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Evaluation of Sprinkler Application Rate Models Used in Frost Protection[1]

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Abstract. **Two related sprinkler application rate models used in frost protection, published in the mid-1960s, are shown to include an assumption leading to the erroneous conclusion that humidity does not affect the determination of the application rate. A third, 1981 model documents the effect humidity has on the application rate calculation. A distribution factor accounting for nonuniform application is described.**

The current awareness of fossil fuel shortages and subsequent inflated cost have triggered a renewed interest in sprinkling crops with water for frost protection. Two models, one by J. A. Businger (3) and a related one by J. F. Gerber and D. S. Harrison (4), published in the mid-1960s, calculate the required application rate for adequate protection from given atmospheric conditions. Both these models used a heat budget approach relating the sprinkling rate to the rate of heat loss from the plant part, i.e., supplying the heat of fusion at the necessary rate to maintain a constant temperature above the damaging level. These 2 models are evaluated in relation to a recent intermittent application study (7). A 3rd model by B. J. Barfield et al. (2) is also reviewed. A significant difference between the 2 earlier models (3, 4) and the more recent one (2) is noted. The difference is that the earlier models (3, 4) assumed no humidity effect in the determination of the application rate. The later model (2) documents the humidity effect. Ignoring humidity can cause a rather large error to be made by underestimating the required rate. This information is of great horticultural significance, because most sprinkling systems have been designed based on the extension publication (5) which resulted from the Gerber and Harrison work (4). The more recent work must be considered in future designs. This significant difference between the Businger (3) and Gerber and Harrison (4) models and the Barfield et al. (2) model is described herein.

Humidity effect. The approaches used by Businger (3) and Gerber and Harrison (4) are very similar. Input parameters required by these models are critical temperature, point below which damage will occur, dry leaf temperature, air temperature, characteristic dimension, and wind speed. Both models determine the energy balance for a dry unprotected leaf and the energy balance for a sprinkled leaf maintained at the critical temperature. Two equations document this approach.

$$CdT_l/dt = LE_l + K_l + R_l = 0 \qquad \text{[Equation 1]}$$

and

$$CdT_c/dt = LE_c + K_c + R_c + I = 0 \qquad \text{[Equation 2]}$$

where C = Heat capacity of a cross sectional area of the leaf
T = Dry leaf temperature
LE = Latent heat exchange
K = Convective heat exchange
R = Radiative heat exchange
I = Application rate
Subscript l = Dry leaf
Subscript c = Sprinkled leaf at critical
T_c = Critical temperature

If equations [1] and [2] are solved for I and it is assumed that

$$dT_c/dt = dT_l/dt,$$

the following expression results for the application rate,

$$I = (LE_l - LE_c) + (K_l + K_c) + (R_l - R_c) \qquad \text{[Equation 3]}$$

Both models (3, 4) assume for both the sprinkled leaf and the dry leaf that the vapor pressure at the leaf surface is at saturation. Such an assumption is not necessarily correct for the case of the dry leaf. The vapor pressure at the surface of such a leaf should be a function of the relative humidity of the ambient air. By assuming the vapor pressure at the dry leaf surface to be at saturation conditions, the application rate is not affected by humidity. This assumption is implicit in the Businger (3) and Gerber and Harrison (4) models.

The Barfield et al. (2) model uses only equation [2] to determine I. The same input parameters used in the Businger (3) and Gerber and Harrison (4) models are required with the addition of relative humidity. The existing atmospheric conditions are used to determine the 3 heat transfer parameters required

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Table 1. Comparison of model-predicted sprinkling rates to maintain leaf temperature at 0°C when air temperature = −5°, wind speed = 2m sec^{-1}, distribution factor = 1.0, and characteristic dimension = 6cm.

Model	Sprinkling rate predicted (mm/hr)		
	Relative humidity		
	50%	80%	100%
Gerber and Harrison (4)	---	---	5.1
Businger (3)	---	---	3.6
Barfield et al. (2)	6.9	5.7	5.0
Perry et al. (7)	9.5	7.4	6.0

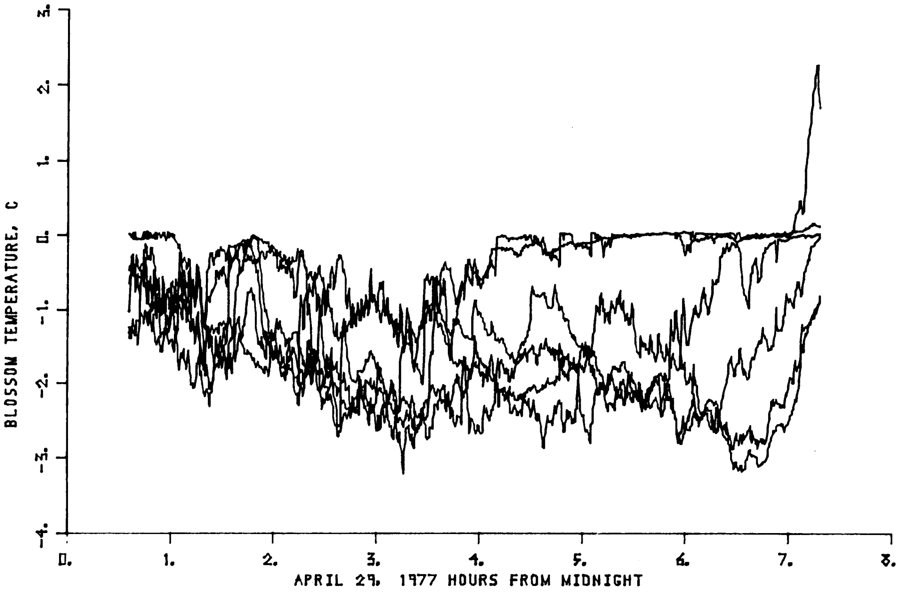

Fig. 1. Temperatures of 6 sprinkled apple blossoms vs. time during sprinkling demonstrates that blossoms are being coated with varying amounts of water and ice.

to solve equation [2]. The actual vapor pressure at the leaf surface is used, thus humidity does affect the determined application rate. Subtracting equation [1] from equation [2] is not necessary in the Barfield et al. model, thus the error due to neglecting humidity in the calculation of I is eliminated.

Barfield et al. (2) provide a sample computation. They demonstrate that for air temperature −5°C, wind speed 2ms^{-1}, and relative humidity 50%, ignoring humidity will cause a 28% underestimate of sprinkling rate. A similar model used by Perry et al. (7) shows as much as a 37% error can be made in underestimating sprinkling rate. When a relative humidity of 80% is considered, these error percentages are 12% and 19%, respectively (see Table 1). Thus, the assumption made by Businger (3) and Gerber and Harrison (4) can lead to the use of inappropriate sprinkling rates and subsequent damage to valuable horticultural crops.

Distribution factor. A factor is described in all 3 sprinkling rate models (2, 3, 4) which accounts for plant parts being exposed to different surroundings, i.e., some "seeing" sky, others "seeing" ground, and some surrounded and thus radiatively protected by other foliage or blossoms. This factor is used to quantify the average environment of the plant part in the orchard and to make an allowance for plant parts being of different shapes and sizes. This factor is referred to as a *multiplier* by Gerber and Harrison (4), a *factor* by Businger (3), and a uniformity *coefficient* by Barfield (2). The factor is important but it is not quantitatively determined in these models. This is not surprising when one considers the complexity of the system it seeks to describe. Barfield et al. (2), however, do suggest using the leaf area index in the absence of experimental data. Experimental data does exist.

Table 2. Average fraction and distribution factor for 50 and 90% protection as a function of stage of development in apple trees (Olsen B400 sprinklers set 3 × 5.5m and 0.6m above trees).

Flower stage^z	Avg fraction^y (I_f/I_o)	Distribution factor 50%	Distribution factor 90%
4–6	1.21	1.0	1.8
7–8	1.09	1.0	2.7
9	0.77	1.3	3.7

^{z}4–6 = Tight cluster to full pink; 7–8 = First to full bloom; 9 = Postbloom.

^{y}(amount of water applied in field)/(amount of water applied in laboratory without trees).

The interception and channeling of water along leaves and branches in the tree canopy creates nonuniform coverage within the tree. The variation in amount of water distributed within the canopy in effect provides a variation in sprinkling rate. Thus, the availability of water fusing to ice and liberating heat is not equal for all leaves or blossoms, so varying degrees of protection are realized, resulting in different temperatures. This is apparent in sprinkled blossom temperatures taken during a 1977 spring frost (Fig. 1). Earlier literature implies uniformity of temperatures with adequate coverage (3, 4).

To quantitatively evaluate this effect, a distribution factor was determined from field data described by Jarrett et al. (6). This distribution factor is a component of the factor used in the aforementioned models. The data used were observed application rates in a 75-point, 3-dimensional grid within a tree canopy during sprinkling. The observations were repeated at 3 stages of apple leaf and blossom development ranging from tight cluster to postbloom (1) over a period of 10 days in May 1978 (Table 2). These rates observed in the field (I_f) were divided by rates identically observed in a laboratory without the presence of a tree (I_o). The result was a distribution of the amount of water actually applied to points within the tree canopy relative to the amount of water applied without interference by the tree canopy, i.e., a distribution of fractions (I_f/I_o). The reciprocal of the average of these fraction or (I_o/I_f) was taken to be the distribution factor for 50% protection. That is, when this distribution factor is used, 50% of the blossoms are assumed to receive protection. If this reciprocal was less than 1.0, the distribution factor was taken to be 1.0 (Table 2). After ranking fractions from low to high, the value above which 90% of the fractions were ranked was determined to be the distribution factor for 90% protection. The average fractions greater than 1.0 are due to the channeling of water within the canopy. The distribution factor increases as blossom and leaf development proceed, a 30% increase for 50% protection and over a 200% increase for 90% protection, between tight cluster and postbloom stage. Thus, the distribution factor changes as the frost protection season progresses. It is determined by the developmental stage of the orchard. The frost protection practitioner should multiply the calculated sprinkling rate by the distribution factor for the field application rate.

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