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An Orchard Foliage Temperature Model[1]

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Abstract. **A model that computes orchard foliage temperature distributions in a heated orchard is described. The energy balance for individual foliage elements is computed, considering thermal radiation from the environment, plus the radiative and convective effects of an array of orchard heaters. The model is used to analyze various heater configurations and densities, and to determine rates of fuel consumption required for frost protection. The results indicate that radiative heating of the foliage by the heaters is as important as convective heating of the air, even though only one-fifth of the fuel contributes to radiation emission. Further, results suggest several simple passive methods for increasing the efficiency of orchard heating.**

The purpose of modeling a heated orchard is to provide quantitative guidelines for the efficient use of heaters. Such guidelines address questions involving when to begin heating, what rate of fuel consumption is needed to provide a certain level of protection, the appropriate number and arrangement of heaters, etc. While fuel oil was relatively inexpensive, heaters were used with little consideration of efficiency. The models developed during this period reflect this attitude toward fuel use. Crawford's (1) and Gerber's models (6) provide guidelines concerning the necessary heat input to protect the orchard as a whole. Crawford's approach is to consider a box of orchard size with depth equal to the depth of the heated layer of air, and to compute the heat necessary to keep the air in the box at a certain temperature. No mention is made of leaf or blossom temperature, nor is allowance made for warming due to the radiative output of the heaters. Implicit in Crawford's model is the assumption that heating requirements are met by varying the number of fires rather than individual fire size. The model should be used iteratively when this is not the case. Gerber (6) takes a similar approach, but includes an orchard-sized leaf in the box. The temperature differences between this leaf and the air outside the box, and between the air inside the box and that outside, are somewhat arbitrarily chosen. Large scale (box) models such as these can't do more than provide large scale guidelines; either the orchard is protected or it isn't.

In reality, foliage at various locations within the orchard will be at different temperatures, depending on exposure to the sky, the ground, the fired heaters and other foliage. To predict this distribution of foliage temperatures, a model must consider all the important variables that affect energy exchanges of individual foliage elements. Obviously the spatial scale of such a model must be comparable to the size of the individual foliage elements. The important variables include tree spacings, the size, shape, and foliage density of individual trees, the orientation, distribution and spectral properties of the foliage, and the location, size, shape, and burn rate of the heaters in the orchard. Such an analysis should be able to predict relative degrees of damage (fractions of blossoms which are at or below some critical temperature) for various conditions, and thus be used to evaluate optimum heater locations, sizes, and burn rates, as well as providing guidelines for day-to-day frost protection decisions.

Materials and Methods

Model description. The orchard consists of a finite number of trees arranged in a regular array. Each tree constitutes a canopy, and these volumes may or may not be overlapping. Interspaced among the trees are heaters of variable size, arranged in any regular or irregular array. Canopy size and shape are defined in a statistical sense; each individual canopy need not adhere to specifications, but if superimposed, all the canopies would exactly fill a volume of specified size and shape. Usually that shape is taken to be spherical, but the general case of ellipsoidal canopies has been treated (19). Within each canopy, the foliage is considered to consist of randomly distributed flat plates. The amount of foliage is characterized by a foliage density ("one-sided" foliage surface area per unit volume of canopy). If necessary, further refinement may be gained by considering the individual canopy to be two or more ellipsoids, each fully contained by the next larger, but none having to be concentric or similarly shaped. A foliage density for each resulting layer may then be specified (19).

The foliage elements are assumed to have a spherical orientation distribution; within any foliage-containing volume, the fraction of the foliage area facing a particular direction may be computed from the fraction of the surface area of a sphere that is facing the same direction. This foliage orientation distribution gives rise to a foliage temperature distribution for any location in the orchard. Foliage oriented perpendicular to a ray from a nearby heater will receive more radiation from that heater than foliage parallel to the ray. Diffuse radiation received from the natural environment (sky, soil, etc.) is not a function of a foliage element's orientation.

This model also considers the effect of an array of heaters spaced throughout the orchard. Heaters are taken to be upright cylinders of variable length, radius, and height above the ground. Burning heaters will heat the air, radiate directly to the foliage, and have indirect effects, such as heating the soil.

The temperature of a particular foliage element results from a balance between radiant and sensible heat fluxes:

$$R_t = \frac{2\rho\, c_p\,(T_f - T_a)}{r_h} + 2\epsilon_f \sigma T_f^4 \qquad [1]$$

where R_t is the total incoming radiant flux density (W m^{-2}), ρ is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure (J kg^{-1} K^{-1}), T_f is temperature of the foliage element (K), T_a is ambient (heated) air temperature in the orchard (K), ϵ_f is foliage emissivity, r_h is leaf boundary layer resistance (s m^{-1}) and σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}). The total incident radiation R_t comes from 2 sources: the natural environment R_e (W m^{-2}) and the heaters, R_h (W m^{-2}).

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$$R_t = R_e + R_h \quad [2]$$

The natural irradiance of a leaf is assumed to have three sources; thermal radiation from the sky R_u (W m^{-2}), from the orchard floor R_ℓ (W m^{-2}) and from other foliage in the orchard radiating at some mean temperature $\overline{T}_f$ (K). To calculate the incoming radiation on a leaf, the strength of those sources must be combined with the relative view that the irradiated leaf has of the sky, ground, and other foliage. For example, a leaf within a dense crown will receive most of its radiation from other foliage while a leaf at the top of a crown will receive most of its radiation from the sky. Environmental irradiance may thus be expressed as

$$R_e = \tau_u R_u + \tau_\ell R_\ell + (2 - \tau_u - \tau_\ell)\, \epsilon_f \sigma \overline{T}_f^4 \quad [3]$$

where τ_u and τ_ℓ are the diffuse transmittances for the upper and lower hemispheric views of the leaf in question. τ_u and τ_ℓ are computed by integrating the probability of beam penetration (beam transmittance) over the appropriate hemisphere (14):

$$\tau_u \text{ or } \tau_\ell = \frac{\iint_{\text{hem.}} p(\theta,\phi) \sin\theta \cos\theta \, d\theta \, d\phi}{\iint_{\text{hem.}} \sin\theta \cos\theta \, d\theta \, d\theta} \quad [4]$$

where θ and ϕ are zenith and azimuth angles, and $p(\theta,\phi)$ is the probability of a beam of radiation passing through the orchard from direction (θ,ϕ) to the leaf without being intercepted by other foliage. This may be expressed (12) as

$$p(\theta,\phi) = \exp(-k\,\mu S(\theta,\phi)) \quad [5]$$

where $S(\theta,\phi)$ is the accumulated distance (m) through tree canopies between the leaf in question and the edge of the orchard in the direction (θ,ϕ), μ is foliage area (one side) per canopy volume (m^{-1}), and k is the fraction of foliage area projected toward the beam of radiation. For spherically oriented foliage elements, k is always 0.5 (2). Equations for $S(\theta,\phi)$ as a function of tree canopy size, shape, and spacing are given in Welles (19). Sky radiation R_u can be measured, or estimated by an empirical scheme (8):

$$R_u = \sigma T_o^4 (1 - 0.261 \exp(-7.77 \times 10^{-4} (273 - T_o)^4)) \quad [6]$$

where T_o is initial, unheated, air temperature (K). Radiation from the orchard floor is

$$R_\ell = \sigma T_s^4 \quad [7]$$

where T_s is surface temperature (K). Mean foliage temperature $\overline{T}_f$ must be estimated initially to calculate R_e from equation [3]. It is, after all, the distribution of T_f that the model computes. Fortunately T_f usually is within a few degrees of air temperature even though individual $\overline{T}_f$ values may vary over a much wider range. Therefore, substituting ambient air temperature (T_a or T_o, depending on whether or not the heaters are burning) for $\overline{T}_f$ usually suffices. When this is not a good assumption (very dense foliage), the model can be used iteratively with a previously computed value for $\overline{T}_f$.

Radiation from the heaters, R_h, is mostly from the stacks. However, a portion of R_h will arrive at the leaf via the ground around each heater, either through reflection or absorption and re-emission. Heaters can have a marked effect on adjacent soil temperature (4); therefore the ground surface within 1 or 2 meters of each heater (a disc-shaped area) is treated separately from the rest of the orchard floor, and is included with the heater array in calculating R_h.

$$R_h = \sum_{i=1}^{N} P_i (R_s F_i + R_d F_i^*) \quad [8]$$

where N is the number of fired heaters; P_i is the probability of a beam of radiation passing unintercepted from the i^{th} heater to the leaf in question; F_i and F_i^* are respectively the view factors between the i^{th} heater stack and the leaf, and between the disc of ground surface beneath the i^{th} heater and the leaf; R_s is radiation emitted by an individual stack (W m^{-2}); and R_d is the radiation coming from the underlying disc (W m^{-2}). Stack radiation R_s is a function of burn rate per heater B (ℓ h^{-1} heater^{-1}), radiant fraction f_r, and stack area per heater (m^2):

$$R_s = \frac{B f_r a}{A_h} \quad [9]$$

where a = 1.05 × 10^4 W h^{-1} ℓ^{-1} for no. 2 diesel fuel. Radiant fraction can vary with the type of heater and burn rate (15). The expression for beam transmittance, P_i, is similar to equation [5], except $S(\theta,\phi)$ becomes S_i, the distance (m) which is occupied by canopy, between the i^{th} heater and the leaf.

$$P_i = \exp(-k\mu S_i) \quad [10]$$

The view factor between a leaf and a heater stack is a function of leaf position with respect to the heater, and the size and shape of the heater. Hamilton and Morgan (7) and Eckert and Drake (3) provide the basis for view factor relations (19, 20). The contribution from the disc R_d is negligible for typical soils because a 2-m diameter disc receives about 1/6 of the radiant output from the heater. This energy can contribute significantly to R_h if the discs are modified to enhance their thermal reflectivity, or reduce their thermal conductivity, and prevent energy loss to soil heat flux. The emitted radiation from a disc can be calculated using an energy balance between increased net radiation from the heaters, increased soil heat flux, and increased sensible heat flux on a series of independent, concentric rings making up the disc (19). Tests using this model indicate that the contribution of absorbed and re-emitted energy from the discs is minor; hence, the formulations for its calculation are not presented. Reflection from the disc can contribute, however, when the disc is covered with a highly reflective material. Assuming that the radiation from a disc is entirely due to reflection,

$$R_d = (1 - \alpha_d) F_d R_s \frac{A_h}{A_d} \quad [11]$$

where α_d is disc absorptivity, A_d is exposed disc area (m^2), and F_d is the fraction of R_s that is intercepted by the disc (20). It is assumed that each disc is affected only by the heater sitting on top of it.

The ambient air temperature T_a in equation [1] is also influenced by the burning heaters. Crawford's (1) model can be used to estimate the air temperature increase due to the heaters. Crawford's (1) final equation is of the form

$$H = A\Delta T_a + I(\Delta T_a)^{1.5} + R_n \quad [12]$$

where H is the amount of heat added convectively to the orchard by all the heaters (W m^{-2}), ΔT_a is the temperature increase (K) of the air in the orchard ($\Delta T_a = T_a - T_o$), $A\Delta T_a$ is the advection term (W m^{-2}), $I(\Delta T_a)^{1.5}$ is the induced flow term, (W m^{-2}), and R_n is net radiation (W m^{-2}) for the orchard block. Equation [12] may be solved for ΔT_a if rearranged as follows:

$$\Delta T_a = \frac{H - R_n}{A + I(\Delta T_a)^{0.5}} \quad [13]$$

Because of its form the solution must be done iteratively. Equations for A and I can be found in Crawford (1), and R_n is simply ($R_u - R_\ell$). The amount of heat added convectively to the orchard is the sum of convective heater output and radiant output not lost to the sky (assumed to be ½):

$$H = \frac{NBa}{A_o} [(1-f_r) + 0.5 f_r] \quad [14]$$

where A_o is orchard area (m^2).

The leaf energy balance (equation [1]) can be linearized in ΔT_f, where $\Delta T_f = T_f - T_a$.

$$R_t = \frac{2\rho c_p \Delta T_f}{r_h} + 2\, \epsilon_f \sigma (T_a^4 + 4T_a^3 \Delta T_f) \quad [15]$$

This expression is readily solved for ΔT_f:

$$\Delta T_f = \frac{R_t - 2\epsilon_f \sigma T_a^4}{\frac{2\rho c_p}{r_h} + 8\epsilon_f \sigma T_a^3} \quad [16]$$

Leaf boundary layer resistance is assumed to result from forced convection. From Monteith (13),

$$r_h = 180\,(d/u)^{1/2} \quad [17]$$

where r_h has units of (s m^{-1}), d is leaf diameter (m), and u is canopy level wind speed (m s^{-1}).

Computing temperature distributions. Foliage temperature distributions are computed by applying the leaf energy budget to a number of locations within one or more canopies in the orchard. At each location, equation [16] must be applied to each foliage orientation class (azimuth and inclination of the leaf normals) being considered. The locations (at least 15 per tree) should be chosen to give a good sampling of the foliage in a tree's canopy. Frequently, the heater arrangement is such that different trees in the orchard will "see" different configurations of heaters; (Fig. 1). In these circumstances a tree representing each configuration must be considered if a true average is to be calculated for the entire orchard. Thus, running the model once involves applying equation [16] hundreds of times; once for each orientation class, at each location in a given tree canopy, for one or more representative trees. The mean foliage temperature at each location in a tree canopy is the average of ΔT_f for each orientation class weighted by the leaf area per class (Fig. 2). Whenever the heaters are burning, foliage at any location will have a distribution of temperature (Fig. 3a, 3b, 3c, 3d), since foliage in various orientation classes have different views of nearby heaters. When dealing with the tree as a whole, temperature distributions from all the locations within that tree canopy can be combined into a cumulative temperature distribution (Fig. 4a). All temperatures – foliage or air – are referenced to T_o, the unheated air temperature; thus, the axis of Fig. 4a is temperature difference, ΔT. If some critical foliage temperature T_c can be specified such that when $T_f < T_c$, the foliage is lost, then $\Delta T_c = T_c - T_o$. From the example in Fig. 4a, if $\Delta T_c = -0.5$ C and the burn rate is 2 ℓ h^{-1}heater^{1}, then about 60% of the foliage will be lost. The cumulative temperature distribution can be transformed onto a more useful diagram if the burn rate is the abscissa, fraction of foliage lost is the ordinate, and lines of equal ΔT_c are drawn (Fig. 4b); this is a required-burn-rate diagram that can be used to specify the burn rate required to yield some minimum loss fraction given the conditions (ΔT_c). In practice, the model produces a family of curves on a required burn rate diagram (Fig. 5) as its output.

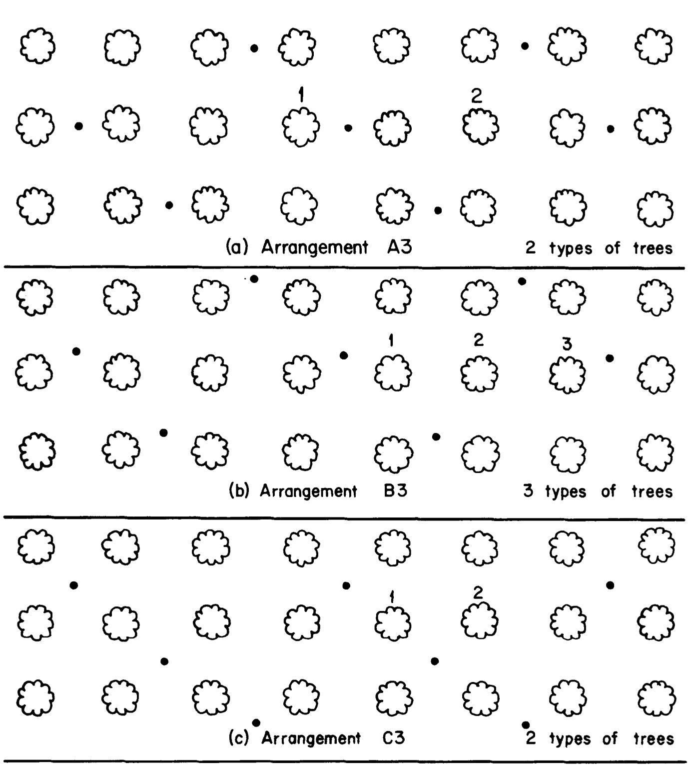

Fig. 1. Three sample heater arrangements (dots) tested by the model. With each arrangement, different trees "see" a different heater configuration. The letter in the heater arrangement name (A, B, C) denotes location of heaters in relation to rows and the number (e.g. 2 in A2) is the number of trees between each heater in the row.

Results and Discussion

The model was applied to a 1 hectare 'Golden Delicious' orchard at The Pennsylvania State University's Rock Springs Agricultural Research Center, with important orchard parameters as in Table 1. The heater arrangement in the Rock Springs Orchard is denoted A3 in Fig. 1. Other heater arrangements and densities are considered in the model.

The relative importance of the radiant output of heaters to their convective output has never been quantitatively determined. However, most authors (5, 9, 10, 15, 17, 21) agree that radiant output is important, especially under windy conditions. Valli (18), however, concludes from a deficient argument that the radiant fraction is not the best measure of a heater's effectiveness. This question can be addressed with the model by using areas on a cumulative foliage temperature distribution diagram (Fig. 6), the heated foliage temperature distribution being the curve at the right (result of radiant as well as convective heater effects). In this example, the nonheated foliage is uniform in temperature (no heater effects) at 2 C less than the unheated air temperature because of net radiation losses to the cold sky. With the heaters burning, but with radiant effects neglected, the air temperature increases by 1.2 C; thus the effect of convection alone results in a uniform foliage temperature only 0.8 C below that of the unheated air (dashed line in Fig. 6). The relative foliage protection derived from heater radiation versus that derived from convection can be expressed as the ratio of areas in Fig. 6, and is designated R/C. The relative importance of heater radiation vs. convection depends on burn rate, wind speed, distance from the heaters and the amount of foliage on the trees. From Fig. 7, the relative importance of radiation increases as the amount of foliage decreases, the distance from the heaters decreases, the burn rate increases, and the wind speed increases. Because the ratio R/C varies from 0.3 to 2 over the relatively narrow range of conditions used in Fig. 7, the controversy over the importance of heater radiation has persisted. Note that although only 1/5 of the energy liberated from the fuel contributes to radiation, a comparable amount of protection is obtained. This suggests that greater fuel economy may be possible by enhancing the radiant effects of the heaters. A more direct way of evaluating the radiant importance can be simulated by increasing the radiant fraction of the model heaters and determining the net effect from required burn rate curves (Fig. 8a). Although the heated air temperature decreases as the radiant fraction increases, the increased radiation more than compensates for the convective loss with a net fuel saving for the same protection.

The specific locations of individual heaters in the orchard can significantly affect the distribution of radiant energy over the foliage. The three heater arrangements (Fig. 1) are compared using their required burn rate curves because fuel use for a given amount of protection can be read directly from this graph (Fig. 8b). All of the heater arrangements yield at

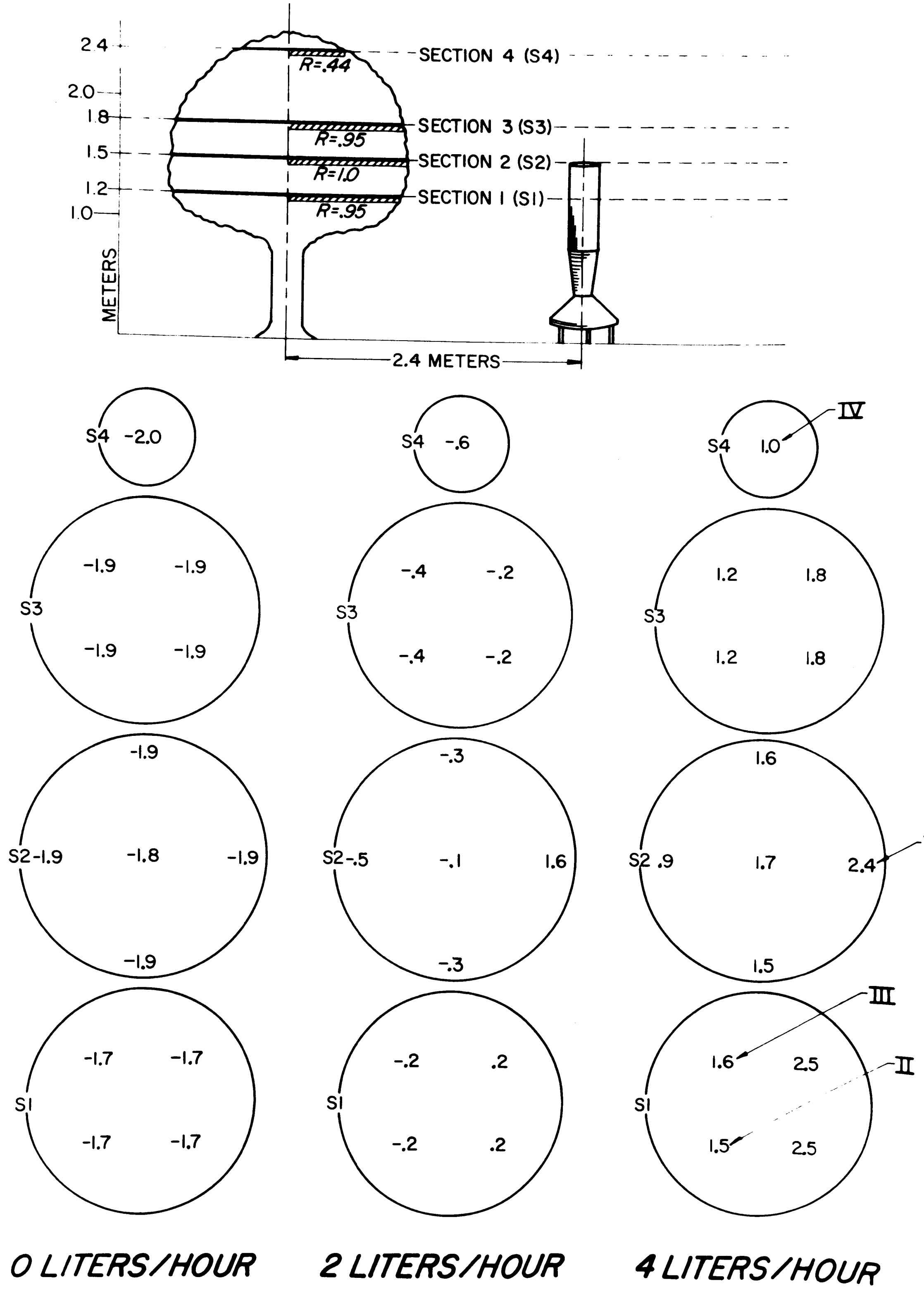

Fig. 2. Effect of burn rate per heater on mean foliage temperature at several locations within a canopy at position 1 in Fig. 1. Plotted numbers are mean $T_f - T_O$. Foliage is dense ($0.57\ m^{-1}$) and wind calm ($20\ cm\ s^{-1}$). (The actual foliage temperature distributions at locations I, II, III, and IV are shown in Fig. 3.)

least two types of trees, in terms of heater location (Fig. 1). Since an orchard average is desired, weighted averages for the results of each tree type are used in Fig. 8b. For a given ΔT_c, arrangement A3 can provide the same "average" protection at burn rates 10 to 40% less then C3. This is accomplished by protecting more foliage on fewer trees, because a given heater in arrangement A3 is close to 2/3 of the trees (type 1 tree in Fig. 1) and very far from 1/3 of the trees (type 2 tree in Fig. 1). With arrangement C3 the heaters are more nearly uniformly spaced from the trees. Thus the spacial distribution of protected foliage is different with the two arrangements with C3 providing fairly uniform protection and A3 protecting the

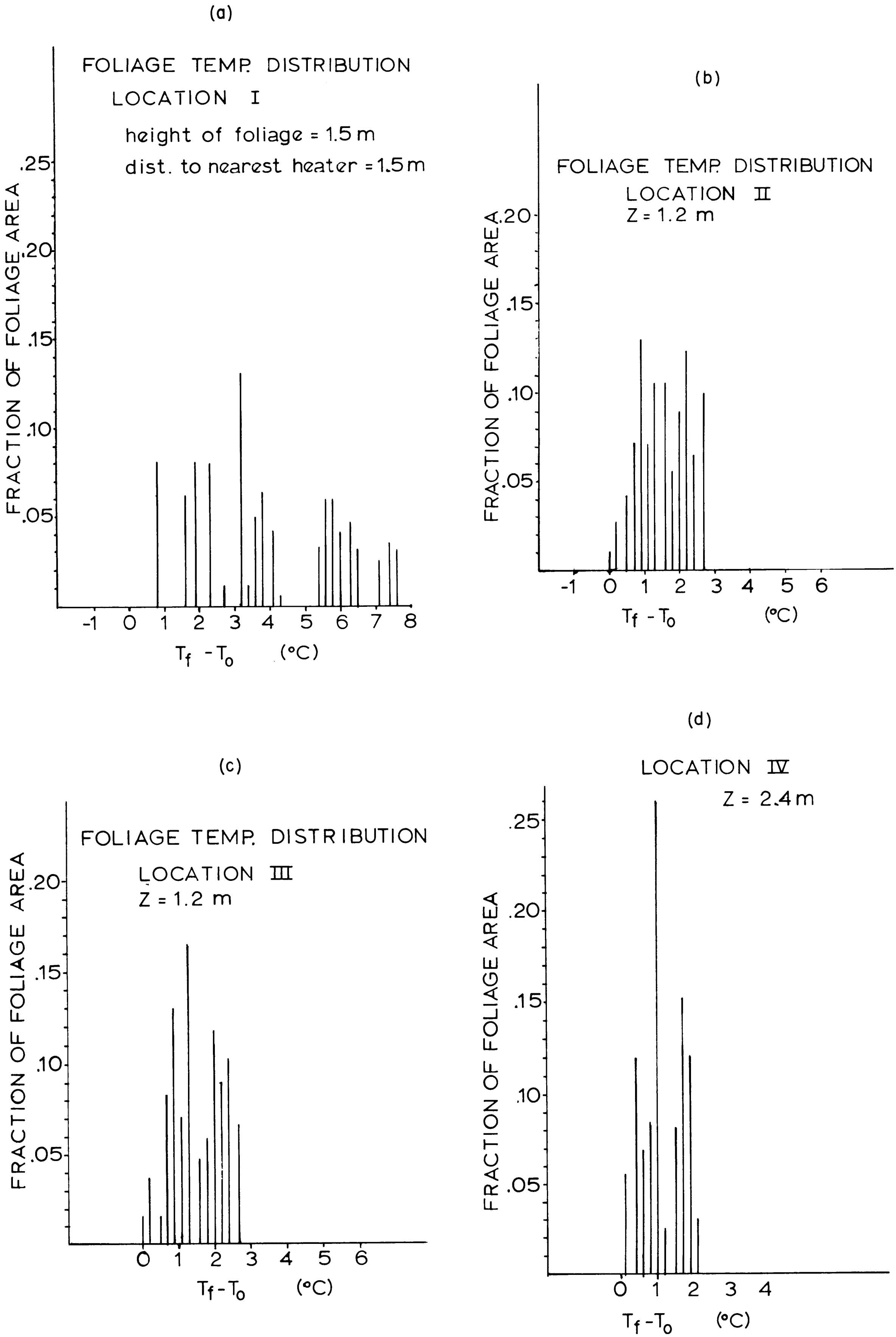

Fig. 3. Foliage temperature distributions at 4 locations in a canopy (see Fig. 2) as computed by the model. Although locations II and III are symmetric with respect to the nearest heater, they have different distributions as a result of the rest of the heater array.

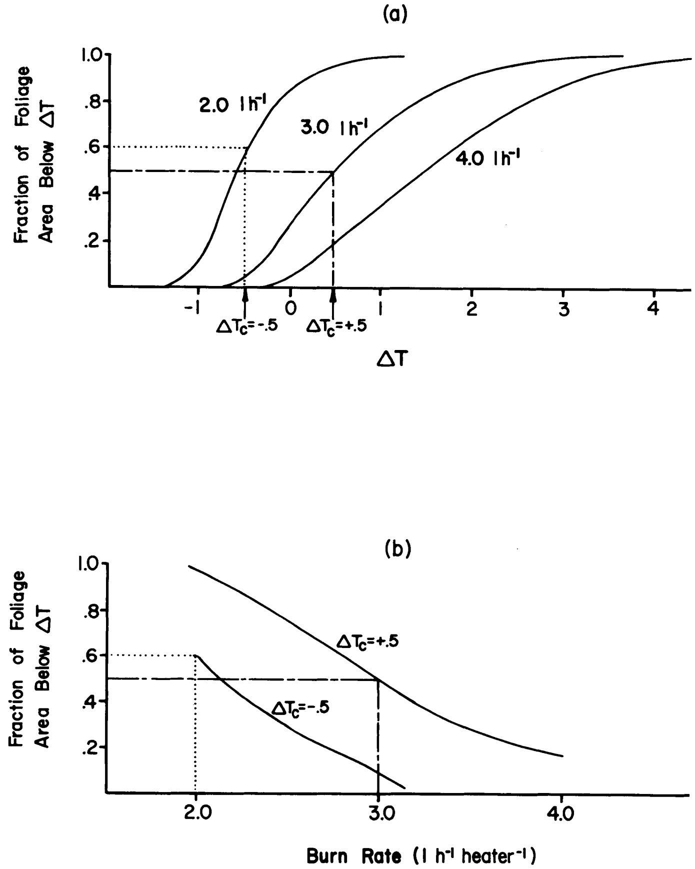

Fig. 4. (a) Cumulative foliage temperature distributions for three different heater burn rates (2.0, 3.0, and 4.0 ℓ h^{-1}), (b) burn rate curves from which heating requirements (burn rate) may be read directly, given conditions (ΔT_c, where $\Delta T_c = T_c - T_o$) and minimum desired loss.

Table 1. Parameters used in test cases.

Orchard	
Number of rows	16
Trees per row	20
Row spacing	7.3 m
Tree spacing	4.8 m
Canopy	
Shape	Spherical
Radius	1.0 m
Center height above ground	1.5 m
Foliage	
Density	
Sparse	0.17 m^{-1}
Dense	0.57 m^{-1}
Orientation classes	
Elevation	5
Azimuth	9
Diameter and shape	3.0 cm disc
Distribution	Spherical
Environment	
Wind	
In canopy	
Calm	0.2 m s^{-1}
Windy	0.6 m s^{-1}
At 4 m	
Calm	1.0 m s^{-1}
Windy	3.0 m s^{-1}

nearest trees with significant fuel savings. Under colder conditions, arrangement A3 is clearly best because the burn rates required for comparable protection with C3 are unattainable. With windy conditions in a dense orchard, similar results were found, although arrangement B3 was slightly better than the others on the low loss portion of the curves.

Wind influences foliage by determining the boundary layer resistance (equation [17]). As wind speed increases, the boundary layer resistance of the foliage decreases, and foliage temperature approaches the air temperature (16). When air temperature

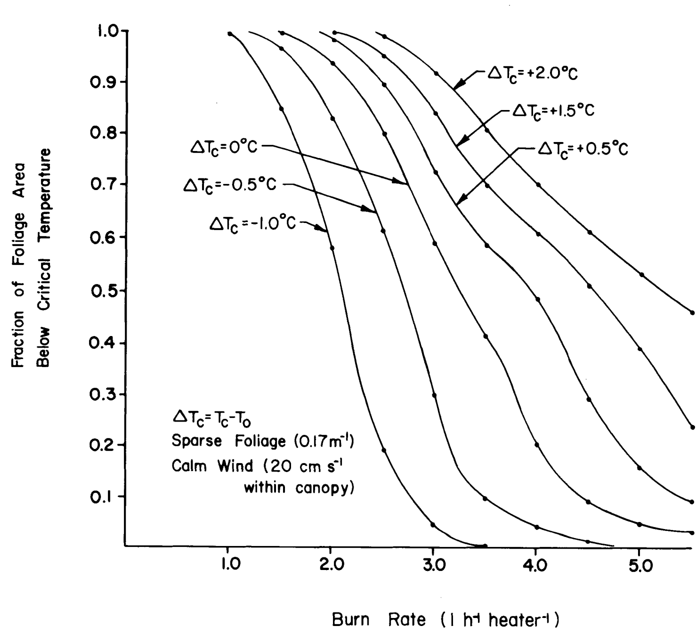

Fig. 5. Fraction of foliage area lost (below critical temperature) as a function of burn rate per heater for various conditions (see Table 1).

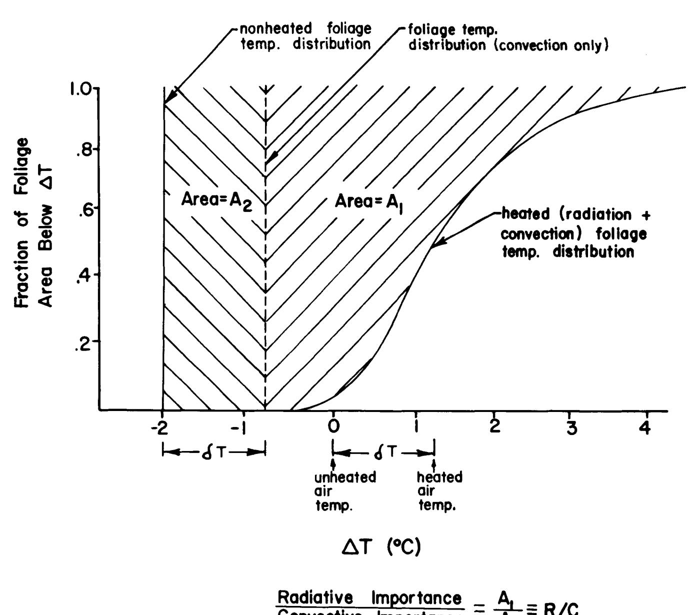

Fig. 6. Estimation of the relative importance of radiation and convection to the protection of foliage based on model calculations (see Table 1).

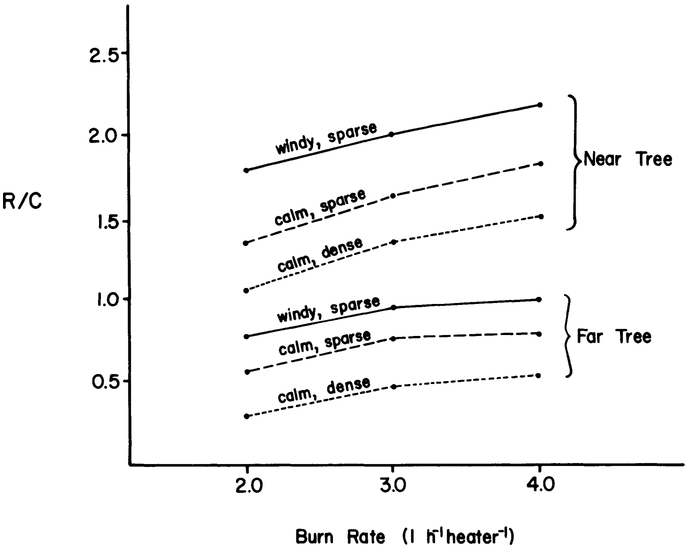

Fig. 7. Ratio of radiant to convective importance (R/C) for two trees in an orchard with heater arrangement A3 (Fig. 1). Near tree is 1 in Fig. 1a, and far tree is 2. Sparse and dense are 0.17 m^{-1} and 0.57 m^{-1} respectively. Calm and windy are 20 cm s^{-1} and 40 cm s^{-1} within the canopy.

is above critical foliage temperature ($\Delta T_c < 0$), increased wind will lower heating requirements (Fig. 8c); during more typical frost conditions, however ($\Delta T_c > 0$), increased wind will increase the heating requirements (Fig. 8c).

One rule in frost protection is that many small fires are better than a few large ones (17). This is readily examined by the model with required burn rate curves. Heater arrangement A was used for the test, and three heater densities were considered: A3, 1 heater every 3 trees, 100 heaters per ha; A2, 1 heater every 2 trees, 157 per ha; and 2A3, 2 heaters every 3 trees, 200 per ha. The abscissa for this comparison must be a burn rate per unit ground area (liters per hour per hectare: $\ell\ h^{-1}\ ha^{-1}$), rather than burn rate per heater. Required burn rate curves for two ΔT_c conditions (critical foliage minus unheated air temperature) for the three heater densities indicate that larger heater densities provide more protection for the same total fuel use (Fig. 8d). Furthermore, higher heater densities can provide protection under extreme (high ΔT_c) conditions (because of the lower burn rate per individual heater) when fuel use values would be beyond the capabilities of less dense heater configurations. Perhaps the basic advantage of high heater densities stems from convective considerations. Crawford (1) assumed that the convective output per heater, not per unit ground area, determined the heated depth. By holding output per unit ground area constant and increasing the heater densitity, the output per heater goes down, the heated depth decreases, and the air can become warmer. This has not been demonstrated experimentally because of the difficulty of devising and executing such experiments (11). The increase in fuel prices, the increase in tree density (trees/ha), and the demand for more reliable frost protection all favor a decrease in size of the individual heaters accompanied by an increase in their density and at least as high a radiant fraction.

Another method for increasing the efficiency of heaters for frost protection involves placing a thermally reflective material around the base of each heater to prevent some of the radiant energy from being lost to soil heat flux. A required burn rate curve was plotted for each of the two types of trees with heater arrangement A3 (Fig. 8e). Reflectors (1 m radius) under each heater benefitted the trees close to a heater somewhat more than those at a distance. Given the geometry of the Autoclean heaters used, the 1 m radius disc intercepts 16% of the radiant output, and a 2 m radius disc intercepts 27%. The data in Fig. 8e resemble those in Fig. 8a, since reflecting 16% of the radiant output, most of which may otherwise be lost, is not unlike increasing the radiant fraction a similar amount.

A sensitivity test was performed to determine the effect that the mean temperature of the entire orchard floor (soil) had on fuel requirements. Required burn rate curves were calculated for four cases, two with soil temperature below, and two with soil temperature above unheated air temperature. The pronounced impact that warm soil has on the heating requirements (Fig. 8f) suggests that efforts to increase storage of solar energy in the surface layer of the soil (for release during freeze conditions) may be worthwhile.

Summary

Although fed by only 1/5 of the energy input, the radiation emitted by heaters was similar in importance to the convective output. Under windy conditions, with sparse foliage and a weak inversion, the radiant importance may be several times that of convection. Heaters in the rows are more effective under adverse conditions than heaters between the rows. A larger number of smaller fires is better than a small number of large ones; although this is entirely through theoretical convective considerations. Placing thermal reflectors around the base of each heater can decrease the necessary fuel input up to 10%. Increasing the temperature of the entire orchard floor a few degrees C (due to increased storage of solar energy, for example) has a pronounced effect on reducing heat requirements.

List of Symbols

- A_h – Heater stack area (m^2).
- A_d – Area of the underlying disc (m^2).
- A_o – Area of the entire orchard (m^2).
- a – Heat of combustion for fuel oil: 1.05×10^4 W h ℓ^{-1}.
- B – Burn rate per heater ($\ell\ h^{-1}\ heater^{-1}$).
- c_p – Specific heat of air at constant pressure (J kg^{-1} C^{-1}).
- d – Leaf or foliage element diameter (m).
- F_d – Fraction of radiant energy emitted by a heater that is intercepted by the underlying disc.
- F_i^* – Fraction of a leaf's hemispheric view that is occupied by the disc under the ith heater.
- F_i – Fraction of a leaf's hemispheric view that is occupied by the ith heater stack.
- f_r – Radiant fraction of a heater.
- H – Convective energy added to the orchard by heaters (W m^{-2}).
- h – Time (hours).
- h_a – hectare (10^4 m^2).
- i – Subscript denoting heater number.
- k – Fraction of foliage projected in some direction.
- N – Total number of heaters.
- P – Probability of penetration of a beam of radiation from the ith heater if P_i, or from direction (θ,ϕ) if $P(\theta,\phi)$.
- R_d – Radiation reflected by a disc below a heater (W m^{-2}).
- R_e – Irradiance from the natural environment on a leaf (W m^{-2}).
- R_h – Leaf irradiance from heaters (W m^{-2}).
- R_ℓ – Radiation emitted by orchard floor (W m^{-2}).
- R_n – Large scale orchard net radiation (W m^{-2}).
- R_s – Radiation emitted by a heater stack (W m^{-2}).

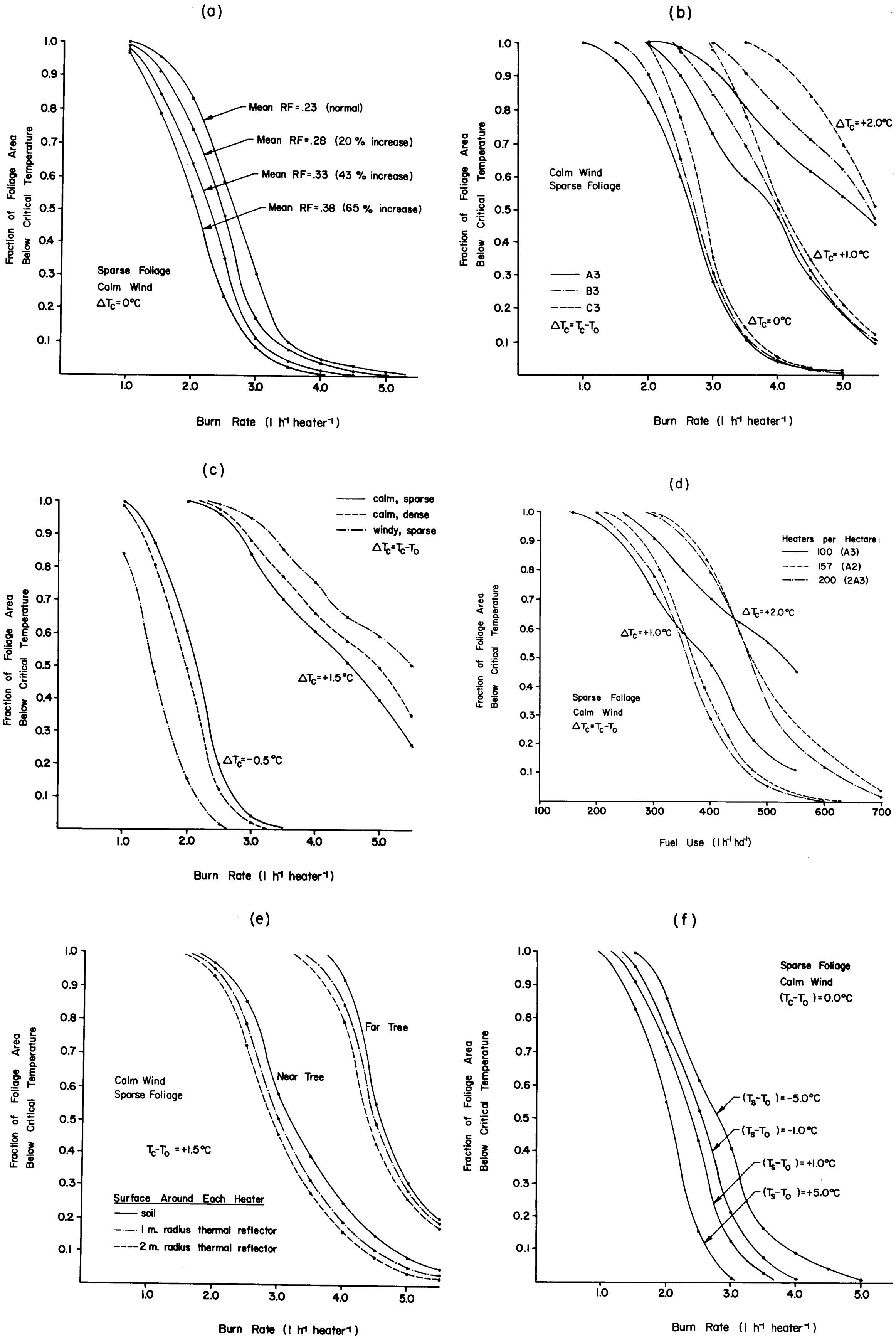

Fig. 8. Burn rate curves calculated from the orchard foliage temperature model to illustrate the expected importance of several factors. The values of model input parameters used for these calculations are listed in Table 1. (a) Heater radiant fraction for Autoclean heaters, (b) heater arrangement (see Fig. 1), (c) wind speed and foliage density, (d) heater density, (e) thermal reflector on soil surface around each heater (near the far tree refers to 1 and 2 in Fig. 1a), and (f) soil surface temperature.

R_t – Total leaf irradiance from sky, soil, foliage, terrain and heaters (W m^{-2}).
R_u – Thermal sky radiation (W m^{-2}).
r_h – Boundary layer resistance for a leaf (s m^{-1}).
S – Distance through the orchard that is occupied by one or more tree canopies: S_i is distance between a leaf and the ith heater, $S(\theta,\phi)$ is distance between a leaf and the edge of the orchard in direction (θ,ϕ) (m).
s – Second (time).
T_a – Ambient (heated) air temperature in an orchard (K).
T_c – Critical foliage temperature (K).
T_f – Temperature of a foliage element (K).
$\bar{T}_f$ – Mean foliage temperature in the orchard (K).
T_o – Initial, unheated air temperature or air temperature upwind of the orchard (K).
T_s – Orchard floor temperature (K).
ΔT_a – Increase in air temperature due to heaters: $T_a - T_o$ (K).
ΔT_c – Critical foliage and unheated air temperature difference: $T_c - T_o$ (K).
ΔT_f – $(T_f - T_o)$ (K).
u – Wind speed within the canopy (m s^{-1}).
α_d – Disc thermal absorptivity.
Δ – Denotes the difference between some temperature and non-heated air temperature (K).
ϵ_f – Foliage emissivity.
θ,ϕ – Zenith angle and azimuth angle (^{o}).
ρ – Air density (kg m^{-3}).
μ – Foliage density: leaf area (one side) per canopy volume (m^{-1}).
τ_u, τ_ℓ – Diffuse noninterceptances for upper (τ_u) or lower (τ_ℓ) hemispheres around a leaf.
σ – 5.67×10^{-8} W m^{-2} K^{-4}.
ℓ – liter, but as a script indicates lower.

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