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# Shading screens for frost protection [1]

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## Abstract

Shading screens stretched horizontally above the ground, were found effective in reducing the risk of frost damage. The screens reduce the net amount of long-wave radiation from the ground to the sky during the night and thus keep the temperature of the plants under the screens at a higher temperature than ambient. A model for calculating the reduction in long-wave radiation exchange between the ground and the sky, due to the presence of a screen, was devised and verified by experiments. The model suggests that three parameters affect net radiation under the screen, shading percentage of the screen, radiometric properties of the screen and the ratio between screen area and the ground area beneath it. Of several types of screens that were tested, an aluminized screen was found to be the most effective in reducing frost damage. A simple model for calculating leaf temperature is offered and used for calculating the temperature of an upper leaf. The experimental data and calculations show that during the night the temperature of the leaves is lower than the air temperature and therefore frost protective devices should be controlled according to leaf temperature and not air temperature.

## 1. Introduction

The greatest agricultural risk in connection with low temperatures is frost, which can cause severe destruction of fruit, vegetables and plants. The sensitivity of a crop to low temperatures depends on many factors, including the severity of the temperature drop and for how long the cold persists. Plant species differ greatly in their susceptibility to chilling injury. Two kinds of frosts may be distinguished: radiation frost and advection frost. The former occurs on clear nights when a large amount of heat is radiated towards

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the sky, and its occurrence is generally spotty; the later results from the incursion of cold air masses. The damage due to radiation frost differs from that due to advection frost mainly in its degree. Plants that are killed by advection frost are usually only partially damaged by radiation frost (Critchfield, 1966).

Prevention of crop damage due to radiation frost is more feasible than advection frost. During radiation frost, only a thin layer of air immediately above the ground is cooled while the overlaying layers are warmer (Rosenberg et al., 1983; Oke, 1987; Gat and Karni, 1993). A light wind is generally sufficient to mix the cooler and warmer layers and thus dispel the frost. Prevention of radiation frost can be achieved by breaking up the inversion that accompanies intense night-time radiation. This is generally accomplished by stirring the air, heating it, providing a protective blanket of smoke or by any combination of these. One of the oldest proposals for frost protection (Brooks, 1961) is "...artificial cloud screening to reduce the rate of heat loss to the cold sky."

The purpose of the current research was to study the feasibility of using conventional shading screens, stretched over the crop, to reduce long-wave radiation loss to the sky during the night, and thus reduce the risk of frost damage.

## 2. Experimental setup

The experiments were carried out in the Arava region (30.25°N, 35.15°E, alt. 90 m) in the southern part of Israel in two successive winter seasons (i.e., winter 1992/1993 and winter 1993/1994). A commercial area of about 0.25 ha of capsicum was divided into 12 adjacent regions each of an area of 10 × 20 m, over which different types of screens were stretched at a height of about 2.5 m above the ground. Two screens from each type were tested for repetition. The screens are identified by a commercial designation that states the shading percentage of the screen and its color (e.g., '30% black'). They are manufactured from polyethylene sheets that are produced by a blow-bubble extrusion process. Strips are cut from the sheet and stitched to form a woven screen. Aluminized screens were also tested; they are produced by coating a polyethylene film with a thin layer (0.2 $\mu$m) of aluminum. Strips are then cut from the aluminized film and stitched to form a screen.

Air temperature, $T_a$ (°C), ground temperature, $T_g$ (°C), leaf temperature, $T_l$ (°C), and net radiation, $q_n$ ($\mathrm{W\,m^{-2}}$) were measured simultaneously under each screen. One sensor was used for each type of measurement. The sensors were placed at the center region under each screen to eliminate interference from adjacent screens. A schematic representation of the experimental setup is shown in Fig. 1(a). The tested screens were:

1. '20% white',
2. '30% black',
3. '40% black',
4. '50% black', and
5. '50% aluminized'.

A photo of two screens, '50% black' and '50% aluminized', is shown in Fig. 1(b). Ambient conditions (wind and temperature) were monitored continuously. Ground temperature and leaf temperature were measured only in the winter of 1993/1994.

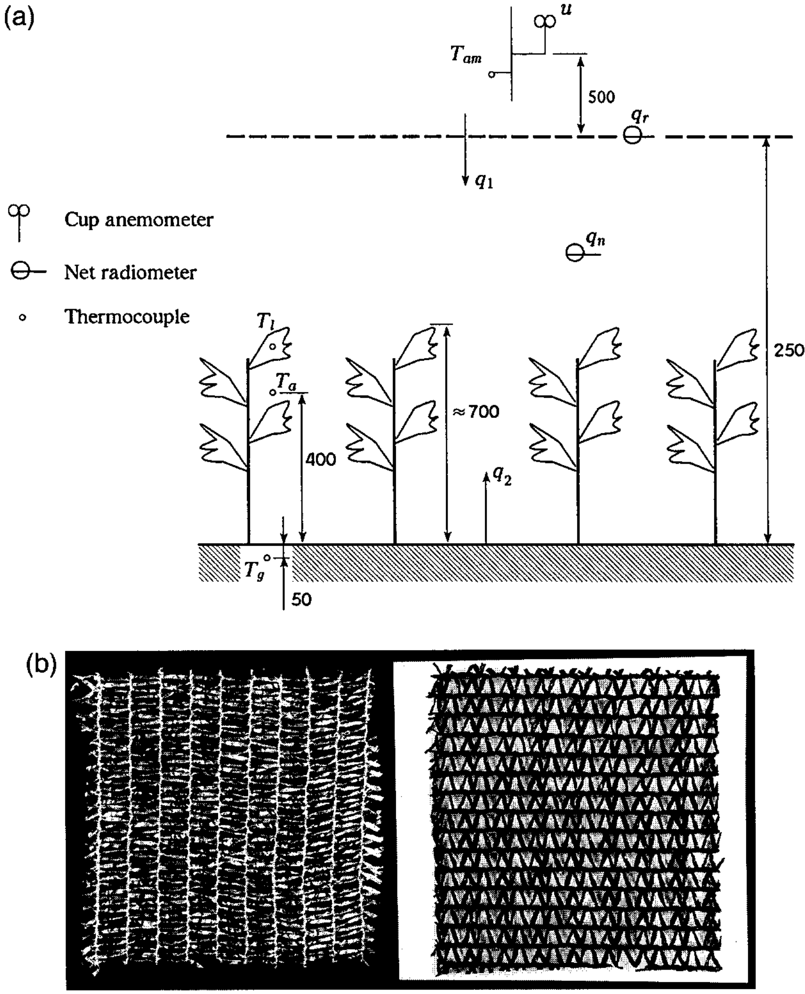

Fig. 1. (a) Schematic view of experimental setup. $q_n$, net radiation; $q_r$, reference net radiation; $q_1$ and $q_2$, thermal radiation flux from the sky and the ground, respectively; $T_a$, air temperature; $T_l$, leaf temperature; $T_{am}$, ambient temperature; $u$, air velocity. Dimensions are in mm. (b) Photo of '50% black' screen (right) and '50% aluminized' screen (left).

Since low tunnels are also used to grow capsicum in the Arava (in this case the screens are spread over the crops) temperature was also measured at crop level inside a low tunnel, made of '30% black' screen material for comparison with a horizontal screen.

## 2.1. Temperature measurements

The air temperature under each of the tested screens was measured by means of copper–constantan thermocouples having a wire diameter of 0.5 mm. The thermocouples were placed within the crop at a height of about 0.4 m above the ground. Special caution was given to place the thermocouples among the leaves to protect them from radiation. In addition, the temperatures of upper leaves of the crop were measured under part of the screens, by inserting fine-wire thermocouples (wire diameter of 0.1 mm) into the midribs of the leaves. Ground temperature under the screens was measured by inserting a thermocouple into the ground to a depth of about 5 cm. All thermocouples were sampled once per minute by a Campbell Micro-logger. The collected data were averaged and stored in memory, once every 30 min.

### 2.2. Radiation measurements

Net radiometers were used to measure the net radiation under the screens during the night. The radiation was measured by means of Radiation Balance 8110 net radiometers (0.3–60 $\mu$m) manufactured by Philipp Schenk. The sensitivity of the probes is about 0.009 mV $W^{-1}$. The radiometers were positioned at a height of 0.9 m above the ground (about 0.2 m above the plants) and close to the thermocouples that measured air temperature under each tested screen. Net radiation without a screen (for reference), $q_r$, was measured by cutting a hole in one of the screens and placing the radiometer at screen level. Ambient temperature, $T_{am}$, and wind velocity, $u$, were measured by a radiation-shielded thermocouple and cup anemometer, respectively, at a height of about 0.5 m above the screens.

## 3. Theoretical consideration

Crops are usually grown in the field under two main configurations of shading screens: (a) a flat horizontal shading screen; and (b) a hemicylindrical tunnel made of shading-screen material. The former is more popular among growers in Israel.

Unlike the case in which continuous films that are stretched above the crops, not all the upwardly directed long-wave radiation leaving the crop and ground is incident on the shading screen, because of the gaps in the screen. Some fraction of the radiation passes through the gaps towards the sky. The amount of radiation that passes through the gaps is dependent on the shading percentage of the screen, $\phi$. It is defined here as $\phi = A_s/A_c$, where, $A_s$ ($m^2$) is the blocked area of the screen (projected area of the fabric, by normal projection) and $A_c$ ($m^2$) is the total area of the screen (including the gaps). In addition, we define a radiation shape factor, since radiation heat transfer between two surfaces is dependent on the shape factor between them (Love, 1968). The radiation shape factor, $\eta_{jk}$ is the fraction of diffusely distributed radiation leaving a surface $A_j$ ($m^2$) and reaching surface $A_k$ ($m^2$) directly. The first subscript of the shape factor denotes the emitting surface, while the second subscript denotes the surface receiving the radiation.

The total net radiative energy, $Q_n$ (W) transferred to a surface by thermal radiation is defined as the difference between the incident flux density and the emitted flux density, i.e., $Q_n = A(q_i - q_e)$, where, $A$ ($m^2$) is the area of the surface, and $q_i$ ($W m^{-2}$) and $q_e$ ($W m^{-2}$) are the incident and emitted flux densities.

It can be shown (Teitel and Segal, 1995) that the net radiation under a screen forming a tunnel is given by:

$$q_n = \frac{1-\phi+\beta\phi}{1-(1-\beta)(1-\eta_{sf})\phi}(q_1-q_2) \tag{1}$$

where $q_n$ ($\mathrm{W\,m^{-2}}$) is the net long-wave radiation; $\beta = 0.5\epsilon_s + \tau_s$, is the transfer factor of the screen material which is dependent on the long-wave emissivity, $\epsilon_s$, and long-wave transmissivity, $\tau_s$, of the screen material; $\eta_{sf}$ is the radiation shape factor between the screen and the ground and is dependent on the ratio between screen area $A_c$ and the ground area beneath it; $q_1$ and $q_2$ are the long-wave flux densities from the sky and the ground, respectively. From Eq. (1) it follows that net radiation under a screen is dependent on three parameters. Namely, screens' shading percentage, radiometric properties of the screen and the radiation shape factor which is derived from the ratio between the total area of the screen and the ground area beneath it. Note that without a screen the net radiation is $q_n = q_1 - q_2$.

The following assumptions were made in the derivation of the expression for net radiation under screens:

1. all surfaces are isothermal;
2. all surfaces are diffusive;
3. air does not participate in the radiative thermal exchange;
4. the radiant flux densities are uniform;
5. both sides of the screen have identical properties;
6. in the case of a horizontal screen stretched above the ground, the screen is infinitely large and is placed close to the ground so that $L \gg d$, where $L$ (m) is a characteristic dimension of the screen and $d$ (m) is its distance from the ground; and
7. the screen is made of untwisted strips which are cut from a very thin film.

For the case of a very large, flat, horizontal screen, $\eta_{sf} = 1$ and the expression for net radiation reduces to:

$$q_n = (1-\phi+\beta\phi)(q_1-q_2) \tag{2}$$

Eq. (2) can also be used to obtain net radiation under a horizontal thermal screen made of a continuous film, by setting $\phi = 1$. The net radiation is then $q_n = \beta(q_1 - q_2)$. This expression is identical to that given by Bailey (1981) and Amsen (1975).

A transfer factor $F$ ($0 \le F \le 1$) can next be defined as:

$$F = \frac{q_n}{q_1 - q_2} \tag{3}$$

From Eqs. (2) and (3) we get for a horizontal screen:

$$F = 1 - \phi + \beta\phi \tag{4}$$

The transfer factor represents the fraction by which a screen reduces the thermal radiation energy exchange between the ground and the sky. As expected, Eq. (4) emphasizes the desirability of a screen with low emissivity, low transmissivity and a high value of shading percentage when low radiative heat losses are required.

## 4. Experimental verification

Experiments were carried out in order to verify the theoretical results. Two types of woven screen were used, made of aluminized polyethylene and of black polyethylene. Commercial as well as in-house-made screens were tested. The in-house screens were made by punching holes in a polyethylene continuous film. Screens with various solidities were tested. It should be emphasized that the error in evaluating the shading percentage of the commercial screens is relatively large. In the present experiments, the shading percentage was determined by stretching the screens over an opening in a black box, and illuminating them from above. Light intensities beneath and above the screen were measured with a luxmeter and the ratio between these measured intensities was equal to $1-\phi$. The commercial screens, each measuring 3 × 3 m, were stretched at a height of about 1.5 m above the ground and the in-house screens, each measuring 0.6 × 0.6 m, were stretched at a height of about 15 cm above the ground. The net radiation under the screens was measured by means of net-radiation radiometers. The radiometers were placed 30 cm below the commercial screens and about 5 cm below the in-house screens, to minimize their exposure to radiation from surrounding objects. An additional net radiometer was positioned beside the screens to measure ambient net radiation, for reference. The data from the radiometers were sampled by a 21X Campbell Micrologger every minute and averaged over 5-min intervals. The averages were stored in memory for further data processing on a personal computer. Data collected on 15 nights (between 18:00 h and 05:00 h) were used to calculate the averages and the standard deviations of the net radiation. Fig. 2 shows the transfer factor obtained from the experimental data. The error bars on the experimental data represent the standard deviation. The theoretical values, calculated from Eq. (4), are also presented

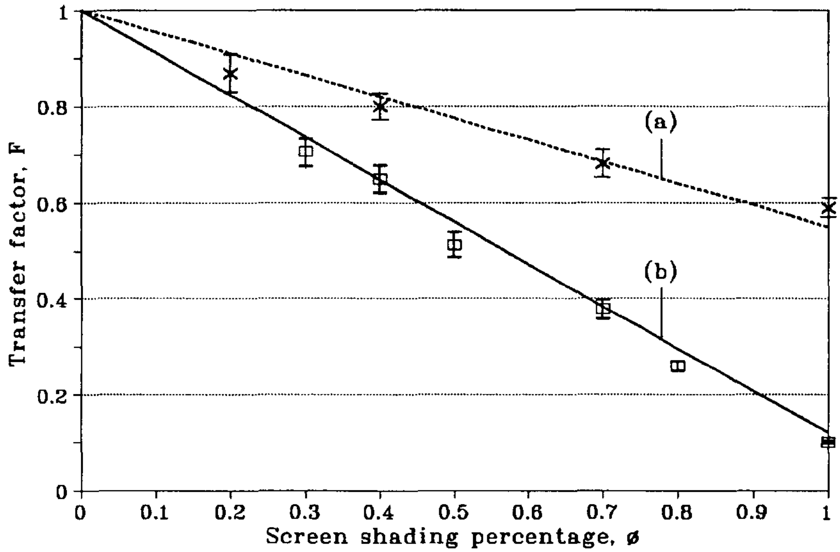

Fig. 2. Transfer factor, $F$, of a horizontal screen. (a) black screen, Eq. (4) $\beta = 0.55$; (b) aluminized screen, Eq. (4) $\beta = 0.12$; (□) aluminized screen, experimental; (×) black screen, experimental.

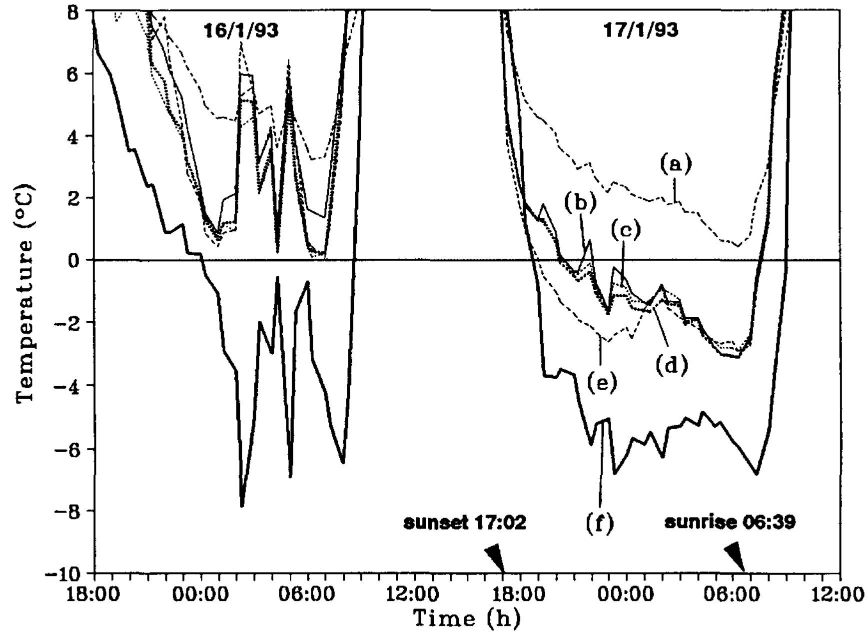

Fig. 3. Air temperature, $T_a$, under the tested screens. (a) 50% aluminized; (b) 30% black; (c) 40% black; (d) 20% white; (e) low tunnel; (f) ambient.

in the figure for comparison. The agreement between experimental and theoretical values is good, considering the uncertainty involved in determining the screens' shading percentage and also that the theoretical results were obtained for the case of a very large screen ($L \gg d$). The agreement between experimental results and theoretical results appears to be a little better for the aluminized than for the black screen.

Owing to the woven structure of the screens, the radiometric properties of the screens (especially at low shading percentages) appear to differ from those of the foil from which they were manufactured. In addition, it should be noted that the theoretical results were obtained for a steady-state case whereas in the present measurements the temperature of the ground decreased gradually during the night. These differences may also have contributed to the observed differences between the theoretical and experimental results. The trends observed in the theoretical and experimental results are, however, similar. The difference between the black and aluminized screens is small when the shading percentage of the screens is small and it increases with the increase in shading percentage.

## 5. Results

Air temperatures under the various screens, over the two successive coldest nights of the 1992/1993 winter season, are shown in Fig. 3. The figure clearly shows that the ambient temperature dropped below zero for several hours during these nights. It should

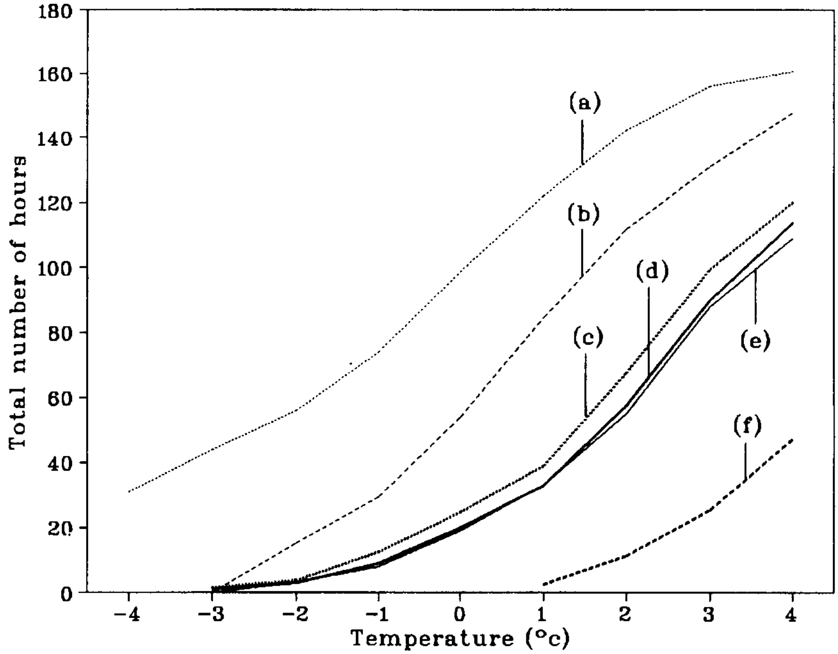

Fig. 4. Total number of hours that the air under the screens was below a certain temperature. (a) ambient; (b) low tunnel; (c) 20% white; (d) 30% black; (e) 40% black; (f) 50% aluminized.

be emphasized that during that winter, subzero temperatures were registered over eight successive nights. Such a long period of frost is most likely to cause severe damage to crops. Indeed, severe damage was observed under all type of screens except under the aluminized screen. The lowest temperature, about −8°C, was registered on 16/1/93, as shown in Fig. 3. Large fluctuations of temperature were observed on that night. These fluctuations are apparently due to the stirring of air caused by local winds (helicopters were also operated during that night to help to stir the air).

The air temperature under the aluminized screen was consistently higher than that measured under the other screens, over the entire experimental period. It should be noticed, however, that the differences in air temperature among all other types of the screens were negligible. It appears that the temperature under the low tunnel was lower than that under all other screens and for much of the time was about 2°C lower than that measured under a '20% white' screen.

The total number of hours, over a period of twelve nights, that the air temperature under each screen was below a certain temperature, was calculated and is presented in Fig. 4. These results suggest that the temperature never decreased below zero under the aluminized screen, while the maximum number of hours — about 96 — below zero, were registered under ambient conditions. For the other screens, i.e., '20% white', '30% black', '40% black' and low tunnel, the total number of hours below zero were 24, 19, 18 and 54, respectively. It therefore appears that low tunnels are least effective in

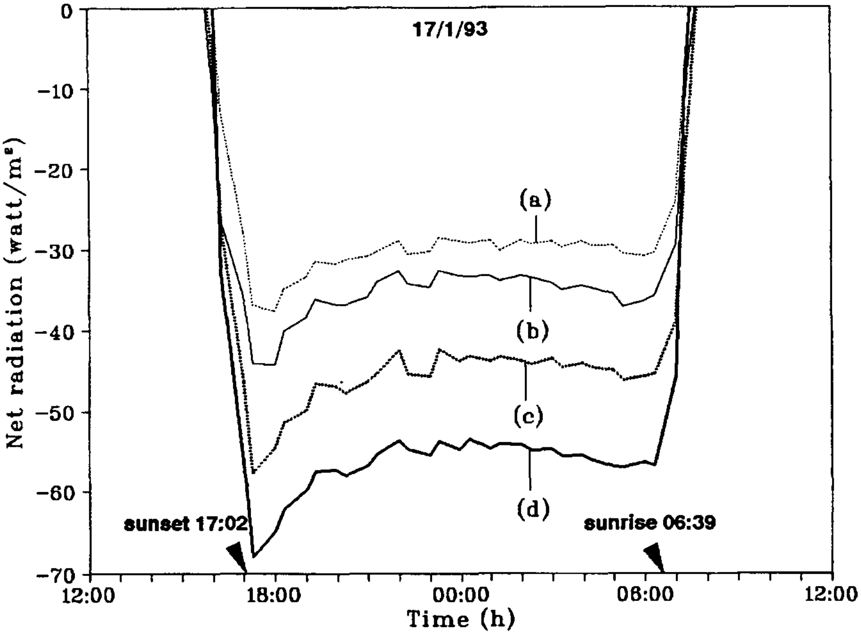

Fig. 5. Net radiation, $q_n$, under the screens. (a) 50% aluminized; (b) 40% black; (c) 30% black; (d) 20% white.

prevention of frost damage. The figure also shows that under all screens except of the aluminized one, the lowest temperature was −3°C. The temperatures under the screens did not decrease further even at ambient temperatures lower than −4°C. The figure also shows that the effectiveness of the screens increases as ambient temperature decreases, i.e. the ratio between the number of hours below a certain temperature with a screen to that without a screen, is decreasing as ambient temperature decreases. It can therefore be inferred that the effectiveness of the screens is non-linearly dependent on ambient conditions.

Net radiation under the various screens is shown in Fig. 5. While the net radiation is positive during the day it becomes negative during the night. The negative values were expected since at night the ground temperature is higher than that of the sky and therefore heat is radiated towards the sky. The average radiation measured by the reference radiometer (the one placed in the hole), $q_r$, was about $-74$ W m$^{-2}$ during the night. Negative values were also measured under the screens, but their absolute values were lower than those measured by the reference radiometer, as expected. The data suggest that net radiation under the aluminized screen has the lowest absolute value while the highest absolute value was observed under a ‘20% white’ screen. Over most of the nights the variations in net radiation under the screens were similar to those observed on 17/1/93.

The largest radiative flux towards the sky is at about 17:00 h and it decreases with time. The sun sets by 17:00 h but the ground is still warm and it loses a large amount of heat by radiation. Consequently its temperature drops resulting a decrease in its radiative

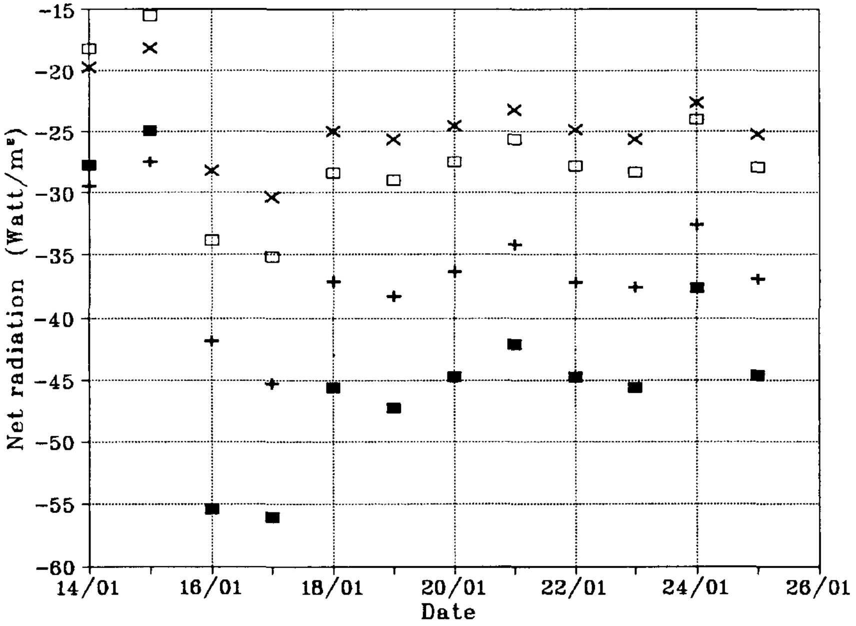

Fig. 6. Average, night-time (18:00 h to 06:00 h) net radiation for the period 14-26 January 1993 under 4 types of screens. (×) 50% aluminized; (□) 40% black; (+) 30% black; (■) 20% white.

heat loss. This process apparently results an exponential decrease of net radiation with respect to time.

Average net radiation over night time (between 18:00 h and 06:00 h) was calculated from the experimental data for the different types of screens and is presented in Fig. 6. The values for the '20% white', '30% black', '40% black' and '50% aluminized' screens were −45, −35, −28, and −25 $\mathrm{W\,m^{-2}}$, respectively. Smaller values were obtained on 14 and 15 January 1993, apparently because the sky was cloudy. This assumption is supported by the reduction in day time radiation that was observed on the 13/1/93 (data not shown).

Temperatures of the ground, the upper leaves and the air are shown in Fig. 7(a) and (b), for the two most efficient frost protective screens '50% black' and '50% aluminized', respectively. The data was obtained on the 26/1/94 and presents typical temperature variations that were measured during the coldest week of winter 1993/1994. Note that during that winter, the ambient temperatures were higher than zero. The lowest ambient temperature was 4°C and therefore no frost damage could be observed. The figures suggest that during the night (starting at about 17:00 h) the temperature of the ground, air and leaves start to drop and reached a minimum level at about 06:00 h-06:30 h. During the morning (between 06:30 h and 08:30 h) the average change of temperature of the ground with respect to time, was less steep than those of the air and the leaves. The moderate change of ground temperature is due to the larger thermal mass of the ground and the rapid change in heat flux from the sun during the morning. On the

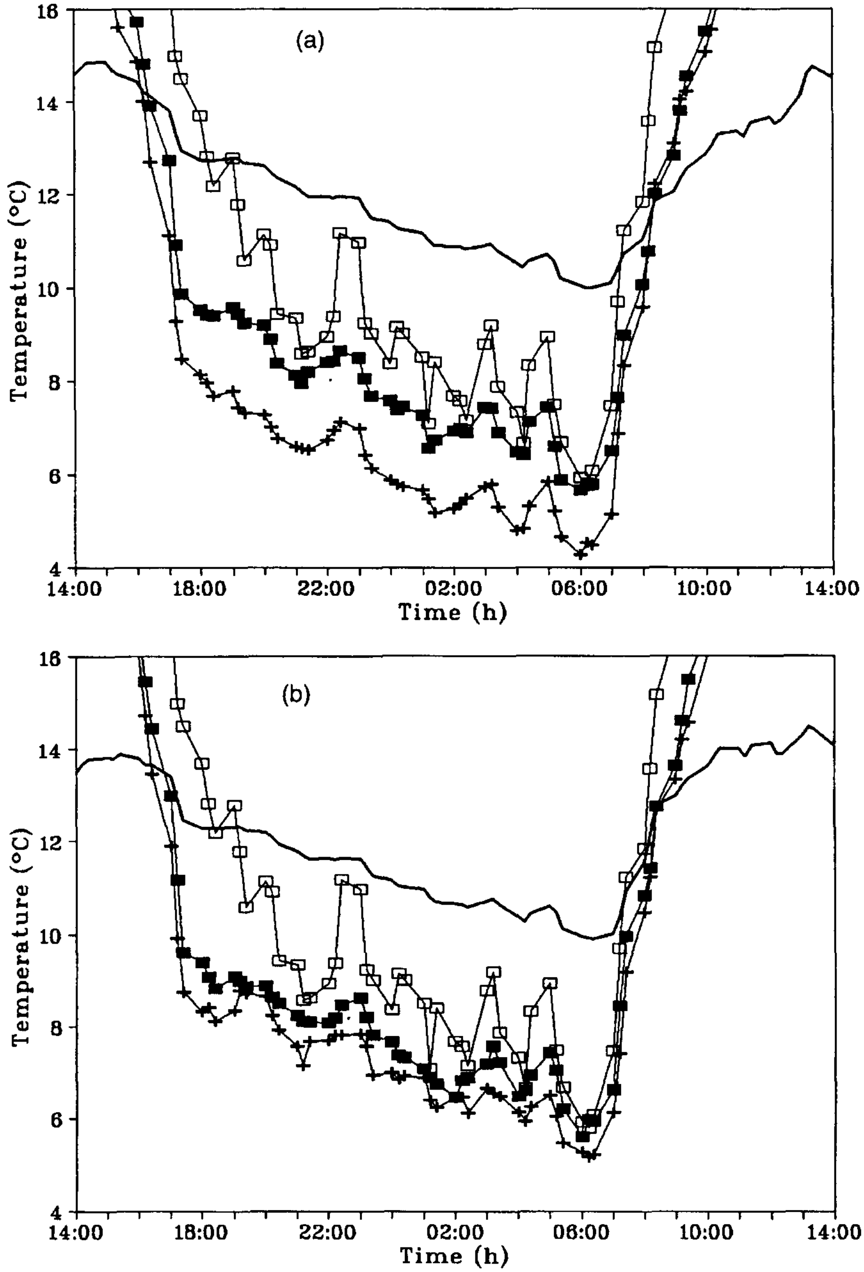

Fig. 7. (a) Temperatures under a '50% black' screen. (—) ground; (□) ambient; (■) air; (+) leaf. (b) Temperatures under a '50% aluminized' screen. (—) ground; (□) ambient; (■) air; (+) leaf.

other hand, during the night the change in heat flux is much slower than in the morning, resulting in similar overnight average temperature drop with respect to time in the ground, in the air and in the leaves.

While the air and ground temperatures under the '50% black' and '50% aluminized' were approximately equal during winter 1993/1994, the temperature of the upper leaves under these screens appears to be different. The temperature of an upper leaf under the '50% aluminized' is higher than that under the '50% black' by about 0.8-1°C. The higher leaf temperature is due to better protection, from radiative heat loss, of the aluminized screen. Under both screens the temperature of the leaves was lower than air temperature. This behavior was observed under all tested screens. Actually such a behavior was expected since the leaves loose heat by long wave radiation and therefore cool to a lower temperature than the air.

Since the accurate measurements of leaf temperature over long periods of time is difficult to accomplish with thermocouples, because of the injury caused to the leaf due to thermocouple insertion, an attempt is made here to estimate the temperature of an upper leaf from conventional measurements of air temperature, wind velocity and net radiation. Assuming that the temperature variations with respect to time are slow and that the heat storage in the leaf, the transpiration from it and the net radiation from the lower side of the leaf are negligible during the night, the energy balance equation on a leaf reduces to:

$$2h(T_a - T_l) = N \tag{5}$$

where $h$ ($\mathrm{W\,m^{-2}\,K^{-1}}$) is the heat transfer coefficient from the leaf, and $N$ ($\mathrm{W\,m^{-2}}$) is the net radiation from the leaf. Note that the net radiation from the lower surface of the upper leaf is negligible since it exchanges heat with other leaves beneath it which are at approximately the same temperature as that of the upper leaf.

The heat transfer coefficient $h$ is given (Stanghellini, 1987) by:

$$h = \frac{\rho C_p\left(l|T_l - T_a| + 207u^2\right)^{0.25}}{1174 l^{0.5}} \tag{6}$$

where $\rho$ ($\mathrm{kg\,m^{-3}}$) is the density of the air; $C_p$ ($\mathrm{J\,kg^{-1}\,K^{-1}}$) is the specific heat of the air; $l$ (cm) is a characteristic length of the leaf and $u$ ($\mathrm{cm\,s^{-1}}$) is the velocity of the air. Eq. (6) was derived for the case of mixed (forced as well as free) convection and it takes into account findings that a fluctuating flow can expand heat transfer from surfaces (Stanghellini, 1987, 1993)

Assuming that the net radiation from the leaf is equal to that measured by the net radiometers that were positioned about 20 cm above the plants (since the long wave spectral characteristics of the ground and the leaves are approximately equal) and using the experimental data of air temperature and wind velocity we calculated using Eqs. (5) and (6) the temperature of an upper leaf under a '50% aluminized' screen. The calculated result together with the experimental data are shown in Fig. 8. The agreement between the experimental data and the calculations is good resulting an average deviation of about 0.2°C. Since the deviation during night between calculated and measured leaf temperatures is both positive and negative, absolute values are used for

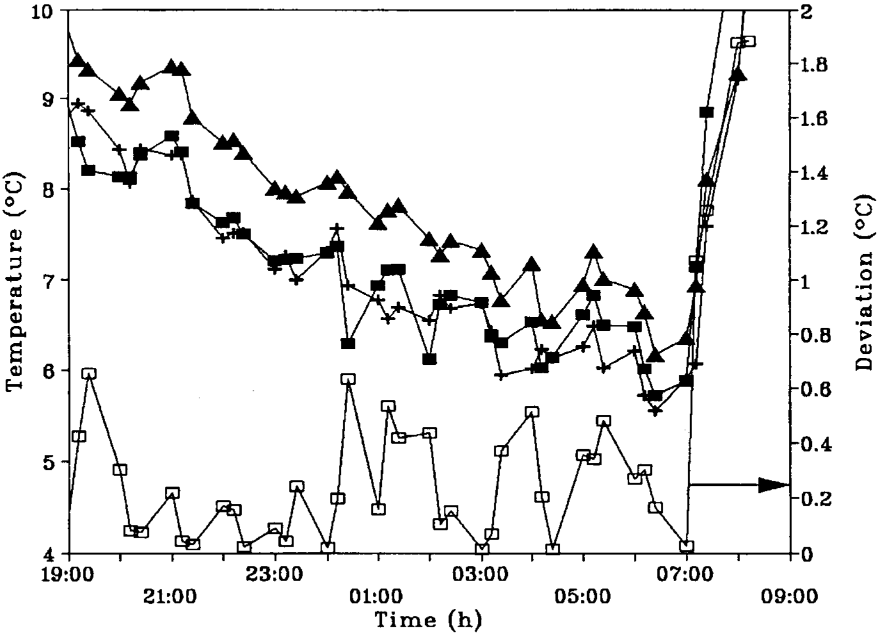

Fig. 8. Temperature of an upper leaf, $T_l$, under a '50% aluminized' screen. (▲) air temperature; (■) calculated, Eqs. (5) and (6); (+) experimental data; (□) deviation. Calculated and experimental data refer to leaf temperatures.

calculating the average deviation. Note that Fig. 8 presents the absolute values of the deviation. The average deviations for the '20% white', '30% black' and '50% black' screens were 0.2, 0.4 and 0.5°C, respectively.

These results suggest that leaf temperature was actually lower by about 0.5–1°C than air temperature. This is in agreement with the results of Shaw (1954), who showed that minimum air temperatures provide little information on the temperature of the leaves during frost. The trigger for operating frost protective means should, therefore, be the leaf temperature and not the air temperature which is usually used at present.

## 6. Conclusions

Shading screens stretched horizontally over the crops can reduce the risk of frost damage; aluminized screens were found to be the most effective. The screens should have high shading percentage. It should be emphasized, however, that the high shading percentage of the screen reduces the amount of light that reaches the plants during the day and thus affects their growth and yield. It is recommended that these screens should be stretched over the crops only when frost is expected.

A model was devised for calculating the decrease in net radiation due to the presence of a shading screen. The model suggests that net radiation under a screen is dependent on the shading percentage of the screen, on the transfer factor of the screen material $\beta = 0.5\epsilon_s + \tau_s$ and on the ratio between screen area and the ground area beneath it. The effectiveness of a horizontal screen appears to be higher than that of a low tunnel formed by spreading a screen over the plants.

The temperature of the leaves, under all types of screens, drops at night to lower levels than air temperature and, therefore, the control of any frost protective-devices in the case of severe frost should be triggered by leaf temperature and not by air temperature.

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