Relationship Between Population Density of Citrus Rust Mite (Acari: Eriophyidae) and Damage to 'Hamlin' Orange Fruit

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ABSTRACT Six studies were conducted to quantify the relationship between fruit surface damage of 'Hamlin' orange, *Citrus sinensis,* and population denisty of the citrus rust mite, *Phyllocoptruta oleivora* (Ashmead). Over time, the damage rate per mite-day increased in sigmoid fashion mainly as a result of a sigmoid increase in cumulative mite-days. The sigmoid increase in cumulative mite-days resulted from the single-peaked, more or less symmetrically-shaped mite population growth. Increasing fruit maturity increased susceptibility to mite feeding. This was indicated by a decline in mite-days required to cause a given percentage of surface damage as fruit maturity increased. Tree age and grove location did not seem to have obvious effect on the general trend in damage rate. A mathematical model was developed to describe the relationship between cumulative damage and cumulative mite-days. The model could be used to predict fruit surface damage based on mite population data.

KEY WORDS *Phyllocoptruta oleivora,* population density, damage rate

THE CITRUS RUST mite, *Phyllocoptruta oleivora* (Ashmead), infests fruit, leaves, and young twigs of all citrus species and varieties. It is a serious pest of citrus in Florida (Knapp 1983) and most humid regions of the world (Commonwealth Institute of Entomology 1970, Hobza and Jeppson 1974, McCoy and Albrigo 1975). Its economic importance is mainly the result of the damage it causes to the fruit surface through extensive feeding (McCoy and Albrigo 1975). Discolored fruit have less market value. Furthermore, if damage occurs early in the fruit growing season, highly damaged fruit have a smaller growth rate and a higher drop rate (Allen 1978, 1979; Allen et al. 1994; Yang et al. 1994). Because the citrus rust mite is very small (≈50–180 μm) and it makes punctures on individual cells, a direct fruit damage–mite density relationship may not be obvious. Using cumulative mite-days, Allen (1976) related mite population density to rust mite damage on 'Valencia' orange, *Citrus sinensis,* fruit. Different citrus varieties may differ in their susceptibility to mite feeding. The current study was undertaken to determine a quantitative relationship between population density of the citrus rust mite and damage to 'Hamlin' orange fruit, which could be used as a damage prediction model in rust mite integrated pest management programs.

Materials and Methods

Mite Damage. This study consists of 6 similar field studies, 5 of which (studies 1–5) were carried out at a research citrus grove of the University of Florida Horticultural Sciences Department, in Gainesville, FL, and the other (study 6) at a commercial citrus grove in Lake Alfred, FL.

The plot size in studies 1–5 was ≈0.8 ha with south–north row orientation, and with each row consisting of 14 Hamlin orange trees that were 8 yr old. The sampling area consisted of the 6 central rows of the study plot. The grove was well maintained and irrigated by a drip irrigation system as needed. A petroleum oil spray was applied on 14 July 1993 to control citrus rust mites, causing a 56% mite population reduction 2 d after the operation.

In study 6, the plot size was ≈2 ha, with south–north row orientation, and with each row consisting of ≈35 Hamlin orange trees that were 4 yr old. The grove was also well maintained. Irrigation was by overhead sprinklers. A nutritional spray was applied on 12 June 1993, but the spray had little effect on citrus rust mite populations. Sampling plans for the 6 studies were as follows.

Study 1. This study was designed to elucidate the relationship between mite population density and fruit surface damage at the grove level. Twenty-five trees were selected randomly, 6 fruit from each tree were then selected and tagged, for a total of 150 fruit. These 150 randomly selected fruit were assumed to be representative of all fruit in the grove. The study period was from 8 May to 11 December 1992.

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Table 1. Summary of experimental designs

Study	Location	Duration	No. fruit	Sampling
1	Gainesville	8 May–11 Dec. 1992	150	Random T[a]
2	Gainesville	17 June–14 Aug. 1992	30	Selected[b]
3	Gainesville	10 July–11 Sept. 1992	45	Selected
4	Gainesville	4 Sept.–11 Dec. 1992	40	Selected
5	Gainesville	24 May–05 Nov. 1993	180	Random T
6	Lake Alfred	8 May–17 Nov. 1993	150	Random[c]
Fruit growth	Gainesville	8 May 1992–17 Feb. 1993	150	Random T

[a] Fruit were selected randomly and tagged at the beginning of the study, and subsequent samplings were conducted on the same tagged fruit.

[b] Fruit with low mite density were specifically selected so that mite population could increase and cause damage at about the same time on all selected fruit.

[c] Fruit were selected randomly at every sampling date.

Studies 2–4. Studies 2, 3, and 4 were designed to determine the possible effect of fruit maturity on mite damage rate. They were conducted in the same grove as in study 1 but on different fruit. In each of these 3 studies, fruit that already had low mite populations were specifically (not randomly) chosen and tagged. Mite population density and surface damage for each fruit were estimated until mite population declined to a very low level. The duration and sample size (n) for each of the studies were as follows: 17 June to 14 August 1992 (study 2, $n = 30$); 10 July to 11 September 1992 (study 3, $n = 45$); 4 September to 11 December 1992 (study 4, $n = 40$).

Study 5. To obtain corroborating information on mite damage rate, a similar study was conducted from 24 May to 5 November 1993 in the same grove as the previous 4 studies. Thirty trees were selected randomly, 6 fruit from each tree were then selected and tagged, for a total of 180 fruit. Fruit were chosen so that they were evenly spaced around the tree.

Study 6. This study was designed to determine possible effects of tree age and location on damage rate. It was conducted at the commercial citrus grove. The sampling area was located at the center of the study plot. Twenty-five trees were selected randomly from each of the central 6 rows at every sampling date, with 1 fruit from each tree, for a total of 150 fruit from 150 trees. The study was conducted from 28 May to 17 November 1993.

In all 6 studies, fruit were chosen from the outer canopy of the tree, and from the region between 0.5 and 1.5 m above ground. This region was where the majority of fruit were located. The sampling interval was 1–3 times a week. Rust mite population density was determined with the help of a 20× hand lens mounted over a piece of clear plastic on which a 1-cm^2 grid had been etched (Allen 1976). The grid was divided into 25 equal subdivisions, each having an area of 4 mm^2. Only mites within the middle 4 squares were counted, for a total area of 4×4 (16 mm^2) per count. In the study at the research citrus grove, 4 counts were made for each fruit (a total of $4 \times 4 \times 4 = 64$ mm^2 fruit surface area), with 1 count from each quadrant of the fruit. In the study at the commercial citrus grove, 8 counts were made for each fruit (a total of $8 \times 4 \times 4 = 128$ mm^2 fruit surface area), with 2 counts from each quadrant. Mite counts from all quadrants were pooled and a mean mite density was obtained based on the pooled data from all the fruit. Mite density was converted to mites per square centimeter for data analysis. The percentage of fruit surface area damaged by the rust mite was recorded for each fruit. This was determined by visually estimating the percentage of 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. 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%.

Fruit Growth. As part of the attempt to determine the possible effect of fruit maturity on mite damage rate, measurement of fruit growth was conducted at the research grove from 8 May 1992 to 17 February 1993. Fruit surface area growth was considered as an indicator of fruit maturity. At the beginning of fruit growing season in early spring, 6 fruit from each of the 25 tagged trees in study 1 were selected randomly and tagged, for a total of 150 fruit. Fruit were chosen so that they were about evenly spaced around the tree. Fruit equatorial circumference was measured with a flexible measuring tape. Measurements were taken once every 1–2 wk. These fruit were kept from mite damage by applying abamectin (Agri-mek, Merk Agvet, Rahway, NJ) when mite populations on the fruit were high. Fruit with high mite populations were dipped into a 1:5,000× (volume) Agri-mek solution of water twice during the study period; once on 16 July 1992, and again on 7 August 1992. A summary of the experimental designs is shown in Table 1.

Data Analysis. To avoid excessive use of symbols, the same symbol in different equations below may have different meanings and values. Mite population density was converted to mites per square centemeter. Because eggs were unlikely to do any damage to the fruit, mite-days were calculated based on the nymphal and adult mite density. The formula for calculating mite-days is mite-days = (mean mite density between 2 consecutive samplings) × (sampling interval). Working on Valencia oranges, Allen (1976) started with the assumption that damage rate per day was proportional to mite density,

$$\frac{dy}{dt} = km(t) \qquad (1)$$

where y is cumulative percentage of damage; $m(t)$ is mite density at time t, and k is damage rate in terms of percentage of damage per mite per day. If k is constant, equation 1 implies that is a linear function of mite density. Equation 1 is equivalent to

$$y = k \int_0^t m(t)\, dt \qquad \text{or} \qquad y = kx(t) \qquad (2)$$

where $x(t)$ = cumulative mite-days (area under the mite population graph) at time t. Data in Allen (1976) suggested that k is probably not constant (but a function of time). Here we adopted a pragmatic approach of fitting the data to a power curve of the form

$$y = ax^b \qquad (3)$$

where y = cumulative percentage of damage; x = cumulative mite-days; a and b = parameters. By taking the derivative of equation 3 we obtained the damage rate in terms of percentage of damage per mite-day

$$\frac{dy}{dx} = abx^{b-1} \qquad (4)$$

where $(dy/dx)$is equivalent to the k of equation 2 (the slope of the damage versus mite-days graph). Here the damage per mite-day (k of equation 2) is a nonlinear function of mite-days.

Fruit was assumed to be spherical, and fruit surface area was calculated based on measurement of fruit circumference. We used a logistic growth function to describe fruit surface area (y_g) growth in relation to time (t)

$$y_g = \frac{c}{1 + \exp(a - bt)} \qquad (5)$$

where y_g = fruit surface area (square centimeters) at time t; t = Julian days (1 = 1 January); a and b = parameters; c = parameter, representing the maximum fruit surface area by the end of the fruit growing season. The growth rate can be obtained by taking the derivative of equation 5, which is

$$\frac{dy_g}{dt} = \frac{c \times b \times \exp(a - bt)}{(1 + \exp(a - bt))^2}. \qquad (6)$$

Data-fitting to equations were performed with TableCurve (Jandel Scientific 1992).

Table 2. Parameter estimates for power curve $y = ax^b$

Study	Parameter a	Parameter b	R^2
1	1.480548×10^{-5}	1.784393	0.9958*
2	1.112907×10^{-7}	2.273361	0.9895*
3	1.662941×10^{-8}	2.567227	0.9860*
4	3.929418×10^{-3}	1.066059	0.9621*
5	1.589922×10^{-7}	2.269957	0.9958*
6	3.287070×10^{-7}	2.203687	0.9973*
Avg from 1, 5, 6[a]	9.180555×10^{-7}	2.086012	NA

NA, not applicable; *, significant at $P = 0.05$.

[a] Average for a and b based on parameter estimates from studies 1, 5, and 6.

Results

Cumulative Fruit Surface Damage Versus Cumulative Mite-Days. The relationship between fruit surface damage and mite-days, from 6 sets of data, are illustrated in Figs. 1a–6a; the parameters for the data-fitted curves are presented in Table 2. All data sets (Figs. 1a–6a) demonstrated similar trends, that is, with the increase of mite-days, damage showed an accelerating increase. This trend was clearly demonstrated by an almost linear increase in damage rate per mite-day in relation to mite-days (Figs. 1a–3a, 5a, 6a) except for the result from study 4 (Fig. 4a). The result from study 4 also showed an increase in damage rate with mite-days in the early stage, but the damage rate stayed almost constant in the late stage (Fig. 4a). This is probably caused by low mite population density in the late stage.

Cumulative Mite-Days Versus Time. When mite-days were plotted against time, they exhibited a sigmoid growth in all six sets of data (Figs. 1b–6b). Because mite-days equals the area under the mite population curve, the shape of the population curve determines the shape of the cumulative mite-days curve. Mite population dynamics curves were more or less symmetrically-shaped in all 6 sets of data (Figs. 1c–6c), resulting in sigmoid cumulative mite-day curves (Figs. 1b–6b). If there were 2 population peaks, we would expect a double-sigmoid curve of cumulative mite-days. If mite population were constant for a rather long time, we would expect a linear increase in cumulative mite-days with regard to time.

Damage Rate Versus Fruit Maturity. The data-fitted function for fruit surface area growth is

$$y_g = \frac{146.3346}{1 + \exp(4.389115 - 0.023039t)}$$

$$(R^2 = 0.9930,\ P < 0.05). \qquad (7)$$

The sigmoid trend of mite damage rate with time did not closely correlate with fruit surface area growth which exhibited a more or less convex growth during the study period (from 8 May 1992 to 17 February 1993) (Fig. 7). This was clearly demonstrated by the results from studies 2, 3, and 4 (Figs. 2b–4b). The 3 sets of data obtained at different times of the year demonstrated similar

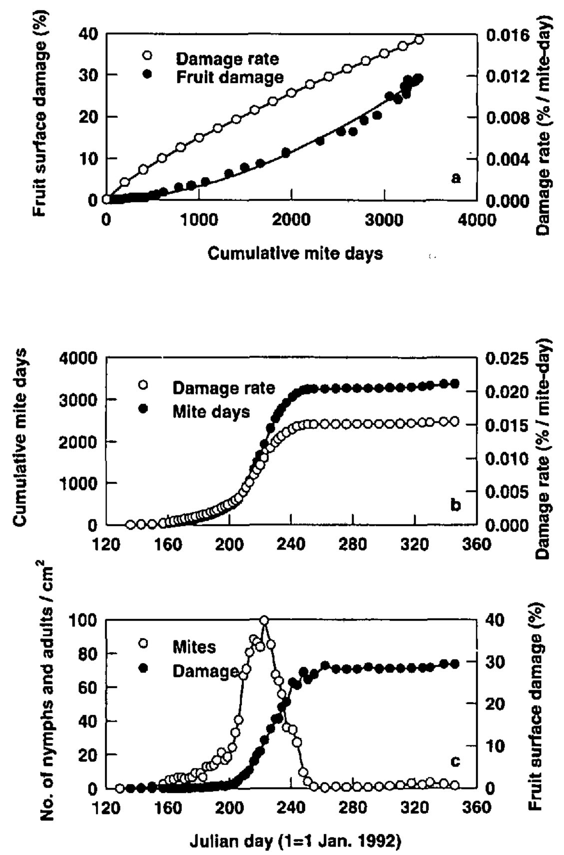

Fig. 1. Relationships between mite population and fruit damage (study 1: Gainesville, FL, 1992). (a) Fruit surface damage and damage rate versus cumulative mite-days; (b) cumulative mite-days and damage rate versus time; (c) mite population dynamics and cumulative fruit surface damage versus time.

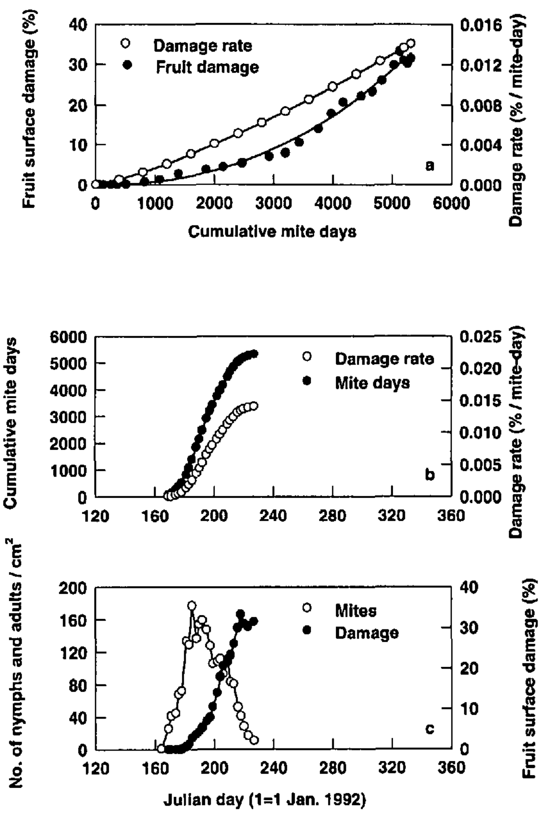

Fig. 2. Relationships between mite population and fruit damage (study 2: Gainesville, FL, 1992). (a) Fruit surface damage and damage rate versus cumulative mite-days; (b) cumulative mite-days and damage rate versus time; (c) mite population dynamics and cumulative fruit surface damage versus time.

sigmoid trend in damage rate, which seemed to be more correlated with the mite population peak than with fruit growth (Figs. 2b and c–4b and c). In Allen's study (1976), he suspected a possible relationship between the time-varying damage rate and fruit maturity, both of which were sigmoid functions of time. The current study indicated that damage rate was not necessarily related to fruit maturity, but accelerated with mite-days. Although the damage rate was not closely correlated with fruit maturity, time (fruit maturity) did affect the damage rate and therefore the damage. This effect was clearly demonstrated through the results of studies 2, 3, and 4 (Figs. 2a–4a); with increasing fruit maturity, it took fewer mite-days to cause the same amount of surface damage. For example, for a 10% fruit surface damage, it took ≈3,100, 2,600, and 1,500 mite-days in June through August (study 2, Fig. 2a), July through September (study 3, Fig. 3a), and September through November (study 4, Fig. 4a), respectively.

Damage Versus Tree Age and Location. Results from the research citrus grove (8 yr old) and from the commercial citrus grove (4 yr old) showed similar trends in population dynamics (Fig. 5c versus 6c). The relationships between damage and mite-days from the 2 studies were also similar in 1993 (Fig. 5a versus 6a). For example, 3,000 mite-days resulted in ≈22% fruit surface damage in both groves (Fig. 5a versus 6a). This was also reflected in the similarity of the damage rate per mite-day between the 2 studies (Fig. 5a versus 6a). The results suggested that the general trend between cumulative fruit surface damage and cumulative mite-days (equation 3) may hold true for trees with different ages and in different areas, for the same citrus variety. This property of mite damage may simplify building damage models for rust mite management programs.

Discussion

Explanations for Increasing Damage Rate with Increase in Mite-Days. Results from this study clearly demonstrated that damage rate increased with increasing cumulative mite-days. Observations on Valencia orange by Allen (1976) also

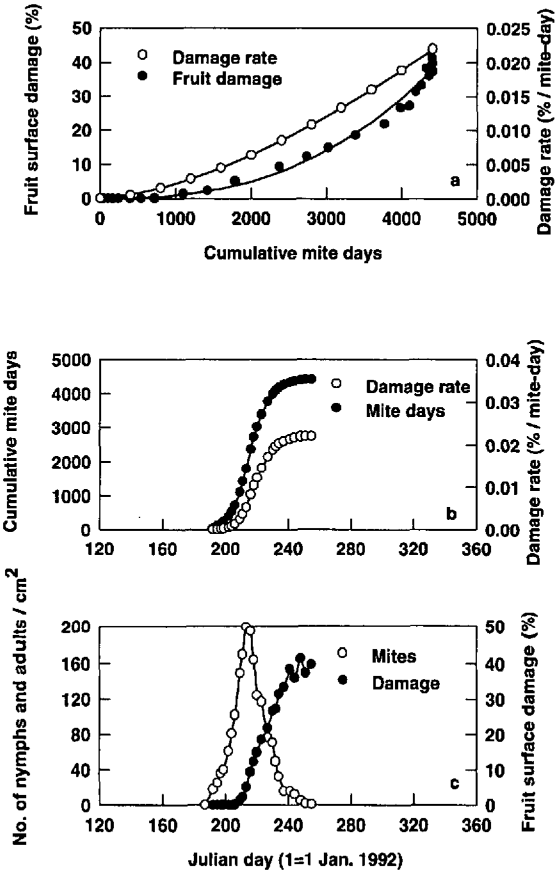

Fig. 3. Relationships between mite population and fruit damage (study 3: Gainesville, FL, 1992). (a) Fruit surface damage and damage rate versus cumulative mite-days; (b) cumulative mite-days and damage rate versus time; (c) mite population dynamics and cumulative fruit surface damage versus time.

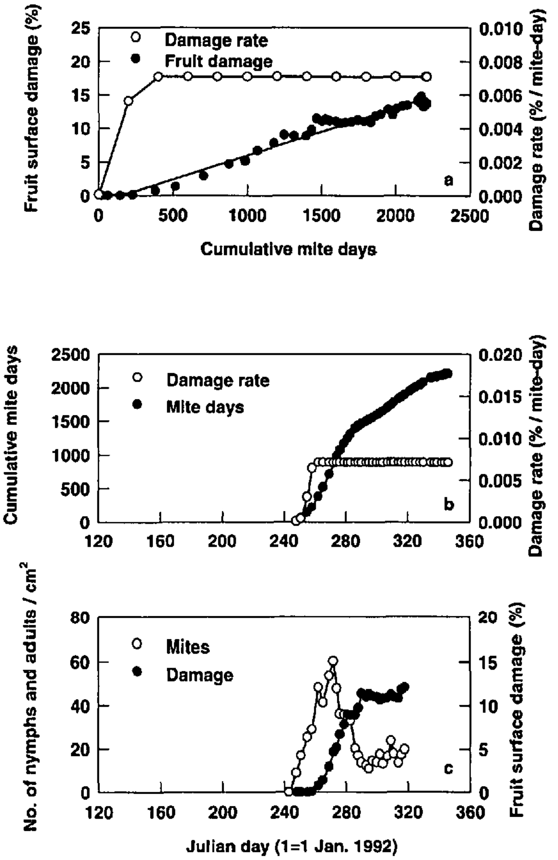

Fig. 4. Relationships between mite population and fruit damage (study 4: Gainesville, FL, 1992). (a) Fruit surface damage and damage rate versus cumulative mite-days; (b) cumulative mite-days and damage rate versus time; (c) mite population dynamics and cumulative fruit surface damage versus time.

indicated a similar trend, although he related the damage rate increase to time instead of cumulative mite-days. There are 3 possible reasons for the increasing damage rate: (1) mites inject digestive enzymes into cells while feeding, these enzymes might accumulate in the cells and cause an increasing rate of death of epidermal cells; (2) death of a cell might expedite the death of adjacent damaged cells; and (3) human eyes are limited in seeing the damage. The mites are so small that they feed on individual cells causing punctures that are much smaller than the cells themselves (McCoy and Albrigo 1975, Allen et al. 1992). Thus, damage accumulates 1 cell at a time. As the accumulation of dead cells becomes visible to human eyes, it might give rise to an artificial nonlinearity, that is, fewer and fewer mite punctures are needed to cause visible fruit surface damage, resulting in a superficial phenomenon of increasing damage per mite-day with season and cumulative mite-days. The observed increase in damage per mite-day is probably a combined result of these factors. Fortunately, regardless of the mechanism(s) involved, the derived empirical equation can still be used in predicting mite-caused fruit surface damage.

Zero Damage Mite Density. It has been suggested (Albrigo and McCoy 1974, McCoy and Albrigo 1975, Allen et al. 1992) that cells may recover from mite punctures, and if so, >1 puncture within a limited time period may be needed to cause the death of a cell. This may be true because fruit can support low mite populations without showing visible surface damage. We define effective cumulative mite-days (ECMD) as the total cumulative mite-days minus the cumulative mite-days that have already recovered from mite feeding, and zero damage density (ZDD) as the mite density at which the number of newly punctured cells equals the number of cells recovered from mite feeding. The relationship between ECMD and ZDD can be described by

$$ECMD(t) = \int_{t_0}^{t} \left[m(t) - ZDD\right] dt \qquad (8)$$

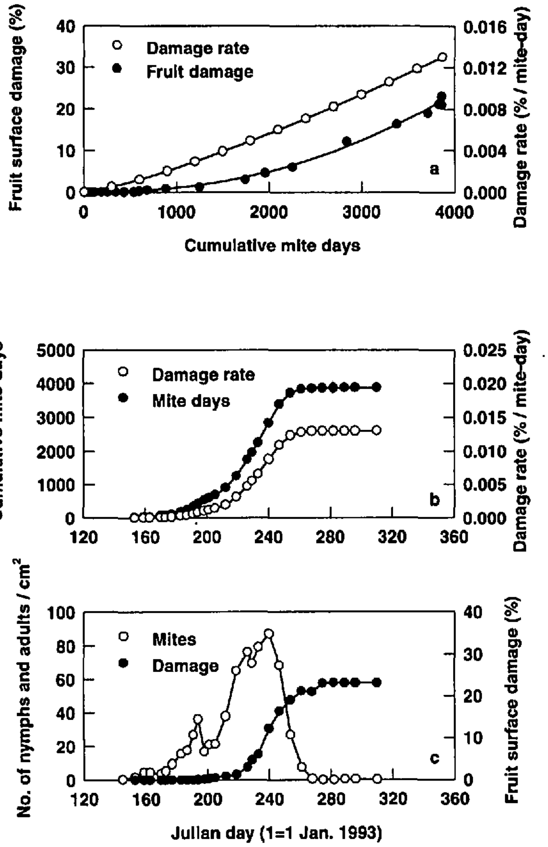

Fig. 5. Relationships between mite population and fruit damage (study 5: Gainesville, FL, 1993). (a) Fruit surface damage and damage rate versus cumulative mite-days; (b) cumulative mite-days and damage rate versus time; (c) mite population dynamics and cumulative fruit surface damage versus time.

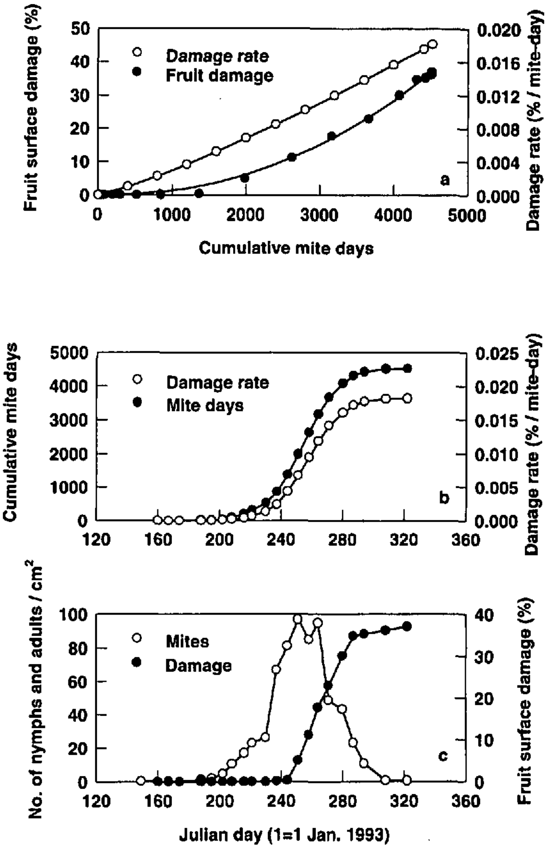

Fig. 6. Relationships between mite population and fruit damage (study 6: Lake Alfred, FL, 1993). (a) Fruit surface damage and damage rate versus cumulative mite-days; (b) cumulative mite-days and damage rate versus time; (c) mite population dynamics and cumulative fruit surface damage versus time.

where t_0 = starting time at a detectable mite density; $m(t)$ = mite density at time t. The zero damage density may be a function of fruit maturity and damage. The effective cumulative mite-days may give better prediction of mite damage than cumulative mite-days, especially when mite populations are low for a long time.

Pesticide-Induced Mite Population Decline and Damage Rate. The damage formula established in the current article (equation 3) was based on data for continuous mite population growth (mite population growth was not interrupted by miticides). Because miticide applications will cause sharp decline in mite population, the established formula may not be used for damage estimation when miticides are used. There are 2 ways the established damage formula may be used: 1st, apply the formula (equation 3) with cumulative mite-days regardless of miticide applications; and 2nd, apply the formula with new cumulative mite-days starting after the spray. These are the 2 extreme predictions. It has been suggested that cells may recover from mite punctures (McCoy and Albrigo 1975, Allen et al. 1992). Some of the punctured cells may recover between sprays (damage may recover somewhat with time). Actual damage may be between the 2 extremes and may be closer to the

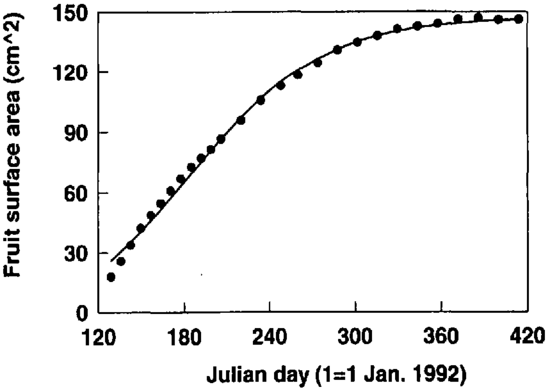

Fig. 7. Relationship between fruit surface area growth and time (Alachua County, Florida, 1992).

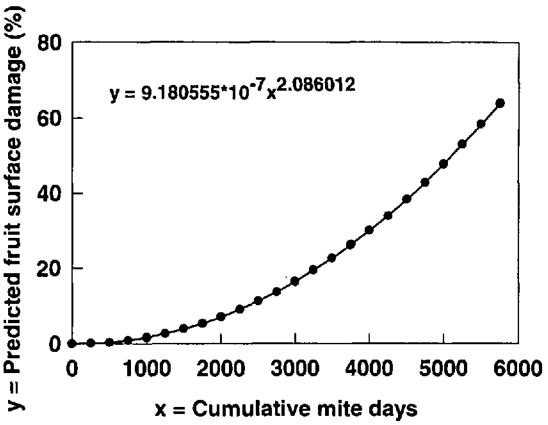

Fig. 8. Predicted cumulative fruit surface damage in relation to cumulative mite-days (see equation 9 in text).

lower extreme beause of cell recovering. This aspect needs to be further studied.

Recommended Formula for Damage Prediction. From the above analysis, it is clear that mite damage is affected by many factors. The relationship between cumulative damage and cumulative mite-days is probably a combined result of these factors. It may take many years of research before we can eventually elucidate the possible effects of these different factors. We suggest a temporary damage prediction model using averaged parameter values from this study. Fruit in studies 2, 3, and 4 were not selected randomly (see *Materials and Methods*), and results from these 3 studies may not represent the general damage trend at the grove level. Fruit in studies 1, 5, and 6 were random samples from the grove, and the results from these 3 studies could better represent the general damage trend at the grove level. The averaged parameter values from studies 1, 5, and 6 are shown in Table 2. The corresponding temporary prediction model is

$$y = 9.180555 \times 10^{-7} \times x^{2.086012} \qquad (9)$$

where y = predicted percent damage; x = cumulative mite-days begining from a detectable mite population. Before more information becomes available to improve equation 9, it could be used to predict fruit surface damage based on cumulative mite-day data. For example, 2,000 cumulative mite-days would result in a damage of $y = 9.180555 \times 10^{-2} \times x^{2.086012} = 9.180555 \times 10^{-7} \times 2{,}000^{2.086012} = 7.06\ (\%)$.

Rearranging equation 9 with x as the dependent variable and y as the independent variable, we obtain the following equation

$$x = \left(\frac{y}{9.180555 \times 10^{-7}}\right)^{\frac{1}{2.086012}}. \qquad (10)$$

Equation 10 could also be used to determine the maximum cumulative mite-days (x) if we want to limit the total damage below a specific level of y (percentage). For example, if our maximum tolerable damage level is $y = 5\%$, then the maximum tolerable cumulative mite-days (x) can be obtained from equation 10 as

$$x = \left(\frac{y}{9.180555 \times 10^{-7}}\right)^{\frac{1}{2.086012}}$$

$$= \left(\frac{5}{9.180555 \times 10^{-7}}\right)^{\frac{1}{2.086012}}$$

$$= 1{,}695 \text{ (mite-days).}$$

This information could help citrus growers time their miticide application to prevent mite damage from reaching a predefined damage level.

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References Cited

Albrigo, L. G. and C. W. McCoy. 1974. Characteristic injury by citrus rust mite to orange leaves and fruit. Proc. Fla. State Hortic. Soc. 87: 48–55.

Allen, J. C. 1976. A model for predicting citrus rust mite damage on Valencia orange fruit. Environ. Entomol. 5: 1083–1088.

1978. The effect of citrus rust mite damage on citrus fruit drop. J. Econ. Entomol. 71: 746–750.

1979. The effect of citrus rust mite damage on citrus fruit growth. J. Econ. Entomol. 72: 195–201.

Allen, J. C., Y. Yang, J. L. Knapp, and P. A. Stansly. 1992. Functional response, reproductive function and movement rate of a grazing herbivore: the citrus rust mite on the orange. Fla. Entomol. 75(1): 72–83.

Allen, J. C., Y. Yang, J. L. Knapp, and P. A. Stansly. 1994. The citrus rust mite story: a modelling approach to a fruit-mite-pathogen system, pp. 619–639. *In* D. Rosen, F. Bennett, and J. Capinera [eds.], Biological control and IPM: a Florida perspective. Intercept, Andover, UK.

Commonwealth Institute of Entomology. 1970. Distribution maps of pests. Series A. Map no. 78 (revised). Commonwealth Institute of Entomology, London.

Hobza, R. F. and L. R. Jeppson. 1974. A temperature and humidity study of citrus rust mite employing a constant humidity air-flow technique. Environ. Entomol. 3: 813–822.

Jandel Scientific. 1992. TableCurve: automated curve fitting software. Jandel Scientific, San Rafael, CA.

Knapp, J. L. 1983. Florida citrus integrated pest and crop management handbook. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville.

McCoy, C. W. and L. G. Albrigo. 1975. Feeding injury to the orange caused by the rust mite, *Phyllocoptruta oleivora* (Prostigmata: Eriophyoidea). Ann. Entomol. Soc. Am. 68: 289–297.

Yang, Y., J. C. Allen, J. L. Knapp, and P. A. Stansly. 1994. Citrus rust mite (Acari: Eriophyidae) damage effects on 'Hamlin' orange fruit growth and drop. Environ. Entomol. 23: 244–247.

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