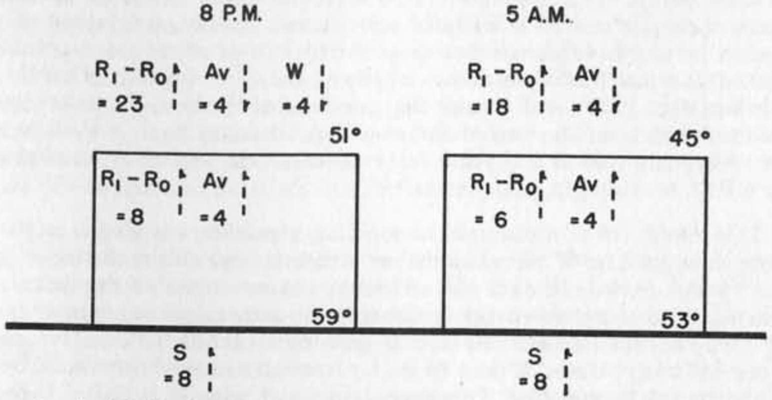

Figure 9. An idealized unheated plastic shelter and its energy budget in B.T.U./hr.ft.^{2} at 8 p.m. and 5 a.m. on a clear night. The plastic is covered by condensed water. Temperatures are in degrees Fahrenheit.

The net fluxes of energy for the energy budget are shown in Figure 9 for an idealized unheated polyethylene shelter at 8 P.M. on a clear night. The net flow of radiation above and below the shelter has been taken from Figure 7. The observed outgoing radiation R_o above the shelter was within 1 B.T.U./hr.ft.^{2} of that calculated for a black body at the temperature of the film; the net exchange between the soil surface and the film was equal to the difference between black body radiations corresponding to the surface and film temperatures.

The idealized shelter also is shown in Figure 9 near the time of the minimum temperature, 5 A.M. The temperatures of the film and soil surface here were taken from Figure 3. The net flow of radiation beneath the shelter was calculated from the two temperatures; the net flow above the shelter was calculated from the film temperature and the sky radiation R_I of Figure 7.

The net flow of energy by convection beneath the shelter at the two times was calculated from the difference between soil surface and film using the Fishenden-Saunders expression for free convection (Fishenden and Saunders, 1932).

The estimation of the net gain of energy by the film from the air above through convection A_v and condensation W is difficult. Because the film is growing colder at 8 P.M., the gains must be less than the losses:

$$\begin{array}{llll} A_v \text{ above} + W & < (R_I - R_o)_{\text{above}} & - (R_I - R_o)_{\text{below}} & -A_{v\text{ below}} \\ \quad '' & < 23 & -8 & -4 \\ \quad '' & < 11 & & \end{array}$$

Thus, the gains from above through A_v and W must be on the lower limit of our estimates made in preceding sections. The gains were set at $A_v = W = 4$ for 8 P.M. (Figure 9). The gain from condensation at 5 A.M. is zero as already discussed; A_v was left at 4. These foregoing estimates of A_v plus W are lower than those compiled by Sutton (1953), are similar to measurements made by us in the early morning on bare Merrimac sandy loam, and are similar to measurements made by Swinbank (1955) at 8 P.M.

The conduction of heat from moist soil is about 8 B.T.U./hr.ft.^{2} as discussed above (Figure 8). This value is nearly constant all night and was entered in Figure 9.

The final picture presented by Figure 9 is one of continuing net loss and falling temperature. The benefit of the shelter at 8 P.M. lies in the difference between the net upward loss of 15 B.T.U./hr.ft.^{2} outside the shelter and 12 within it. The situation at 5 A.M. is about the same. The 2 to 7° of protection is a consequence.

Two factors operate to maintain the degree of protection almost constant in the region of 2 to 7°. First, the omnipresence of water in the soil and on the film in the spring and fall assure us that most mineral soils and most plastics will be nearly equal to the best materials. Second, the rate of loss of heat is roughly proportional to the elevation of the shelter temperature; hence, a dearly bought increase in one source leads inevitably to a greater loss by all other sources.

Finally, we can see how the introduction of a modest amount of heat from fuel can produce a significant increase in temperature. Although doubling one of the natural sources of energy will have slight effect upon the degree of protection, the net loss is modest relative to the quantities of fuel which we are accustomed to expend. Thus, the net loss from the top of the shelter is, after all, only about 15 B.T.U./hr.ft.^{2}. Even if the direction of A_v is reversed, W eliminated and $R_I - R_o$ increased by an amount equivalent to a 20° increase, the loss from the film only becomes 45 B.T.U./hr.ft.^{2}. The reality of this reasoning is established by a comparison with the experiments of Table 2: if the loss of 16000 B.T.U./ft.^{2} occurred in 30 nights of 12 hours each, the rate would be 45 B.T.U./hr.ft.^{2}, an excellent justification of our theoretical calculations.

Thus, considerations of the energy economy of plastic shelters leads to the conclusion that unheated shelters inevitably provide moderate protection, but moderate additions of energy from fuel provide significant increases in temperature. This summary brings to a close the discussion of the physical principles of plastic shelters; now we turn to the practical question of how plants behave beneath the shelters.

Growing Early Plants Under Unheated Shelters

Sheltering early plants from frost is a venerable practice. Many plants that are prized after the long winter months have been grown beneath coverings of waxed paper and early plastics (Conin and Sherman, 1930, and Ware, 1936). In recent times the frost-susceptible tomato has been a favorite subject for plastic row coverings (Emmert, 1955); the first fruit commands an enticing premium in pride and money. We chose the tomato for our practical experiments in frost protection because of its importance as an economic crop and because its frost-susceptibility makes it a model for other plants. These experiments provided a horticultural measure of the degree of protection: the difference between the temperature observed in an instrument shelter on a night when exposed plants freeze and the temperature in the same instrument shelter when sheltered plants

Table 4a. The weather observed at the cooperative Weather Bureau Substation, Mt. Carmel, Connecticut

		Week beginning								
		4/5	4/12	4/19	4/26	5/3	5/10	5/17	5/24	Total
Number of nights on which the temperature fell to 32° F:	1957	4	4	0	0	1	0	0	0	9
	1956	3	4	6	1	1	0	0	0	15
to 25° F:	1957	2	2	0	0	0	0	0	0	4
	1956	0	0	0	0	0	0	0	0	0
Number of days on which the temperature rose to 80° F:	1957	0	0	3	2	3	3	0	1	12
	1956	0	0	0	1	0	1	0	0	2
Hours of sunlight	1957	31	46	50	61	50	40	35	65	378
	1956	32	22	29	30	34	30	40	45	262

freeze. The experiments also provided practical experience with plastic shelters in two contrasting seasons, 1956 and 1957, experience which revealed an important benefit and loss inherent in unheated shelters.

The weather at the Experimental Farm was observed according to the usual Weather Bureau standards in a conventional instrument shelter located on the same north-facing slope as the experimental plots. This is the Mount Carmel Substation, U. S. Weather Bureau. The numbers of nights on which the temperature in the instrument shelter fell to 32 and to 25° are indices of the frost hazard; these numbers are tabulated in Table 4 for 8 weeks in April and May, 1956 and 1957. Plants in a plastic shelter may be damaged by high temperatures on warm, bright days because the temperature inside can easily exceed that outside by 15° (Figure 2). The hours of sunlight and the number of days when the maximum temperature exceeded 80° are indices of the hazard of overheating; these data also are presented in Table 4a. Clearly the spring of 1956 was cool, while the spring of 1957 was warm after the severe frost of April 16.

The degree of protection provided by shelters can be estimated because fortune brought frosts of varying severity in 1957. Tomato plants of the self-fertile Waltham Forcing variety were grown to a height of 6 to 8 inches in a greenhouse at 70° and transplanted into a field of moist Cheshire sandy loam on April 12. The plants were set at intervals of 30 inches in four rows; in each row were four plots of four plants each. The 8-inch tall, waxed paper cones marketed under the name "Hotkaps" were placed over the plants in four plots. Row coverings of 0.0015 inch polyethylene film were erected over the plants in four other plots; the coverings were supported by wire wickets 18 inches tall and 18 inches wide. Row coverings of this same film were erected in the same way over four other plots; this film, however, was perforated with holes of 0.5 inch diameter at intervals of 12 inches beginning 6 inches from the ridge of the tent. The perforations were designed to exhaust hot air in the daytime when turbulence was great and thus prevent overheating; the small openings would permit little loss of precious warm air at night when turbulence was slight; the humidity remained high within the shelters. The fourth set of plots remained exposed to the sky. The plots were so arranged that each shelter appeared once and only once in each row and at each of the four distances into the field.

On April 12 the plants were set and on the following morning the temperature in the instrument shelter fell to 31°. No plants were injured, sheltered or not.

On the morning of April 14 the temperature in the instrument shelter fell to 26°. All of the exposed plants died, all of the covered plants survived.

On the morning of April 15 the minimum temperature observed was 23°. Even the sheltered plants were destroyed except for a few stems which remained green near the soil line. One plant was replaced beneath each shelter.

On the morning of April 15 the minimum temperature observed was 23°. and upper stems of all plants were destroyed.

The consequences of these cold mornings permitted an evaluation of the degree of protection provided by coverings. On a field with rapid air drainage, exposed tomatoes can be said to survive until the temperature reaches 30°, sheltered tomatoes until the temperature reaches 25° in a nearby Weather Bureau shelter. Placing the plants in a field with relatively poor air drainage, lengthening the duration of the frost, or "hardening" the plants might change the difference between instrument shelter and plants, but should not change the 5° difference between covered and exposed plants when freezing occurs. This estimate will be found useful later.

The experiment was begun anew on April 18 when 3 of the 4 plants in each plot were replaced; the fourth plant was left as a specimen that had survived or been killed by the frosts of April 13 to 16. On April 22 two slits 15 inches long were cut along the ridge of the tents of unperforated film; the slit was opened on warm days and otherwise closed by a clothespin. No frost injury occurred to any plants after April 18; the lowest minimum, that of May 3, was exactly 32°.

By May 3, 15 days after transplanting, the plants in the open showed evidence of hardening, that is high anthocyanin concentration, while those beneath the plastic covers were a light green. On May 20 and 21 all coverings were removed.

The "vigor" of the plants was ranked on June 13. Slight difference could be found among the exposed plants and those once sheltered by plastic coverings; those which had been confined for a month beneath the paper cones were less vigorous. The number of fruits that were set on June 13 and 21 were counted (Table 5). Here differences were large: the exposed plants excelled those once beneath the slit coverings which in turn excelled those once beneath perforated coverings and paper cones. The restriction on fruit setting by the shelters was not caused by reduced turbulence or reduced insect activity because Waltham Forcing is a self-fertile variety.

Table 5. The number of tomato fruits set per plant. Average of three plants in four replicates

Date	Exposed	Paper cones	Slit coverings	Perforated coverings
June 13	5.1	0.2	1.2	0
June 21	14.3	4.0	13.3	3.2

The first red-ripe fruits were picked, counted, and weighed on July 9, 92 days after transplanting; the last on August 5, well after the fruit could command a premium for earliness. The size of the fruit was not changed by the shelters. The yield from the exposed plants is presented in Table 6; the relative yield from the previously sheltered plants is presented in Figure 10. Obviously, the shelters were not beneficial in 1957.

Table 6. The accumulated yield and number of tomatoes produced per exposed plant set on April 18, 1957. Average of three plants in four replicates

	Date of harvest							
	July 9	12	15	19	22	26	31	Aug. 5
Yield, lbs.	0.3	0.4	0.5	0.6	1.1	2.4	3.8	5.4
Number	2	3	4	6	10	18	33	56

The fate of the one plant in each plot which had suffered the frosts of April 13 to 16 is shown in Table 7. Even the surviving plants had been destroyed by frost nearly to the soil line and had had to grow from a stump. In contrast to exposed plants killed from April 13 to 16, these plants that had been sheltered produced a crop, but they did not produce as much as the plants, exposed or sheltered, that were set on April 18 after the severe frosts had passed.

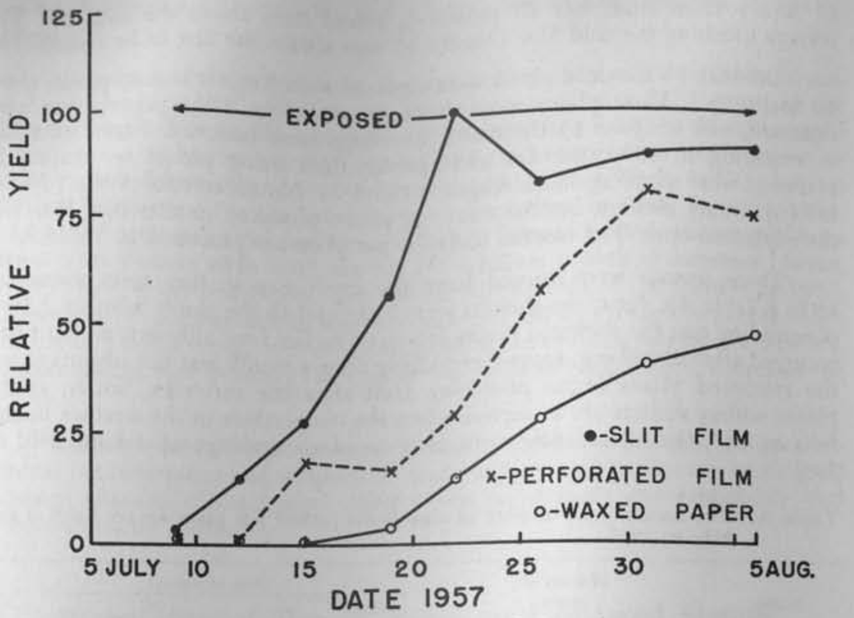

Figure 10. The yield of tomato fruit from sheltered plants from July 9 to August 5 relative to the yield from exposed plants. Shelters were in place from transplanting until May 20 or 21.

Table 7. The accumulated yield, in pounds, of tomatoes produced per plant set on April 12, 1957. Average of one plant in four replicates

	Date of harvest			
Shelter	July 22	26	31	Aug. 5
None	0	0	0	0
Paper cone	0.1	0.1	0.1	0.2
Slit covering	0.1	0.2	0.4	0.6
Perforated covering	0	0.2	0.4	0.8

The effects of the shelters in cool 1956 were different from those in 1957. Clark's Early Best tomato plants 4 to 6 inches tall, grown in a greenhouse at 70°, were transplanted to the field on April 6, 1956. Eleven or twelve plants were covered with paper cones, a perforated polyethylene covering, a slit polyethylene covering, or left exposed. The field was more nearly level than that used in 1957 and, hence, air drainage was slower.

The minimum temperature observed in the instrument shelter during the ensuing 32 days was 26°. No plants survived in the open, 4 out of 11 beneath the paper cones, 5 out of 12 beneath the slit polyethylene, and 7 out of 11 beneath the perforated polyethylene. The surviving plants showed varying degrees of injury from frost, but all showed a sound stem above the soil line. The foliage touching the cold film (Figure 3) was always the first to be frost-bitten.

On May 14 the dead plants were replaced with Rutgers tomato plants about 10 inches tall. These plants were set deeply. On June 8 the paper cones were removed, and on June 13 the plastic coverings were removed. Fruits were late in maturing in 1956, the first red-ripe tomatoes being picked on August 7. Harvests were made again on August 14 and 23. No differences in size of fruit existed among shelters, but the surviving plants produced smaller fruit than did the replanted ones. The number of fruits per plant are presented in Table 8.

Three lessons were learned from the experience in the cooler season of 1956 (Table 8). First, the shelters were beneficial to the plants whether a frost occurred or not; the sheltered plants produced earlier fruit although no frost had occurred after restocking; second, restocking after a month was not advantageous; the restocked plants began producing fruit after the survivors, finally, if the plants within shelters are to survive when the temperature in the weather shelter falls to 26°, the tomato field must have rapid air drainage as did the field of 1957.

Table 8. The accumulated number of ripe fruits picked per plant set on April 6 and May 8, 1956

Snelter	Number of plants	Date of harvest August 7	14	23
		Plants set April 6		
None	0	0	0	0
Paper cone	4	0	2.2	14.5
Slit covering	5	1.0	4.4	12.0
Perforated covering	8	0.5	4.0	37.5
		Plants set May 14		
None	12	0	0.2	0.3
Paper cone	7	0.2	2.2	8.3
Slit covering	6	0	0.3	2.5
Perforated covering	3	0	5.7	20.3

Bringing together the results of the two years' experience with tomatoes and shelters, one can say rather definitely that exposed tomatoes will be killed by frost when the Weather Bureau observation is 30°, sheltered tomatoes will be killed when the observation is 25°, if the field has rapid air drainage. These definite limits will permit us in the next chapter to estimate the probability that shelters will be beneficial.

No significant difference in frost protection should exist between different types of sheltering materials according to the physical measurements and arguments of preceding chapters. This was borne out by the horticultural experience of 1956 and 1957: about equal numbers of plants survived beneath paper cones and polyethylene row coverings (Figure 10 and Table 8).

The benefit and harm done by shelters outside of frost protection are more difficult to define clearly. Apparently, the confinement of the small paper cones can be deleterious (Figure 10), and a larger size or early removal should be chosen.

Also, the usefulness of plastic shelters in May 1956 and their harmfulness in April and May 1957 must be explained. In cool 1956, a 10° increase in the daytime temperature would bring the temperature into a region of more rapid growth and a 5° increase at night would bring the temperature into a region of more perfect flowering and more abundant production (Went, 1957); here is the best explanation for the helpfulness of the shelters in 1956. In warm 1957, a 10 to 20° increase in the daytime temperature frequently made the temperatures beneath the shelters 90 to 100°, too hot for optimum growth of tomatoes (Went, 1957); here is the best explanation for the harmfulness of the shelters in 1957. Obviously, the damage due to high temperatures can be avoided in part through the use of a slit covering or even the removal of the covering during hot weather. Unfortunately, this increases the cost of the operation and, hence, decreases the profit.

The two years of experience with tomatoes growing beneath shelters confirmed the observations of temperature and energy flow. Now we can confidently employ classical climatological observations to estimate the probability that shelters will be beneficial.

Probability of Benefit From an Unheated Shelter

Frost protection. The measurements of temperature beneath unheated row coverings of plastic, the principles of their operation, and the protection they have afforded tomatoes beneath them all together indicate the degree of protection: on nights when the thermometer in the instrument shelter reads 26°, the frost-sensitive tomatoes within plastic shelters will survive in a field with rapid air drainage; when the thermometer reads 25°, they will be killed. On nights when the thermometer reads 31°, exposed tomatoes will survive; when the thermometer reads 30° they will be killed. Factors such as local topography, sky cover, and duration of the cold will modify this rule somewhat; but its accuracy will suffice for our next task, an estimation of the probability that unheated shelters will be beneficial.

The minimum daily temperature has been faithfully observed at hundreds of stations for many years. The probability of occurrence of any given temperature can be calculated from this host of observations. If an event, such as frost, can be related to a given temperature, then its probability also can be calculated. This we shall do for the probability of benefit from shelters.

Shelters are of no use if the temperature does not fall to 30°. Shelters have been seen to be proof against frosts when the temperature observation is 30° to 26°, not when it is 25° or less. Thus, the probability of benefit from a shelter has been set equal to the probability of a 30° less the probability of a 25° minimum temperature.

The date of the last occurrence of temperatures of 25 and 30° in the spring varies from year to year, being most frequent near their average dates of last occurrence. Half of the time they occur before, half of the time after their average dates. The curve describing the frequency of occurrences at different dates is the

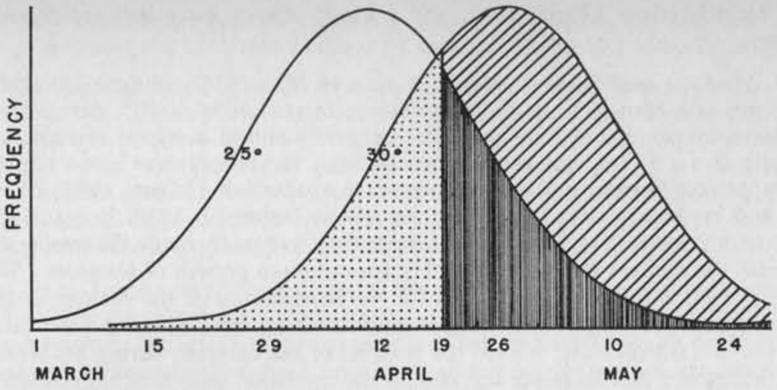

Figure 11. The probability of 30° not occurring (screened), of 25° occurring (black), and of shelters being beneficial (cross-hatched) after April 19 at Mt. Carmel.

well-known "normal" curve (Shaw *et al.*, 1954); hence, the probability of occurrence of 25 or 30° F after a certain date can be estimated easily.

Estimation of the probability of benefit for Mt. Carmel is demonstrated in Figure 11. The frequency of the last occurrence of 30° is shown by the curve on the right; of 25° by the curve on the left. If tomatoes or any similar frost-sensitive plants are transplanted to the shelters at Mt. Carmel on April 19, then no 30° frost will occur after transplanting 28 per cent of the years; these years will have their last 30° temperature earlier than April 19—as shown by the speckled area beneath the curve—and the shelters will not be needed. On the other hand, a temperature of 25° will occur after this transplanting date 26 per cent of the time; in these years—represented by the shaded area beneath the curve—the shelters will not provide sufficient protection. This leaves the cross hatched area of 46 per cent as the probability that the plastic shelters will be beneficial.

The probabilities of benefit from shelters have been calculated by the same device for several possible transplanting dates at Mt. Carmel; these are tabulated in Table 9. The grower who contemplates transplanting on April 19 can compare the premium for earliness with the cost of the shelters and the probabilities that they will not be needed because temperatures will not fall below 30° (28 per cent), that they will be needed and successful because minimum temperatures will be between 25° and 30° (46 per cent), and that they will fail because temperatures will fall below 25° (26 per cent). Similar considerations can guide him for other transplanting dates. As later dates in May are examined, the probability of benefit from the shelters declines; possibly the declining benefit will be accepted if a total loss to a 25° temperature is particularly disastrous.

Table 9 also can serve another purpose if one is interested in choosing a date to transplant tomatoes to the field without shelter. The probability of "no 30°" temperature is the probability that plants set out on a given date will not be exposed to 30° and will survive and grow successfully. For example, if one transplants tomatoes on April 19 at Mt. Carmel they will not be frozen and will survive only 1 year out of 4. On the other hand if transplanting is delayed until May 10, the plants will not be frozen in 8 years out of 10. Thus, these probabilities permit the grower to compare the risk of a loss against the anticipated premium for early transplanting.

The probability of late frost is higher at the Mt. Carmel Farm than one would expect from its latitude. This is because it is at an elevation of 200 feet, lying near Mount Carmel. Consequently, little difference is found between its frostiness and that of Amherst, Massachusetts; Storrs, Connecticut; and Kingston, Rhode Island. Thus, the probabilities given for Mt. Carmel in Table 9 apply to the Connecticut Valley in Massachusetts and the Highland of Rhode Island and eastern Connecticut.

The observations at Hartford in the southern Valley are apparently influenced by the city. Those at New Haven are influenced by both the city and Long Island Sound. Thus, a 30° temperature becomes improbable early in the spring near these two cities or the Sound, and the maximum probability of benefit from shelters requires transplanting in early April.

Table 9. Probability of 30° not occurring, of 25° occurring, and of shelters being beneficial at four localities

Location	Probability of	March			April			May	
		1	15	29	12	19	26	10	24
Mt. Carmel,	No 30°		<1 per cent	2	14	28	47	82	97
Conn.*	25°		97	80	44	26	13	2	<1
	Benefit		3	18	42	46	40	16	3
Hartford, Conn.	No 30°	<1	1	11	47	69	86	>99	
	25°	99	84	43	9	3	1	<1	
	Benefit	<1	15	46	44	28	13	<1	
New Haven,	No 30°	<1	3	23	66	84	95	>99	
Conn.†	25°	98	82	40	8	2	<1	<1	
	Benefit	<2	15	37	26	14	<5	<1	
Cream Hill,	No 30°		<1	<1	2	20	40	72	98
Conn.‡	25°		99	89	53	31	14	1	<1
	Benefit		<1	11	45	49	46	17	2
SE Missouri	No 30°	10	35	70	93	97	>99		
(Decker,	25°	61	25	6	1	<1	<1		
1955)	Benefit	29	40	24	6	<3	<1		

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* The observations at the Mt. Carmel station (elevation 200 ft.) closely resemble those at Storrs and Norwalk, Connecticut; Amherst, Massachusetts; and Kingston, Rhode Island. Hence, the probabilities for the Mt. Carmel station, which is cold for its latitude, can be used for the Connecticut Valley in Massachusetts and the highlands east of the Valley in Connecticut and Rhode Island. The data for Norwalk were analyzed by A. B. Pack.

† The observations at the New Haven station closely resemble those at Bridgeton, New Jersey, the latter data having been analyzed by D. V. Dunlap. Hence the probabilities for the New Haven station, which is warm for its latitude, can be used for the shoreline south and west of that city and for inland southern New Jersey.

‡ The observations at the Cream Hill station in northwestern Connecticut were analyzed by A. B. Pack. They resemble those for Sioux City in northwestern Iowa (Shaw *et al.*, 1954) and can be used for that area in the Midwest.

The trend to earlier dates for maximum benefit are noticed as we move south to New Jersey. For example an analysis of the climate of Bridgeton, New Jersey by Mr. D. V. Dunlap showed that this station 35 miles inland had almost exactly the same probabilities for each date as does New Haven, which is on the Sound. Probabilities are included for the continental climates of northwestern Iowa and southeastern Missouri.

An approximate rule can be derived from Table 9 that will describe the situation in several climates: the maximum chance of beneficial frost protection from shelters, about 4 out of 10 years, is obtained by transplanting near the mean date of last occurrence of 30°; at this time one stands about a 1 in 10 chance of losing the sheltered plants to a 25° frost, 5 chances in 10 of not needing the shelters.

Increased growth through warmth. The warmth furnished by the shelters in the cool May of 1956 was credited with an increase in yield that had nothing to do with frost protection. In contrast to this, the high temperatures created by the shelters in the warm April and May of 1957 were blamed for decreased yields. The critical levels below which the shelters are beneficial and above which they are harmful have not been set definitely in terms of Weather Bureau observations. Nevertheless, two values are known: shelters are harmful at temperatures equal to or greater than those of 1957, beneficial at temperatures equal to or cooler than those of 1956. These are the basis for a first estimate of the chance of improved temperatures for growth due to shelters.

The probabilities of various deviations of average monthly temperatures from long-term means can be calculated. This has been done for Connecticut utilizing the observations for 1926 through 1955 at Storrs. The deviations from long-term means were found to be normally distributed, their variances were calculated, and the normal curve used to estimate probabilities. The deviations for succeeding months are statistically independent.

The probabilities of future Aprils and Mays being colder than those of 1956 or warmer than those of 1957 are shown in Table 10. Evidently, one of these months will be cooler than in 1956 only about 1 out of 10 years, warmer than in 1957 only 2 to 5 out of 10 years. The probability of both April and May being colder than in 1956 is about 1 in 100, of both being warmer than in 1957 is about 1 in 10.

The foregoing considerations make possible the following useful estimates: the increased warmth of the shelters will be as beneficial as in 1956 and produce 10- to 70-fold increases in early tomatoes in 1 to 10 per cent of the seasons. On the other hand, extremely high temperatures beneath the shelter will be as injurious as in 1957 and produce the corresponding loss of early fruit in 10 to 50 per cent of the seasons. Thus, the spectacular benefits from shelters not associated with frost protection which we observed in 1956 may be rare, but the necessity of ventilating the shelters or even removing them may be common.

Table 10. Estimated probability that average monthly temperatures will be colder than in 1956 or warmer than in 1957

Month	1956	1957
April	12 per cent of the months will be colder	21 per cent of the months will be warmer
May	3 "	50 "

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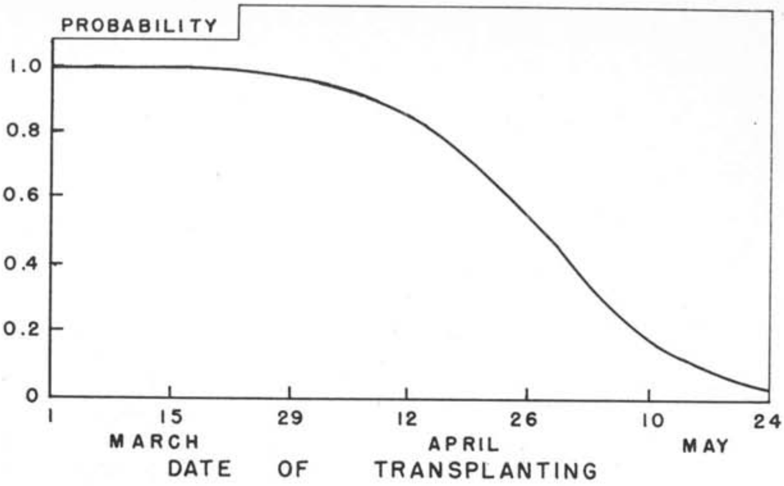

Figure A: Probability of a 30° frost at Mount Carmel. Exposed tomato plants are killed by a 30° frost.

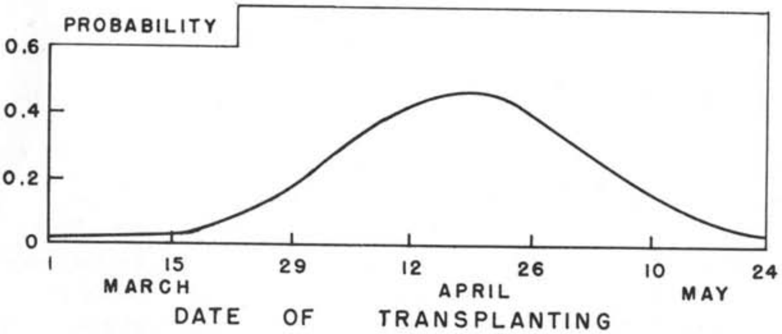

Figure B: Probability of shelters being beneficial to tomato plants at Mount Carmel.

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