Thermal properties of mulch and row cover materials determine, to a significant degree, the microclimate modification afforded by low tunnels used for early-season, field-grown vegetables and fruits. Thermal models, based on well-known physical principles, can be developed to predict the microclimate effects of such tunnels. The models can range widely in complexity, from simple steady-state energy balances to computer-based, transient formulations using techniques such as finite element analysis.

Chandra and Albright (4) reported a model to predict the effect of thermal curtains in greenhouses. The model contained thermal radiation and energy balances, but did not consider the time-dependent effects of thermal storage in the ground. In terms of most thermal energy flows, a greenhouse with a thermal screen is very similar to a row cover with a mulch. However, the importance of the ground is likely to be significantly greater in a tunnel than a greenhouse, where much of the floor is shaded by benches during the day.

The objective of the work reported here is to apply the greenhouse thermal model of Chandra and Albright (4) to a vegetable tunnel. The model will be modified to include time-dependent effects of thermal energy storage in soil under the tunnel.

**Thermal Model Development and Testing Methods**

In a steady-state thermal system comprising several participating members, temperatures stabilize such that both thermal energy and thermal radiation (long-wave) balances are achieved. A thermal energy balance is imposed to ensure that as much energy leaves each member of the system as is received (steady-state). A thermal radiation balance ensures that all long-wave thermal radiation leaving any member is received by other members of the system, and all thermal radiation received by any member must have originated only from members of the system.

Solar radiation is separate, and functions as a boundary condition imposed on the system.

Long-wave thermal radiation balances are not imposed in most thermal models. However, the added restriction of a long-wave thermal radiation balance is essential when thermal radiation is an important component of energy flows, as with row covers.

Thermal radiation that leaves the surface of an object has three components: that emitted directly, that received from elsewhere and reflected, and that received from elsewhere and transmitted through the object, as from one side of a plastic sheet to the other. In any thermal system, long-wave thermal radiation leaving an object depends in part on all other objects, and a radiation balance must be solved as a set of simultaneous equations.

Similarly, thermal energy exchanges typically involve all objects in a thermal system and a temperature change of one object affects temperatures of all others. Thus, a thermal energy balance must also be solved as a set of simultaneous equations. Furthermore, since both thermal energy and radiation affect temperatures, and vice versa, the two balances must be solved concurrently.

**Description of model.** Energy flows in a row cover thermal system include: solar insolation; long-wave thermal radiation exchange among the soil, row cover, and sky; convective exchange between the row cover and air both inside and outside the tunnel; ventilation; lateral heat loss through the ground to soil bordering the tunnel; and thermal storage in soil under the tunnel. Such a system is shown in Fig. 1.

Numerous assumptions are incorporated into the model:

1. All surfaces involved in long-wave thermal radiation exchanges are thermally gray (radiation properties do not change within the expected range of temperature excursions).
2. The soil surface is opaque while the row cover and mulch (if included) may not be.
3. Air inside the tunnel does not participate in thermal radiation exchanges, but air outside does through a model of sky temperature. For this study, the Swinbank (7) model for effective clear sky temperature (\(T_a\)), based on outdoor air temperature (\(T_w\)), was adopted,

\[
T_a = 0.0552(T_w)^{1.5} \tag{1}
\]

where temperatures are Kelvin.

4. Heat is not generated within the tunnel.
5. There is no thermal storage except within soil under the tunnel.
6. Heat storage in soil under the tunnel is a one-dimensional...
heat conduction process, and can be represented using a lumped parameter model.

7) Air within the tunnel, and under the mulch cover if there is one, is well-mixed (uniform temperature).

8) Convective coefficients at the soil, mulch cover, or underside of the tunnel cover are not functions of wind speed or tunnel ventilation rate.

9) Ventilation is steady.

10) Plants are sufficiently small that they do not enter into thermal energy and radiation balances.

11) Thermal energy exchange by condensation and evaporation are not significant compared to other thermal fluxes.

Details of model development for a row cover without a mulch are in the Appendix. More complete details and model development for a row cover with a mulch are in ref. 6.

Model solution. The model was coded for computer solution using Turbo Pascal (Borland International, Inc., Scotts Valley, Calif.) for an IBM PC/XT having an 8087 math co-processor. The program (named TUNNEL) reads air temperature and solar radiation from a text file and output can be written to a disk file for later retrieval and use. If weather data are read from a hard disk file, and results written to a hard disk file, a 24-hr simulation using 15-min time steps requires <1 min of computer time to complete. Output includes temperature histories of air inside the tunnel, soil layers, and all participating thermal system components.

Default values for all parameters used in the model are provided by the program (Table 1). Menus are included to permit convenient parameter value changes.

Testing the model. The model was tested against field measurements as a means to assess its adequacy. Hourly air and soil temperature data were collected from mulch-row cover treatments during a 1985 field study (11). Ambient air temperatures and solar radiation from a small weather station =50 m from the experimental plots were used as inputs to the model.

Default values of parameters (Table 1) were used except for row cover short-wave transmittance, row cover outer surface convective coefficient, and air exchanges per hour. The value of short-wave transmittance was based on the measured transmittance of photosynthetically active radiation (PAR) (table 1 in ref. 11).

The row cover's outer surface convective heat transfer coefficient was determined using a model based on greenhouse experiments (2),

\[ h = 2.8 + 1.2V, \]

where \( V \) is wind speed, m s\(^{-1} \), and \( h \) is the convective heat transfer coefficient, W m\(^{-2} \) K\(^{-1} \).

An air exchange rate of one tunnel volume per hour was assumed to represent a polyethylene tunnel without holes or slits. Estimated deviations from the default value for various materials were based on ventilation characteristics of the material.

Sensitivity analyses. To assess effects of various thermal parameters on the microclimate provided by potential row cover materials, two types of days were examined: warm and sunny, and cool and sunny. Histories to represent each type of day were selected from data for Ithaca, N.Y., using 15-min averages of air temperature and solar insolation, and are shown in Fig. 2 a and b. Clear skies and high solar insolation, and cool and warm days, were selected as the best means to evaluate row cover effects with regard to frost protection at night and excessive heat accumulation during the day.

Default values in Table 1 were used for all simulations. The situation of a row cover but no mulch cover was considered. Specific row cover and environment parameters were varied independently to assess how changing these parameters affects row cover performance. Many simulations and situations are possible; a few are presented as examples.

The following factors were examined for their effects on tunnel air temperature: 1) thermal conductivity of the cover material, 2) long-wave thermal radiation transmittance of the cover, 3) solar radiation transmittance of the cover, 4) row cover surface area relative to ground area, and 5) the ventilation rate.

Results and Discussion

Testing the model. Numerous comparisons of predicted and measured temperatures were made. A typical set was selected for discussion (Fig. 3). For other examples, see ref. 10.

Air temperature predictions during the night have consistently been accurate to within 2°C. Predicted daytime maximum temperatures are normally within a few degrees of measured values, but can differ by as much as 10°C in some cases. More frequent and larger errors for daytime predictions are not surprising, since short-wave as well as long-wave computations (and related assumptions) are involved. Furthermore, wind tends to be more variable during the day, and ventilation is a major component of the energy balances. An incorrectly chosen ventilation rate can lead to significant temperature prediction errors when the actual ventilation rate is near zero. Actual air exchange rates were not measured during field tests.

Soil temperature predictions deviate more substantially and consistently from measured values than do air temperature predictions. Although diurnal patterns of soil temperature (Fig. 3) are similar between predicted and actual field data, the magnitude of temperature oscillation is frequently overestimated by as much as 10°C. Predicted soil temperatures frequently overshoot actual temperatures, both during midday and at night. In part, this difference may be due to improper selection of soil volumetric heat capacitance or thermal conductivity. A value of volumetric heat capacitance greater than the default value would.
Table 1. Default values of parameters used for model testing and simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivities</td>
<td>W·m⁻¹·K⁻¹</td>
<td></td>
</tr>
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<td>Soil</td>
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<td>Row cover</td>
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<tr>
<td>Row cover lower surface</td>
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<td>Long wave radiation properties</td>
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<td>Row cover transmittance</td>
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<td>Fifth layer soil, ( t_5 )</td>
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<td>Air between ground and row covers, ( t_2 )</td>
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<tr>
<td>Upper surface row cover, ( t_u )</td>
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</table>

reduce oscillations in predicted soil temperatures, for example, and a properly chosen value could be found to match field data more closely. However, this form of model adjustment was not attempted. A more complete validation study would begin instead with an independently developed value of the actual volumetric heat capacitance and thermal conductivity rather than one obtained from reference tables.

Another assumption in the model that could lead to soil temperature prediction errors is that soil heat flux is only in the vertical direction. A more complete model could use finite element analysis to model two- or three-dimensional heat fluxes through the soil, and include the effects of solar heating of the ground exterior to the tunnel and variable soil moisture. These suggested improvements would involve major programming efforts, and their worth should be considered in relation to potential benefits of more-accurate soil temperature predictions.

A complete field validation will require more-accurate information on input parameters, but results thus far have been encouraging considering the model's modest level of sophistication. The model appears reasonably robust after experience with a wide range of environmental conditions and 2 years of field data. One aspect of future efforts will be to link TUNNEL predictions of daily air temperature to the degree-day plant growth models discussed in our companion paper (11).

**Sensitivity analyses.** Although TUNNEL simulates diurnal temperature histories, only high and low temperatures are presented. These are usually of greatest interest.

**Thermal conductivity of the cover material.** The effect of thermal conductivity on tunnel air temperature was found to be slight (<0.1°C) due to the small thermal resistance of the cover material compared to the convective thermal resistances at its lower and upper surfaces. The thermal conductive resistance of the default cover is 0.00038 m²·K·W⁻¹, whereas thermal convective resistances at its lower and upper surfaces are 0.25 and 0.05 m²·K·W⁻¹, respectively. Total resistance is the sum of the three; thus, a cover material resistance of at least 0.1 m²·K·W⁻¹ would be required to affect the thermal environment under the cover significantly. Such a large resistance would be unrealistic unless a special cover were used, such as a thin sheet of foamed insulation, which would be a poor transmitter of light.

**Long-wave thermal radiation transmittance.** The greatest chance for frost under the cover (although the effect is slight) is predicted to be when the cover's long-wave transmittance is between 0.3 and 0.5 (Fig. 4). It is not obvious a priori why
both low and high values of transmittance retard frost conditions; however, speculation is appropriate. When transmittance is high, radiation loss from the ground to sky is large, but the ground contains stored heat and thus does not cool rapidly. At the same time, radiation exchange between the row cover and sky is small. (When transmittance is high, emittance is low. Emittance, transmittance, and reflectance sum to unity, and for the same wavelength of radiation, emittance and absorptance are numerically equal.) Thus, the cover temperature is not much below outdoor air temperature (if it were, it would act to cool the air within the tunnel). If the cover does not lose much radiation to the sky, it may in fact be warmer than ambient conditions due to convective heat gain from air within the tunnel.

When transmittance is low, emittance (and absorptance) are high. The soil surface beneath the cover does not exchange radiation significantly with the sky. The cover loses heat by radiation to the sky, but simultaneously gains by radiation from the soil, and, therefore, does not cool as much as if there were no exchange with the soil, which remains relatively warm.

At intermediate values of transmittance (and thus emittance), the soil loses heat to the sky and the cover is heated less by radiation gain from the soil. Concurrently, the cover emittance is sufficiently high to cause significant thermal radiation loss from cover to sky. As a result, cover and soil temperatures are low and act to cool air within the tunnel to below outdoor air temperatures.

Waggoner (9) compared several types of plastic row covers, and concluded that long-wave transmittance had little or no effect in determining frost protection. However, his data, although not completely consistent (temperature differences were often 1K or less), showed that polyvinyl chloride (with a long-wave radiation absorptance of one-half) provided slightly less frost protection than either polyethylene (with an absorptance of one-eighth) or an acrylonitrile-styrene copolymer (with an absorptance of two-thirds). The polyethylene and acrylonitrile-styrene copolymer showed equal frost protection ability. The simulations are thus consistent with Waggoner's data, although in practical terms the effect is minor.

Moisture condensation on the underside of the cover complicates any conclusions one might draw from either Waggoner's work or predictions by our model. If a row cover is ventilated and the weather dry, little condensation may be seen, and long-wave thermal radiation properties of the cover will be important. If there is little ventilation or the weather is damp, condensate will form and act as a thermal radiation barrier (emittance and absorptance of nearly unity) and properties of the cover will be less significant.

If condensation is dropwise (as would be expected with some plastics), water drops may cover half the row cover's lower surface, thereby changing a relatively clear cover to one having an emittance somewhat >0.5, a value that was predicted by our model to provide slightly less protection than would a relatively clear cover. On the other hand, a material designed to have an emittance slightly >0.5 will be changed to one with an emittance...
Fig. 3. Comparison of predicted (—) and field measured (— —) air and soil temperatures for three row cover types. Air exchange rates, tunnel corrective coefficient, and tunnel short-wave transmittance values used for computer simulations are shown in the figures.

The simulations also predict, for solar transmittance of 0.8, a lessening of peak air temperature in a tunnel when the cover's long-wave transmittance is high. This is as expected—the higher the transmittance, the greater the loss of radiation from ground to sky. Separate simulations for intermediate solar transmittance values (e.g., 0.4) showed air temperature within the tunnel to be minimized when the long-wave transmittance is = 0.4. However, the air temperature increase for higher long-wave transmittance values was small. When solar absorptance is high, the cover is heated by the sun. When the long-wave transmittance is concurrently high (and emittance is thereby low) the cover is less able to lose this absorbed solar heat by reradiation to the sky. Thus, the cover is slightly warmer than it otherwise would be, which causes a slightly warmer air temperature in the tunnel.

Solar radiation transmittance. The predicted effect of the row cover's solar transmittance is to cause an air temperature peak at a transmittance value of =0.6 (Fig. 5). This effect is not intuitively obvious, but we advance the following hypothesis: When transmittance is low, little insolation reaches the interior of the tunnel and air temperature is relatively low. When transmittance is near unity, little insolation is absorbed within the row cover material. As a result, little heating of the cover occurs, and it does not retard heat flow from inside the tunnel to
outside more than would be calculated based simply on the conductive resistance of the cover. Absorbed solar radiation does not affect actual thermal resistance. Rather, it acts as a heat source within the cover material to warm the cover slightly and retard convective exchange from air inside the tunnel to the cover.

When transmittance has an intermediate value, there is still sufficient absorption of insolation within the cover material to heat the cover slightly. Less insolation is absorbed within the tunnel, but that absorbed is less able to pass back to the outside, with a resulting slightly higher tunnel temperature. A comparable effect was found by Albright et al. (1), who measured an increase of \( \approx 10\% \) of the overall thermal resistance of a double polyethylene greenhouse cover during the day, ascribed to solar energy absorption within the greenhouse cover.

Row cover area ratio. The row cover area ratio is expressed here in terms of the tunnel height and width, rather than actual area ratios. The assumed width was constant at 1.0 m, and the height was permitted to vary from 0.0 to 1.0 m. Tunnel height has a significant effect (Fig. 6). Higher tunnels present more surface area for thermal exchange with ambient air, and the minimum and maximum temperatures are more closely coupled to ambient air temperature. Greater surface area for heat loss reduces the effect of solar heating during the day, and acts to permit more rapid loss of solar heat that was stored during the day.

To avoid overheating, one could conclude tunnels with a large surface area ratio are best. However, to protect against frost, tunnels with minimal surface area ratio are preferable.

Ventilation rate. The effect of ventilation on daily maximum air temperature is less than we expected (Fig. 7). Even when ventilation is nearly zero, the daily maximum air temperature is predicted to be only a few degrees above ambient. In contrast, our field measurements (10) on sunny days have shown maximum daily air temperatures within a perforated clear polyethylene tunnel (low air exchange rates) to be consistently 5 to 10°C higher than in a clear slitted tunnel (high air exchange rates).

Within the model, air exchange is incorporated as simple mass and thermal energy balances, founded on well-recognized physical principles. Thus, the difference between predictions and experience must arise from causes other than the basic model formulation. Incorrectly assumed values of thermal parameters are likely to be a cause of error.

Small changes of certain assumed thermal parameter values, such as solar absorptance at the soil's surface, volumetric heat capacitance of the soil, soil thermal conductivity, and convective coupling between the soil and air within the tunnel, substantially affect predicted air temperatures. However, varying these parameters to fit predictions more closely to data is an improper way to validate or test a model. For validation, parameter values should be determined independently, then used for predictions, with the accuracy of the predictions subsequently assessed. However, regardless of thermal parameter val-

Fig. 4. Predicted effect of row cover long-wave thermal radiation transmittance on daily high and low temperatures under a row cover.

Fig. 5. Predicted effect of row cover solar transmittance on daily high and low temperatures under a row cover.

Fig. 6. Predicted effect of row cover height on daily high and low temperatures under a row cover.

ues, the ventilation effect rapidly reaches a point of diminishing returns as the ventilation rate exceeds several total volume exchanges per hour.

At night, ventilation offsets the effect of radiational cooling within the tunnel by mixing ambient air with tunnel air and keeping tunnel temperature near ambient (Fig. 7). This phenomenon has been observed in the field. Taber (8) reported cooler nighttime temperatures under row covers compared to treatments without covers (when plastic mulch was used). This relationship apparently was due to restricted advective warming when covers were used.

Summary

A time-dependent thermal model of row covers is presented that includes effects of conductive, convective, and radiative heat exchange, and of ventilation. Heat conduction within the soil is included as a one-dimensional, time-dependent, lumped-parameter phenomenon. The model was tested by comparing its predictions to experimental data, and agreement was found to be reasonably good considering the approximation of thermal parameter values. The model may be useful for several purposes, including: a) comparative predictions of climate effects, b) comparative predictions of effects of thermal parameters de-
scribing row cover materials, c) education and understanding thermal phenomena in row covers, d) linking to degree-day models of plant growth [see Wolfe et al., 11)] to assess the impact of using row covers, and e) extension to a more sophisticated model that relaxes some of the assumptions contained in the current model, should that be desirable at some point.

However, the model is not proposed as a management tool. The value of the current form of the model is greater for education and understanding than for immediate implementation. Further, approximations made to develop a model for heat transfer in soil under a tunnel are relatively crude; this is likely the weakest part of the model.

Predictions using the model showed several probable thermal behaviors of row covers, including: a) they are insensitive to the thermal conductivity of the row cover material, within reasonable ranges of conductivity, b) the least frost protection is offered when the cover material's long-wave radiation emittance (or absorptance) is between 0.3 and 0.5, c) moisture condensation on the underside of a row cover that is relatively transparent to long-wave thermal radiation will likely enhance frost protection, d) the highest air temperature within the tunnel during sunny days occurs when the cover material’s solar transmissivity has an intermediate value, ≈ 0.5, e) the highest degree of frost protection is provided by a row cover having the minimum area ratio (or minimum height), and f) ventilation has relatively little effect on air temperature under row covers if the ventilation air exchange rate is greater than several total volume exchanges per hour.

Appendix

Following is a derivation of thermal radiation and energy balances for a tunnel without a mulch cover. For a tunnel with a mulch cover, the derivation is similar and details are presented by Novak and Albright (6).

Thermal radiation. Total radiation flux leaving surface i (B_i) includes radiation emitted (W) by surface i (which can be represented using the Stefan-Boltzmann relationship, \( W = \varepsilon \sigma T^4 \)), incoming radiation (H_i) reflected by surface j, and incoming radiation (H_i) transmitted from j, the other side of surface i. Radiation fluxes leaving the four surfaces involved in thermal radiation exchange are:

- Surface 1, the soil:
  \[ B_1 = \varepsilon_1 \sigma T_1^4 + (1 - \varepsilon_1) H_1 \]  
  
- Surface 4, lower surface of cover:
  \[ B_4 = \varepsilon_4 \sigma T_4^4 + \rho_4 H_4 + \tau_4 H_5 \]  
  
- Surface 5, upper surface of cover:
  \[ B_5 = \varepsilon_5 \sigma T_5^4 + \rho_5 H_5 + \tau_5 H_4 \]  

- The sky:
  \[ B_s = \varepsilon_s \sigma T_s^4 \]  

The radiation balance assumes \( \rho = 1 - \varepsilon \) for an opaque surface.

Angle factors, \( F_{ij} \), for radiation exchange express the fraction of radiation leaving surface i that is intercepted by j. The angle factor from 1 to 4 is 1.0 because surface 1 can see only surface 4 in a radiation exchange process; it sees neither itself, surface 5, nor the sky. The angle factor from 4 to 1 becomes the ratio of areas (area 1 divided by area 4) by the reciprocity theorem. By definition, the sum of angle factors from surface 1 to all surfaces is unity and the angle factor from 4 to itself, \( F_{4,4} \), is \((1.0 - A_4/A_4)\). The upper surface of the tunnel is assumed to exchange thermal radiation only with the sky, thus \( F_{1,5} \) is unity, and \( F_{5,1} \) is zero.

In an enclosure with thermal radiation exchange, radiation from surface j to i is \( B_A F_{ij} \), which, by reciprocity, is also \( B_A F_{ij} \); the incoming thermal radiation flux is \( B_f j \). Total incoming flux to i from all surfaces is

\[ H_i = \sum_{j=1}^{n} B_f j \]  

(A5)

Noting the previously defined values of angle factors, the thermal flux equations can be substituted into the radiation balance equations to eliminate the H terms, and the result rearranged to yield matrix equation [A6] (Fig. 8). The matrix equation is written to be solved for the B terms. If all temperatures (and other parameters) are known, the total thermal radiation flux leaving each surface may be calculated by solving the matrix equation. The thermal radiation values are part of the overall thermal energy balance.

Thermal energy. For a thermal system having components without significant thermal mass, the sum of all thermal energy flows to these components during a time period must equal the sum of all thermal energy flows from these components during the same time period. When there is significant thermal mass, the difference between that received and that lost equals the change of thermal energy stored.

Heat flow mechanisms can be: thermal radiation, convection (characterized by a coefficient h), conduction (characterized by thermal conductivity k), and ventilation (characterized by a mass flow rate of m). Evaporation and condensation are assumed negligible.

The mass flow rate of ventilation air can be calculated if the areas of openings in the tunnel cover, ambient wind velocity, and wind loading pressure coefficients are known. The calculation procedure is described by Bruce (3) and was incorporated into TUNNEL. The computer program can operate either with a fixed air exchange rate, or with an air exchange rate calculated based on wind velocity.

In summary, the method consists of determining the gauge air pressure inside the tunnel that satisfies mass flow continuity, and then using the Bernoulli flow equation to calculate the net air flow at each opening. The sum of all positive or all negative air flows equals the total ventilation rate. For simulations, constant wind speed was prescribed, but could be permitted to change at each time step if desired.

For surface 1, the soil, thermal energy fluxes are: absorbed long-wave thermal radiation, convective exchange with the air, conduction into the soil, heat loss at the perimeter, and absorbed solar radiation, as follows,

\[ (H_1 - B_1)A_1 + h_1 A_1(T_{s1} - T_1) + (2k/D) A_1 (T_n - T_1) + h_1 p (T_p - T_1) + \alpha_1 \tau_1 A_1 = 0 \]  

(A7)

Thermal energy fluxes that affect the air under the tunnel cover are: convective exchange with the soil, convective exchange with the cover itself, and ventilation, as follows,

\[ h_2 A_1 (T_1 - T_{s2}) + h_2 A_2 (T_4 - T_{s2}) + \rho_m p (T_p - T_{s2}) = 0 \]  

(A8)

At the lower side of the tunnel cover, thermal energy fluxes are: absorbed long-wave thermal radiation, convective exchange with the air, conduction to the upper surface of the cover, and...
solar energy absorbed in the lower half of the tunnel cover, as follows,
\[ (H_4 - B_5)A_4 + h_4A_4(T_{42} - T_4) + \]
\[ (K/D)A_4(T_5 - T_4) + \alpha_4\sigma S_A 4 = 0 \quad [A9] \]

At the upper side of the tunnel cover, thermal energy fluxes are:
absorbed long-wave thermal radiation, convective exchange
with the outdoor air, conduction to the lower surface of
the cover, and solar radiation absorbed in the upper half of
the tunnel cover, as follows:
\[ (H_5 - B_5)A_5 + h_5A_5(T_{50} - T_5) + (k/D)A_5(T_4 - T_5) + \alpha_5\sigma S_A 5 = 0 \quad [A10] \]

With suitable rearrangement, the energy balances become Eq.
[A11] (Fig. 9).

In the thermal energy matrix equation, if all thermal radiation
terms, boundary conditions, and thermal parameters are known,
temperatures of each component of the thermal system can be
calculated by solving the matrix equation. The desired tempera-
tures are air temperature inside the tunnel, and soil tem-
perature. However, before soil temperature may be determined,
soil temperature must be expressed as a function of time, boundary
conditions, and pertinent thermal parameters.

A separate sub-model was required for heat flow and storage
within the soil. A lumped parameter method was used, assuming
the soil to be five layers, as shown in Fig. 1, above “deep
ground” soil at constant temperature, T_d. The diurnal cycle of
soil temperature does not penetrate far into the earth, thus five
layers 50 mm thick with time-varying temperature and thermal
storage were deemed sufficient to model conditions for individ-
ual days. The standard approach of using energy balances on
each layer, and stepping the solution through time using a for-
dward difference approximation of the resulting differential equa-
tions, was adopted. Details can be found in Novak and Albright
(6), and most standard numerical methods textbooks.

In matrix Eq. [A11], unknown terms are the temperatures
that can be determined if all radiation fluxes (and other param-
eters) are known. In matrix Eq. [A6], the unknown terms are
thermal radiation fluxes that can be determined if all tempera-
tures (and other parameters) are known. Thus the two matrix
equations form a pair of coupled matrix equations that must be
solved together.

Solution of the model. Solving Eq. [A6] depends on solving
Eq. [A11], and vice versa. Numerical procedures exist to solve
either alone, so the procedure to solve both must rely on an
iterative approach. In TUNNEL, the solution procedure begins
with an assumption of all temperatures, followed by a solution
for thermal radiation fluxes. The candidate thermal radiation
fluxes are then used to calculate new candidate temperature
values, with the cycle repeated until calculated values of tem-
perature stabilize (to within a prescribed level of stability, 0.05K,
for example). The numerical procedure to solve each matrix
eyequation by itself is Gaussian elimination with pivotal conden-
sation (5).

After temperatures and thermal radiation flux values converge
to stable solutions based on boundary conditions for a particular
time, soil temperatures are determined for the following time
using the forward difference approach and the new soil surface
temperature is used as a boundary condition in the next solution
of the matrix equations.

Typical time steps are 15 min, although hourly time steps
provide stable solutions of soil temperature. Weather data were
available in 15-min averaged values, and the 15-min time step
was retained for all solutions.

A refinement of the iterative procedure is required to assure
stability of the solution when a dark mulch cover is included in
the model. Then, the simple iterative approach oscillates be-
tween two apparently stable solutions. The problem arises be-
cause each matrix equation by itself is ill-conditioned, having
many zero terms off the diagonal.

To prevent oscillation, when its onset is observed, each fol-
lowing iteration begins with values averaged from the two pre-
vious iterations. This ad hoc method provides sufficient stability
that convergence is achieved for all reasonable values of thermal
and weather parameters. It is still possible to find conditions
where convergence is not achieved, but only in extreme and
unlikely cases, such as having solar insolation twice the solar
constant.

As in any numerical, time-dependent solution of a thermal
model, initial conditions are required for the temperature of each
soil layer. The model was used to provide estimates of its own
initial conditions. For a day of given weather, the soil was
initially assumed to be at a uniform temperature equal to deep
ground temperature, and the solution proceeded through the day.
At the end of the simulated day, soil temperatures were no
longer uniform. Values at the end of the hypothetical day were
used as initial conditions to begin the day-long simulation again.
It was found only one cycle was required to provide reasonable
initial conditions, the effect of assuming uniform temperature
had abated to insignificance by the end of one simulated day
and repeating the cycle was not necessary to achieve more ac-
curate initial conditions.

Embedded in this procedure is the assumption that each day
is identical to the previous day, if single-day simulations are
used. If a season-long simulation is desired, the effect of un-
realistic initial conditions dies out during the first simulated day
and may be ignored for all following days.

List of symbols

\[
\begin{align*}
A & \text{ Area, m}^2. \\
B & \text{ Radiosity, radiation flux leaving a surface, W} \cdot m^{-2}. \\
c_{pa} & \text{ Specific heat of air, J} \cdot kg^{-1} \cdot K^{-1}. \\
D & \text{ Depth of each soil layer, m.} \\
D_t & \text{ Thickness of tunnel cover, m.} \\
f & \text{ Shape factor, dimensionless.} \\
f & \text{ Perimeter heat loss factor, W} \cdot m^{-1} \cdot K^{-1}. \\
H & \text{ Radiation flux entering a surface, W} \cdot m^{-2}. \\
h & \text{ Convection heat transfer coefficient, W} \cdot m^{-2} \cdot K^{-1}. \\
k & \text{ Thermal conductivity of soil, W} \cdot m^{-1} \cdot K^{-1}. \\
k_t & \text{ Thermal conductivity of tunnel cover, W} \cdot m^{-1} \cdot K^{-1}. \\
rh & \text{ Mass flow rate of air, kg} \cdot s^{-1}. \\
P & \text{ Perimeter of tunnel, m.} \\
S & \text{ Solar irradiation, W} \cdot m^{-2}. \\
T & \text{ Temperature, K.} \\
\alpha & \text{ Thermal absorptance of a surface, dimension less.} \\
\epsilon & \text{ Thermal emittance of a surface, dimension less.} \\
\rho & \text{ Thermal reflectance of a surface, dimension less.} \\
\sigma & \text{ Stefan–Boltzmann Constant, W} \cdot m^{-2} \cdot K^{-4}. \\
\tau_t & \text{ Thermal radiation transmittance of tunnel cover, dimensionless.}
\end{align*}
\]

Asparagus Aphid Feeding and Freezing Damage
Asparagus Plants

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Abstract. Asparagus aphid (Brachycorynella asparagi (Mordvilko)) feeding without freezing reduced vigor of asparagus (Asparagus officinalis L.), as measured by crown size, fern growth, root necrosis, and bud number, but did not greatly reduce short-term survival. Freezing dormant crowns for 24 hr at —4.5°C killed some crowns and reduced vigor of survivors. Aphid feeding and freezing were synergistic; they reduced survival and vigor of survivors to a much greater extent than either aphid feeding or freezing alone. Aphid feeding resulted in early budbreak and precocious growth. A method for counting aphids per plant was developed.

Growers frequently have noted the inconsistent survival rate of asparagus plants in the state of Washington the spring following an asparagus aphid infestation. Reduced survival has been more of a problem during severe winters, suggesting that freezing temperatures are a factor.

The asparagus aphid was first reported in the United States in New York in 1969 (Wildman, 1984). By late 1981, the aphid had been detected in 20 states and several Canadian provinces. However, in eastern North America, aphid number in most fields was low and the damage attributed to them inconsequential. B. asparagi was first identified in Washington in late 1979. In 1980, the Washington asparagus crop suffered losses estimated at 25% of normal production levels. The aphid has now been detected in California (Castle et al., 1987). Symptoms of asparagus aphid feeding on asparagus include stunting of top and root, premature crown budbreak, and prolific shoot growth in the early spring (Capinera, 1974; Dyck, 1981).

Few studies on asparagus cold hardiness have been reported. Even less is known about the interactions between asparagus pest damage and cold hardiness. Heavy asparagus aphid feeding caused asparagus to break dormancy and initiate spears at a lower temperature, earlier in the spring (Dyck, 1981). Additionally, —5°C was found to be the threshold for freezing damage of asparagus crowns (unpublished data). The purpose of this study was to determine the effects of aphid feeding followed by exposure to freezing temperatures on asparagus seedling growth.

Materials and Methods
Four separate trials that subjected asparagus to aphid feeding, followed by dormancy induction and crown freezing, were conducted in 1985 and 1986. Aphids used in these experiments were provided by the USDA, Yakima, Wash, and were reared on healthy asparagus plants in cages 120 x 90 x 90 cm in a greenhouse. A high-pressure sodium vapor 400-W lamp was used to supplement photoperiod and compensate for shading by the cage. Aphids reproduced rapidly under these conditions. At the commencement of the feeding treatments, aphid-infested plants from the cages were placed in an isolated 5 x 5-m green-