Frequency Distribution of Citrus Rust Mite (Acari: Eriophyidae) Damage on Fruit in 'Hamlin' Orange Trees

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ABSTRACT Frequency distribution of the citrus rust mite, *Phyllocoptruta oleivora* (Ashmead), damage on 'Hamlin' orange, *Citrus sinensis* fruit was studied from 24 August to 13 October 1993, in Lake Alfred, FL. The study plot consisted of 4-yr-old Hamlin orange trees, with a north–south row orientation. Fruit on the north quadrant of the tree were found to have the highest mean surface damage, followed by the east, south, and west quadrants. The frequency distribution of fruit surface damage changed with mean damage levels. When the mean damage was low, most of the fruit had no rust mite damage. With increasing mean fruit damage, the proportion of fruit without damage decreased, and the proportion of fruit with higher damage correspondingly increased. The resulting frequency distribution changed from an exponential decay curve to a more or less symmetrical unimodal curve, with the peak shifting toward higher damage classes as mean fruit surface damage was increased. The frequency distribution was fitted to a 2-variable logistic distribution function of mean fruit surface damage and damage class, using maximum likelihood estimation method. Fruit without rust mite damage was considered a discrete point at zero, and its relative frequency was determined as the height of the cumulative logistic at zero. The model approximated the actual data well at low mean fruit surface damage, but gave a poor fit at high mean values.

KEY WORDS *Phyllocoptruta oleivora*, frequency distribution, yield loss model

EXTENSIVE FEEDING BY the citrus rust mite, *Phyllocoptruta oleivora* (Ashmead), causes fruit surface discoloration (russet) (Albrigo and McCoy 1974, McCoy and Albrigo 1975), and reports indicate that heavy surface russet reduces growth and increases drop of the damaged fruit (Allen 1978, 1979; Yang et al. 1994). Reduced fruit grade and growth, and increased fruit drop directly affect citrus crop yield. Mite damage is not equally distributed over all the fruit in a grove (Hall et al. 1991), and furthermore, only a high percentage of surface damage shows obvious effects on fruit growth and drop (Allen 1978, 1979). It is therefore important to know the fractions of fruit in a grove that fall into different damage categories (the frequency distribution). This would then permit us to calculate average losses over the distribution from reduced fruit grade, reduced growth, and increased drop (Allen 1978, Allen et al. 1994). Allen and Stamper (1979) reported that the relative frequency distribution of mite damage on 'Valencia' and 'Pineapple' orange, *Citrus sinensis*, and on 'Duncan' grapefruit, *Citrus paradisi*, can be described with a modified beta distribution, with the mean as its only parameter. Because zero is the lower limit of the beta distribution, proportion of fruit without damage (at zero) cannot be estimated. In this article we seek to develop a simpler, closed-form cumulative distribution function that avoids the somewhat awkward beta function in integral form. Our purpose was 2-fold: 1st to determine the frequency distribution of percentage of damage on Hamlin orange fruit, and 2nd to express the distribution in terms of the mean percentage of surface damage with a simple mathematical formula which could be used to construct loss models from rust mite damage.

Materials and Methods

This study was conducted at a commercial citrus grove in Lake Alfred, FL, from 24 August to 13 October 1993 when late-season fruit surface damage occurred. The grove consisted of 4-yr-old Hamlin orange, *Citrus sinensis*, trees on Swingle rootstock. The trees were ≈2 m high. The study plot consisted of an area of ≈2 ha with 8 rows of trees running from north to south, each row consisting of ≈35 trees. The sampling area was located at the center of the study plot. Ten trees were tagged at each of the central 6 rows before any visible mite damage occurred. Ten fruit at 0.5–1.5

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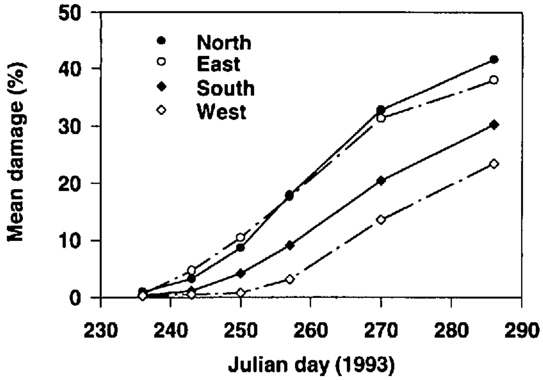

Fig. 1. Observed distribution of damaged fruit on trees (Lake Alfred, FL, 1993).

Table 1. Estimates for parameters *a* and *b* of equation 2 with different levels of mean fruit surface damage

Date	Mean damage, %	Parameter		R^2	χ^2
		a	*b*		
24 Aug. 1993	0.6	−22.1316	8.1912	0.9998[a]	0.5087
31 Aug. 1993	2.4	−10.2754	8.4173	0.9887[a]	25.4273
7 Sept. 1993	6.2	−4.5313	10.8237	0.9978[a]	4.0302
14 July 1993	12.2	5.7488	11.41588	0.9536[a]	96.3916
27 Sept. 1993	25.0	21.5870	11.5172	0.9045[a]	172.4409
13 Oct. 1993	34.0	30.6732	11.6107	0.5663	546.3630

[a] Significant at $P = 0.05$.

m above ground were selected randomly from each of the 4 quadrants (south, east, north, and west) of a tagged tree, for a total of 40 fruit per tree. Sampling was made once every 1–2 wk for a total of 6 sample dates. The total number of fruit for each sample date was 40 × 10 × 6 (2,400). The 2,400 randomly selected fruit were assumed to be representative of all fruit in the grove at the time of sampling.

The percentage of fruit surface area damaged by the rust mite was recorded for each fruit. This was determined by visually estimating the percentage pf russeted area on one side of each fruit and then turning the fruit 180° and repeating the estimation on the other side. Damage estimation was based on the portion of the fruit surface that was completely discolored, with a resolution of 5%. The region under direct solar exposure was usually avoided by the citrus rust mite, and was considered as undamaged. A comparative study by J.C.A. indicated that average variation in damage estimation for the same person and among different people was ≈5–10%. The study plot was under regular management during the study without any pesticide application.

Fruit were grouped into a zero class and 10% intervals of percentage of surface damage, that is, 0, 1–10, 11–20, . . . , 91–100%. Frequency data were fitted to a logistic distribution function using the maximum likelihood estimation procedure by Dennis et al. (1986).

Results

Fruit surface damage in the study grove occurred late in August because of a slow buildup in citrus rust mite population. Mean fruit surface damage was about 0.6% on 24 August, but increased quickly during September. By 13 October, the mean fruit surface damage reached 34% (Fig. 1; Table 1).

Damaged fruit were not equally distributed among the 4 quadrants of a tree (Fig. 1). In the early stage of mite damage when the mean fruit surface damage was low, fruit on the east quadrant of the tree had the highest mean surface damage, followed by the north quadrant. But in the late stage of mite damage when the mean fruit surface damage was increased, fruit on the north quadrant of the tree had the highest mean surface damage, followed by the east quadrant. The west quadrant always had the lowest mean surface damage. By the time of the last observation (13 October 1993), mean damage for the north, east, south, and west quadrants were 42, 39, 30, and 24%, respectively. Because fruit surface damage is directly related to total mite population supported by the fruit, the north side of the tree should have the highest mite population, followed by the east, south and west. Published research showed that citrus rust mites were usually unevenly distributed in trees (Yothers and Mason 1930, Albrigo and McCoy 1974, Allen and McCoy 1979, and Hubbard 1885).

Frequency Distribution of Damaged Fruit. The frequency distribution of fruit surface damage changed with mean damage (Fig. 2). When the mean damage was low, most of the fruit had no rust mite damage. With the increase of mean fruit damage, the proportion of fruit without damage decreased, and the proportion of fruit with higher damage correspondingly increased. The resulting frequency distribution changed from an exponential decay curve to a more or less symmetrical unimodal curve, with the peak shifting toward higher damage classes as mean fruit surface damage was increased (Fig. 2).

Allen and Stamper (1979) tested beta, gamma, and normal distributions for their frequency distribution data on Valencia and Pineapple oranges and grapefruit; they found beta distribution gave the best fit to their data. These 3 theoretical distributions have no closed forms for their cumulative density functions. Furthermore, beta and gamma distributions are discontinuous at point zero. This means proportion of fruit without damage (that is, zero damage) cannot be determined using the fitted beta or gamma distribution. But fruit without damage is of primary interest as far as management is concerned.

These considerations led us to look for alternative distribution functions. Based on the trend of

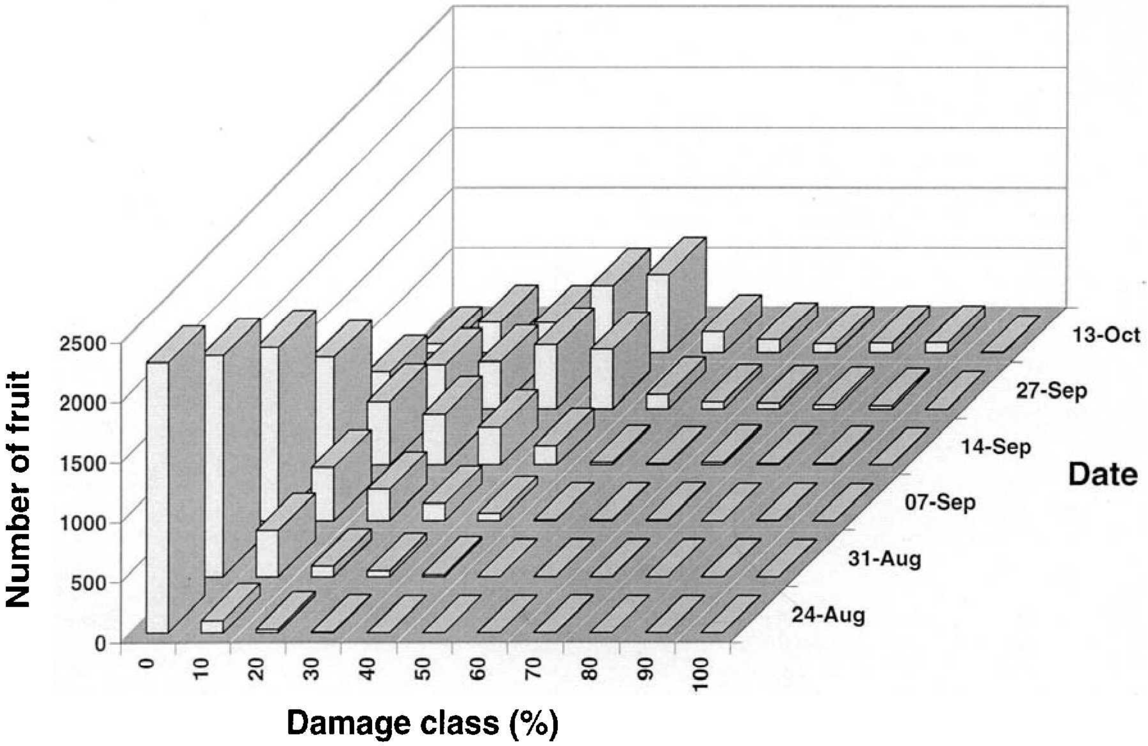

Fig. 2. Observed frequency distribution of mite damage over time on fruit (Lake Alfred, FL, 1993).

the frequency data (Fig. 2), we used the logistic distribution to fit the frequency data, using the maximum likelihood estimation procedure by Dennis et al. (1986). The logistic distribution function is

$$F(x) = \frac{1}{1 + \exp\left[-\frac{(x-a)}{b}\right]} \qquad (1)$$

where a, b = parameters. The mean of the logistic distribution is a; the variance of the logistic distribution is

$$\frac{\pi^2}{3}b^2$$

(Patel et al. 1976). We found that the frequency distribution over damage classes (0, 100)% in our study could be described using equation 1. This approach assumed that the frequency at zero damage class was the height of the cumulative logistic distribution at zero.

Although the logistic distribution (equation 1) describes a continuous distribution from negative infinity to positive infinity, our damage classes are limited to the range of (0, 100)%. Because the frequency at zero damage class was assumed the height of the cumulative logistic distribution at zero, we were dealing with a range of $(-\infty, 100\%)$ in the logistic distribution. The truncated logistic distribution is

$$F(x) = \frac{1}{A}\,\frac{1}{1 + \exp\left[-\frac{(x-a)}{b}\right]} \qquad (2)$$

where $F(x)$ = the proportion of fruit with a percentage damage of less than or equal to x, and

$$A = F(100) = \frac{1}{1 + \exp\left(-\frac{100-a}{b}\right)}.$$

Equation 2 should be interpreted as follows: the proportion of fruit without damage is the cumulative density up to zero, that is, $F(0)$; the proportion of fruit between damage (x_1, x_2) is $F(x_2) - F(x_1)$, where $x_1 > 0$, $x_2 > 0$, and $x_2 > x_1$. Equation 2 reaches a value of 1 at the upper limit of x = 100. This makes its probability density function integrate to 1 between $(-\infty, 100\%)$. The density function is

$$f(x) = \frac{1}{A} \times \frac{\frac{1}{b}\exp\left[-\frac{x-a}{b}\right]}{\left[1 + \exp\left(-\frac{x-a}{b}\right)\right]^2}. \qquad (3)$$

Using equation 2 and the maximum likelihood estimation procedure by Dennis et al. (1986), parameters a and b were obtained for each of the 6 sets of data (Table 1). They were found to change with mean fruit surface damage (μ). We therefore

Table 2. Parameter estimates for equations 4 and 5 by 2 different methods

Method	Equation	Parameter	Parameter	Parameter	R^2	χ^2
MLE-NLIN[a]	4	$a_0 = -11.0444$	$a_1 = 1.2588$	$a_2 = -21.4017$	0.9968	936.6989[b]
	5	$b_0 = 11.6649$	$b_1 = -4.2538$	$b_2 = 0.20180$	0.9472	NA[c]
MLE[d]	6	$a_0 = -11.8936$	$a_1 = 1.2954$	$a_2 = -16.0044$	0.9363[b]	844.1892[b]
		$b_0 = 12.3524$	$b_1 = -5.5660$	$b_2 = 0.1991$	NA[c]	NA[c]

[a] Fit equations 4 and 5 separately using the maximum likelihood estimates for *a* and *b* from each of the 6 sets of data.
[b] Results for the combined 6 sets of data.
[c] Not applicable.
[d] Insert equations 4 and 5 into equation 6 before data fitting, using maximum likelihood estimation method.

assumed that parameters *a* and *b* were functions of mean fruit surface damage (μ), that is, $a(\mu)$ and $b(\mu)$. The following function was found to give a good fit to parameter *a* in relation to mean fruit surface damage (μ)

$$a(\mu) = a_0 + a_1\mu + a_2\exp(-\mu) \quad (4)$$

where a_0, a_1, a_2 = parameters. The following function was found to give a good fit to parameter $b(\mu)$

$$b(\mu) = b_0 + b_1\exp(-b_2\mu) \quad (5)$$

where b_0, b_1, b_2 = parameters. The final form of the cumulative frequency distribution was the following 2-variable logistic function of mean fruit surface damage (μ) and damage class (x)

$$F(x, \mu) = \frac{1}{A}\,\frac{1}{1 + \exp\left[-\dfrac{x - a(\mu)}{b(\mu)}\right]} \quad (6)$$

where $a(\mu)$ and $b(\mu)$ are functions of μ as defined in equations 4 and 5. The corresponding probability density function is

$$f(x, \mu) = \frac{1}{A} \times \frac{\dfrac{1}{b(\mu)}\exp\left[-\dfrac{x - a(\mu)}{b(\mu)}\right]}{\left\{1 + \exp\left[-\dfrac{x - a(\mu)}{b(\mu)}\right]\right\}^2}. \quad (7)$$

In equations 6 and 7,

$$A = F(100) = \frac{1}{1 + \exp\left[-\dfrac{100 - a(\mu)}{b(\mu)}\right]}.$$

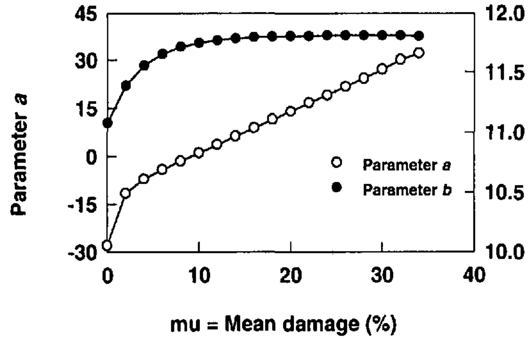

Fig. 3. Relationship between parameters *a* and *b* in the logistic equation (equation 2) and mean fruit surface damage.

We used 2 methods to estimate parameters in equations 4 and 5. In the 1st method, parameters *a* and *b* in equation 2 were estimated using data for each sample date, using the maximum likelihood estimation procedure by Dennis et al. (1986). Parameters in equations 4 and 5 were then estimated using estimates for parameters *a* and *b* from each of the 6 sets of data, using SAS-NLIN procedure (SAS Institute 1985). Parameter estimates are shown in Table 2. This is a 2-step method. In a better approach, we replaced $a(\mu)$ and $b(\mu)$ in equation 6 with equations 4 and 5, and then used the maximum likelihood estimation procedure by Dennis et al. (1986) for simultaneous estimation of all 6 parameters (a_0, a_1, a_2, b_0, b_1, b_2) based on the original 6 sets of data. The results are shown in Table 2. Based on the chi-square values, the simultaneous estimates gave a better fit than the 2-step method. Parameter estimates from this 1-step method were then used in the model. Thus, we have

$$a(\mu) = -11.8936 + 1.2954\mu - 16.0044\exp(-\mu) \quad (8)$$

$$b(\mu) = 12.3524 - 5.5660\exp(-0.1991\mu). \quad (9)$$

The relationships of parameters $a(\mu)$ and $b(\mu)$ to mean fruit surface damage (μ) are shown in Fig. 3. The predicted frequency distribution is shown in Fig. 4. The probability density function can be obtained by replacing parameters $a(\mu)$ and $b(\mu)$ in equation 7 with equations 8 and 9. The predicted probability density function is shown in Fig. 5, where probability for 0 damage class is not shown. The probability for 0 damage class can be calculated from equation 6 by setting damage x at 0.

Discussion

Properties of the Cumulative Frequency Distribution Function. The logistic distribution function (equation 1) has been used to model insect phenology (Dennis et al. 1986, Kemp et al. 1986, Dennis and Kemp 1988) as a stochastic process. Here we used the truncated logistic function (equation 6) for describing the frequency distribution of rust mite damage on citrus fruit. As shown in Fig. 3, parameter $a(\mu)$ exhibits a sharp increase when the mean fruit surface damage is low, and a slower linear increase with further in-

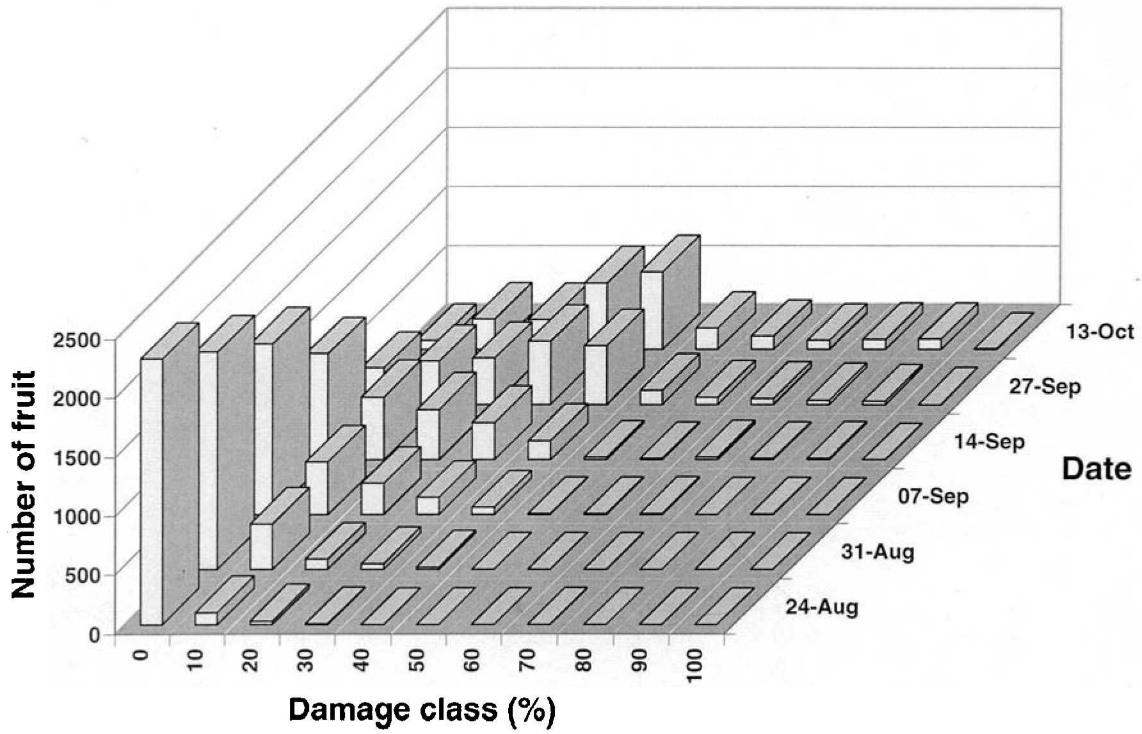

Fig. 4. Predicted frequency distribution of mite damage over time on fruit (Lake Alfred, FL, 1993).

crease in mean damage (equation 8; Fig. 3); parameter $b(\mu)$ also exhibits a sharp increase, but approaches a constant value with further increasing damage (equation 9; Fig. 3). Because $a(\mu)$ is the mean of the untruncated logistic distribution, whereas $b(\mu)$ is positively related to standard deviation of the untruncated logistic distribution, this indicates that as the peak of the density function shifts towards higher damage, there is little change in the variance after the data mean exceeds ≈20%. This is similar to shifting a density curve to a higher mean without changing the shape (variance). High chi-square values (Tables 1 and 2) were mainly caused by large deviations in a few data points. These deviations might be caused by random errors. Although the chi-square statistic might reject the hypothesis of the logistic, the fit is adequate for practical purposes. When the mean damage was between 0 and 25%, model predictions were at an accuracy of >75% as compared with the observed data. Model predictions were poor at higher mean damage values.

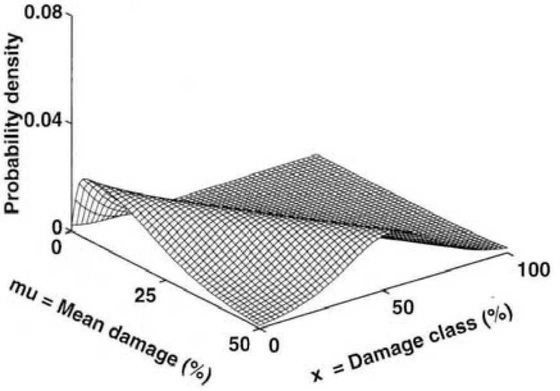

Fig. 5. Predicted probability density function of mite damage on fruit where probability at zero damage class is not shown (Lake Alfred, FL, 1993).

Application of the Cumulative Distribution Function. The cumulative frequency distribution function (equation 6) will enable us to determine the proportion of fruit that falls into a specific damage class if the mean fruit surface damage is known. For example, the proportion of fruit that falls between damage x_1 and x_2 is $F(x_2, \mu) - F(x_1, \mu)$. In commercial citrus production, it is often necessary to determine the proportion of fruit that can go to the fresh fruit market. If fruit with more than x percentage of surface damage is rejected from the fresh fruit market, then the proportion of fruit that can go to the fresh fruit market (the packout) would simply be

$$F(x, \mu) = \frac{1}{A}\,\frac{1}{1 + \exp\left[-\dfrac{x - a(\mu)}{b(\mu)}\right]} \tag{10}$$

For example, if we assume the packout level is $x = 5\%$, and the mean fruit damage in a Hamlin orange grove is $\mu = 10\%$, then the proportion of fruit that can go for the fresh fruit market can be calculated from equation 10:

$$F(5, 10) = \frac{1}{A}\,\frac{1}{1 + \exp\left[-\dfrac{5 - a(10)}{b(10)}\right]} = 0.5773$$

where $a(10)$ and $b(10)$ can be calculated from equations 8 and 9, respectively. This means that 57.73% fruit have a damage of ≤10%, and they can go for the fresh fruit market, and 42.27% (100–57.73%) fruit have a damage >10%, and they can only go for the processed fruit market.

Another intended application of the established equation is to determine yield loss from rust mite damage. Rust mite damage reduces growth and increases drop of damaged fruit (Allen 1978, 1979; Allen et al. 1994; Yang et al. 1994). But these effects are not uniformly distributed over damage classes, with larger effects on heavily damaged fruit. It is therefore necessary to integrate these effects over all damage classes, based on the frequency distribution of damaged fruit. Mathematical models describing the relationships between fruit growth and drop and fruit surface damage have been developed (Allen 1978, 1979; Yang et al. 1994). Allen et al. (1994) established differential equations to estimate volume loss from reduced fruit growth and drop. These differential equations combine the frequency distribution model with growth and drop models. The frequency distribution model (equation 6) developed in this study could also be used in a similar way. This model should be further improved and tested using field data before it could be applied in rust mite management practices.

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