Potato Aphid, *Macrosiphum euphorbiae* (Thomas), in Tomatoes: Plant Canopy Distribution and Binomial Sampling on Processing Tomatoes in California

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J. Econ. Entomol. 97(2): 490–495 (2004)

ABSTRACT A binomial sampling method for the potato aphid, *Macrosiphum euphorbiae* (Thomas), on processing tomato plants, *Lycopersicon esculentum* (Mill), is proposed. Relationships between mean number of *M. euphorbiae* per leaf and proportion of leaves infested [P(I)] with *M. euphorbiae* for both upper and interior leaves of the processing tomato varieties 'Alta' and 'Halley' are presented. A split-plot design was used with variety, position in the plant canopy, and block as the factors examined through linear regression and analysis of variance (ANOVA). Results supported the hypotheses that *M. euphorbiae* densities on upper canopy leaves are predictive of densities on inner canopy leaves and that proportion of *M. euphorbiae* infested leaves are predictive of mean densities per leaf. Mean *M. euphorbiae* density was greater on 'Alta' than 'Halley' tomato plants, supporting the assumption that 'Alta' is the more susceptible variety. Taylor's Power Law coefficients, *a* and *b*, were similar for proportion of *M. euphorbiae*–infested upper and inner leaves of both 'Alta' and 'Halley'. Taylor's *b* coefficients ranged from 1.57 to 1.74, indicating a highly clumped distribution for *M. euphorbiae*.

KEY WORDS Taylor's Power Law, *Macrosiphum euphorbiae*, *Lycopersicon esculentum*, sampling, distribution

THE POTATO APHID, *Macrosiphum euphorbiae* (Thomas), is commonly found on processing tomatoes, *Lycopersicon esculentum* (Mill), in the San Joaquin and Sacramento Valleys of California (Davis et al. 1998). *M. euphorbiae* often increase rapidly on processing tomatoes (Barlow 1962, Walker 1982), inflicting serious feeding damage (Houser et al. 1917). They also have the potential to transmit plant viruses (Kennedy et al. 1962). Walgenbach (1997) determined that high levels of aphids in staked, fresh market tomatoes cause significant fruit quality and yield losses. Fruit quality loss also results from sunscald because of plant defoliation resulting from aphid feeding. Other damage can occur from feeding by Hemipterans, which Walgenbach (1997) hypothesized are attracted to high aphid populations and use the fruit as an alternate food source.

In California processing tomatoes, *M. euphorbiae* are attacked by a number of parasites and predators, but populations of these natural enemies usually build up after the aphids have already reached high densities (F.G.Z., personal observation). Growers often treat the tomatoes to avoid yield loss if *M. euphorbiae* densities exceed 50% infested leaves (Zalom et al. 2000). The proportion of *M. euphorbiae*–infested leaves is estimated by sampling the leaf below the highest open flower of 30 randomly selected plants in the field. A leaf is considered infested if at least one aphid is present. Use of a 30-leaf sample was recommended because it complements an established sampling method for *Helicoverpa zea* (Boddie) eggs within an existing integrated pest management (IPM) program (Zalom et al. 1990). Additionally, leaves below the highest flowers of processing tomato plants are more accessible than are leaves within the plant canopy, making sampling more time efficient (Zalom et al. 1990). The relationship of proportion infested leaves to number of aphids per leaf has not been established for California processing tomatoes, prompting concern by some growers and crop consultants who have observed that *M. euphorbiae* inner canopy processing tomato leaves are more heavily infested than are outer canopy leaves.

Two major purposes of sampling are to estimate population density for research or IPM decision-making (Wilson and Room 1983). Population sampling is typically used by researchers who often value precision in determining population size more than the reduction of sampling cost. Decision sampling is used by growers and pest control advisers to quickly estimate population densities to make commercial control decisions (Wilson et al. 1989). Common approaches to decision sampling include binomial and enumerative

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procedures. Binomial sampling involves determining the presence or absence of an organism on sampling units within the sampling universe, whereas enumerative sampling involves counting the actual number of organisms on each sampling unit. Binomial sampling is generally faster, particularly for organisms that are numerous (Wilson et al. 1989). Binomial sampling is also an efficient method for determining within-plant distribution of a pest (Wilson and Room 1983). Because of its efficiency and potential for straightforward integration into the existing processing tomato IPM program in California, we sought to establish the parameters for developing a binomial sampling program for *M. euphorbiae* in that system.

This study describes the relationship between mean number of *M. euphorbiae* per leaf and proportion of leaves infested for both upper and interior leaves of a processing tomato plant canopy. Two hypotheses were proposed: *M. euphorbiae* densities on upper canopy leaves are predictive of densities on lower, interior canopy leaves; and proportion of *M. euphorbiae* infested leaves are predictive of mean densities per leaf for upper canopy leaves.

Materials and Methods

Processing tomatoes, varieties 'Alta' and 'Halley', were direct seeded in single- row beds, each 150 cm wide, at the UC Davis Vegetable Crops Department Farm in Davis, Yolo Co., CA, on 13 April 2000. 'Alta' is believed to be highly susceptible to *M. euphorbiae* infestation and was used in a previous study by Zalom and Miyao (personal communication), which established the damage relationship reported in University of California management guidelines (Davis et al. 1998). 'Halley' was the most widely planted processing tomato variety in 2000. A split plot design was used, consisting of five paired replicates of 'Alta' and 'Halley'. Each plot was five beds wide and 16 m long, with only the middle three rows used for sampling. The significant α level for statistical analysis was set at 0.05.

Aphid populations developed naturally. Artificial infestation was rejected because of concern that *M. euphorbiae* distribution would be adversely affected. Micronized sulfur was applied to control the tomato russet mite, *Aculops lycopersici* (Massee). Sulfur does not reduce *M. euphorbiae* densities (Zalom et al. 1990). *Bacillus thuringiensis* was applied to control caterpillars when needed. Sampling commenced once *M. euphorbiae* began to infest plots on 26 June 2000, 8 wk before harvest. Samples were taken from all plots once a week over the 8-wk period.

Thirty plants were randomly selected from each plot on each sampling date for binomial sampling of an upper canopy leaf (upper leaf) and an interior, lower canopy leaf (inner leaf). The upper leaf was the leaf below the highest open flower on the plant. The inner leaf was the fifth leaf below the highest open flower on the same stem and was always located well within the canopy. If no fresh open flowers were present on the plant selected, unopened flowers, or the site of the most recently opened flower, was selected. A leaf was considered infested if at least one *M. euphorbiae* was present on either side. Ten of the same 30 plants used for binomial sampling were also randomly selected for sampling by an enumerative method, where *M. euphorbiae* were counted on the same upper leaf and inner leaf that was used for binomial sampling. The same set of plants was used for binomial and enumerative sampling to establish the relationship between proportion of leaves infested [P(I)] and actual counts of aphids per plant within each replicate.

Mean *M. euphorbiae* per leaf was calculated as the average of upper or inner leaves from 10 enumeratively sampled 'Alta' or 'Halley' plants per replicate and was determined for each of the five replicates. P(I) was calculated as the proportion of 30 leaves infested with *M. euphorbiae* per replicate and was determined for all five replicates. The relationship between the mean number of *M. euphorbiae* per leaf and the proportion of leaves infested was determined by iterative regression using the formula of Wilson and Room (1983):

$$P(I) = 1 - e^{-\bar{x}\cdot\ln(a\cdot b^{-1})} \cdot (a \cdot \bar{x}^{b-1} - 1)^{-1}$$

where a and b are Taylor's coefficients, $\bar{x}$ is the mean number of *M. euphorbiae* per leaf, and P(I) is the proportion of infested leaves.

According to Taylor (1961), a is a numerical sampling coefficient based on sample size and serves as a method of population variance estimation, whereas b is a measure of population dispersion. Taylor's b reflects the degree of aggregation (henceforth referred to as clumping) that a species exhibits in populations and can be influenced by external factors such as a pesticide application. If $b > 1$, the species is clumped; $b = 1$ reflects a random distribution; and $b < 1$ reflects a near-regular distribution (Taylor 1961).

The relationship between observed proportion of infested upper canopy leaves versus proportion of infested inner canopy leaves was determined using linear regression analysis (SAS Institute 1999), with inner leaf as the dependent variable and upper leaf as the independent variable. Linear regression (SAS Institute 1999) was also used to determine the relationship between observed mean number of aphids per inner canopy leaf and mean number of aphids per upper canopy leaf, with inner leaf as the dependent variable and upper leaf as the independent variable. The mean density of *M. euphorbiae* was not normally distributed for 'Alta' or 'Halley' variety tomato plants. The transformations $\log_{10}(x + 1)$ for 'Alta' and $\log_{10}(x + 0.1)$ for 'Halley' were necessary to meet the assumptions of normality. Analysis of covariance (ANCOVA) (SAS Institute 1999) was used to determine the relationship between the slopes of mean upper versus mean inner for 'Alta' and 'Halley'. Mean density of aphids on inner canopy leaves was the dependent variable, while variety, week, and aphids on upper leaves were the independent variables. Repeated measures analysis of variance (ANOVA) (SAS Institute 1999) was used to examine the effects of week (the repeated factor), block (plot), variety, leaf position, and their two-way interactions on P(I). Repeated measures ANOVA (SAS Institute 1999) was also used to examine the effects of week, block, variety, leaf position, and their interactions on observed mean *M. euphorbiae* per leaf.

Results

Taylor's coefficients for 'Alta' were as follows: upper leaves $a = 3.89$, $b = 1.74$, $r = 0.98$, $P < 0.001$; inner leaves $a = 4.47$, $b = 1.77$, $r = 0.95$, $P < 0.001$. Taylor's coefficients for 'Halley' were as follows: upper leaves $a = 4.74$, $b = 1.57$, $r = 0.98$, $P < 0.001$; inner leaves $a = 3.91$, $b = 1.60$, $r = 0.97$, $P < 0.001$. Because $b > 1$, the *M. euphorbiae* were clumped in distribution (Wilson and Room 1983), and it is advantageous to use binomial sampling to determine the population densities for purposes of decision-making. Taylor's a and b values, along with the mean aphids per leaf, were used in Equation 1 to determine the predicted P(I). The predicted P(I) and mean were plotted with the observed P(I) and mean, with mean as the independent variable and P(I) as the dependent variable (Fig. 1). The mean number of *M. euphorbiae* per leaf and the corresponding proportion of leaves infested for the varieties 'Alta' and 'Halley', and for the upper and inner leaves of each are shown in Fig. 1. Also included are predicted values from the iterative regression using the Wilson and Room (1983) formula. Linear regression of $\log_{10}(x + 1)$ transformed mean number of aphids per leaf versus $\log_{10}(x + 1)$ transformed variance indicated highly significant relationships between variety and canopy location ('Alta': upper leaves, $F_{1,23} = 463.69$, $P < 0.05$, $r^2 = 0.95$; inner leaves, $F_{1,23} = 204.58$, $P < 0.05$, $r^2 = 0.90$; 'Halley': upper leaves, $F_{1,23} = 262.32$, $P < 0.05$, $r^2 = 0.92$; inner leaves, $F_{1,23} = 306.99$, $P < 0.05$, $r^2 = 0.93$).

Linear regression for transformed mean number of *M. euphorbiae* per leaf on upper leaves versus inner leaves resulted in significant relationships for both varieties 'Alta' $\log_{10}(x + 1)$ ($F_{1,23} = 19.03$, $r^2 = 0.45$, $P < 0.05$) and 'Halley' $\log_{10}(x + 0.1)$ ($F_{1,23} = 18.98$, $r^2 = 0.45$, $P < 0.05$). Linear regression analysis for proportion infested upper versus inner canopy leaves resulted in significant relationships for both 'Alta' ($F_{1,23} = 27.01$, $r^2 = 0.54$, $P < 0.05$) and 'Halley' ($F_{1,23} = 51.8$; $r^2 = 0.69$; $P < 0.05$; Fig. 2, A and B).

Repeated measures ANOVA found no significant interaction between week (sampling date) and variety for either proportion infested leaves ($P = 0.78$) or mean number of aphids per leaf ($P = 0.12$; Fig. 3), indicating that the sampling method is consistent over time and by variety. Also, there was no significant relationship between P(I) and position sampled (upper versus inner; $P = 0.78$; Fig. 3B). Repeated measures ANOVA indicated significant differences in mean number of aphids per leaf on the two varieties ($F_{1,80} = 28.52$, $P < 0.05$; 'Alta' $\bar{x} \pm$ SE $= 10.34 \pm 2.13$; 'Halley' $\bar{x} \pm$ SE $= 5.60 \pm 1.25$).

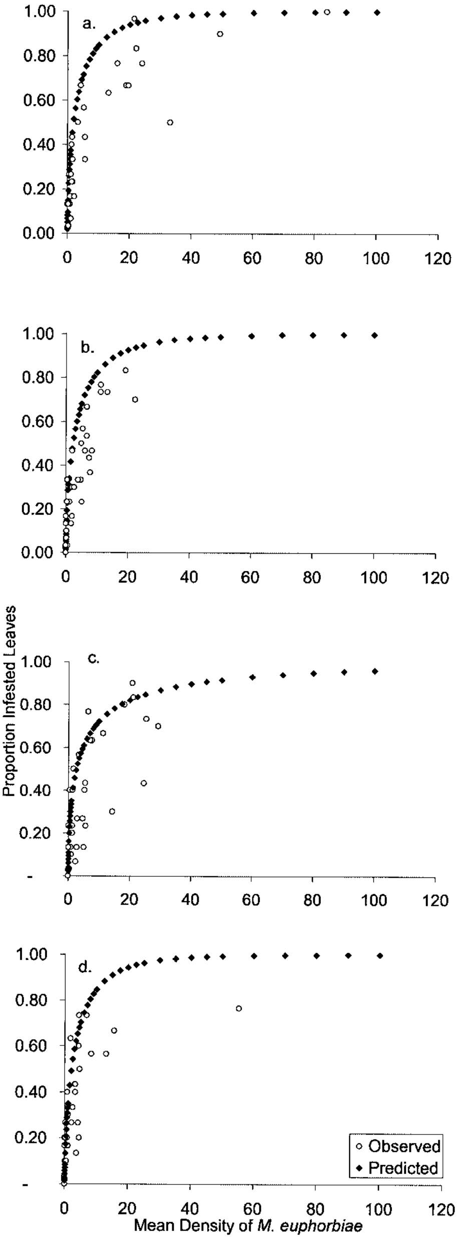

Fig. 1. Predicted and observed mean *M. euphorbiae* per leaf versus proportion of leaves infested for (A) 'Alta' upper canopy leaves ($P(I) = 1 - e^{-\bar{x}\cdot\ln(3.89\cdot\bar{x}^{0.74})\cdot(3.89\cdot\bar{x}^{0.74}-1)^{-1}}$, $r^2 = 0.96$), (B) 'Halley' upper canopy leaves ($P(I) = 1 - e^{-\bar{x}\cdot\ln(4.47\cdot\bar{x}^{0.77})\cdot(4.47\cdot\bar{x}^{0.77}-1)^{-1}}$, $r^2 = 0.90$), (C) 'Alta' inner canopy leaves ($P(I) = 1 - e^{-\bar{x}\cdot\ln(4.74\cdot\bar{x}^{0.57})\cdot(4.74\cdot\bar{x}^{0.57}-1)^{-1}}$, $r^2 = 0.96$), and (D) 'Halley' inner canopy leaves ($P(I) = 1 - e^{-\bar{x}\cdot\ln(3.91\cdot\bar{x}^{0.60})\cdot(3.91\cdot\bar{x}^{0.60}-1)^{-1}}$, $r^2 = 0.94$].

Discussion

The results of our study support the hypotheses that *M. euphorbiae* densities on upper canopy leaves are predictive of densities on inner leaves and that proportion of *M. euphorbiae* infested leaves are predictive

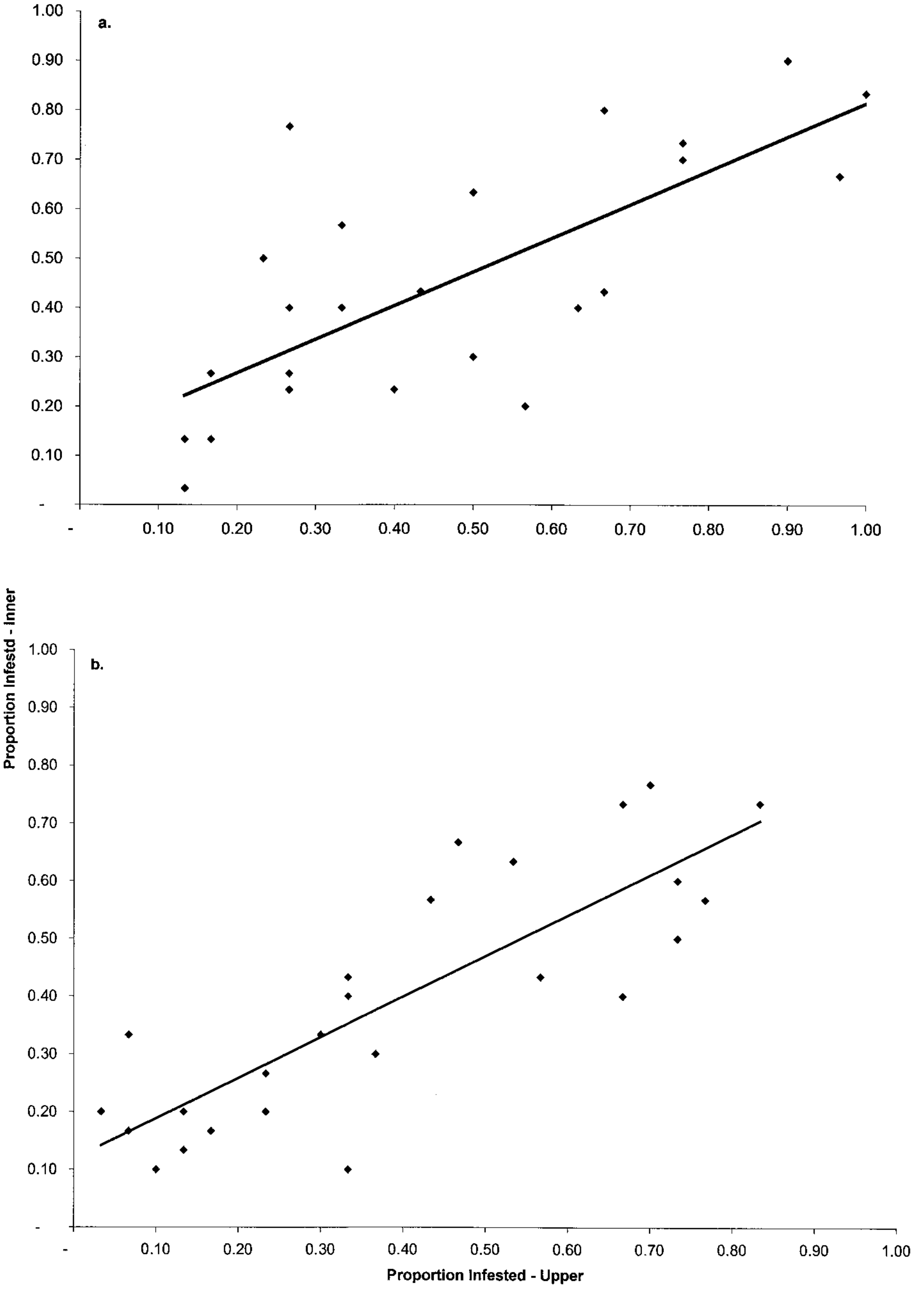

Fig. 2. Proportion of upper versus inner canopy leaves infested with *M. euphorbiae* for tomato varieties (A) 'Alta' ($r = 0.73$, $P < 0.05$) and (B) 'Halley' ($r = 0.83$, $P < 0.05$).

of mean numbers per leaf for upper canopy leaves. Mean density of *M. euphorbiae* was greater on 'Alta' than 'Halley' variety tomato plants, supporting the assumption that 'Alta' is the more susceptible variety. Aphid densities were greater on inner canopy leaves than upper canopy leaves in the following proportions: 'Alta': 0.68 inner, 0.32 upper; and 'Halley': 0.70 inner, 0.30 upper. These results do not agree with those of Walker et al. (1984), who reported that *M. euphorbiae* on processing tomatoes in Ohio were found on upper versus inner canopy leaves in a ratio of ≈2:1. Our results, however, support those of Shands et al. (1954), who found *M. euphorbiae* densities were greater on inner canopy leaves than upper canopy leaves of potato. By contrast, Bradley (1952) and Radcliffe and Lauer (1970) found *M. euphorbiae* densities to be greater on upper than inner canopy leaves.

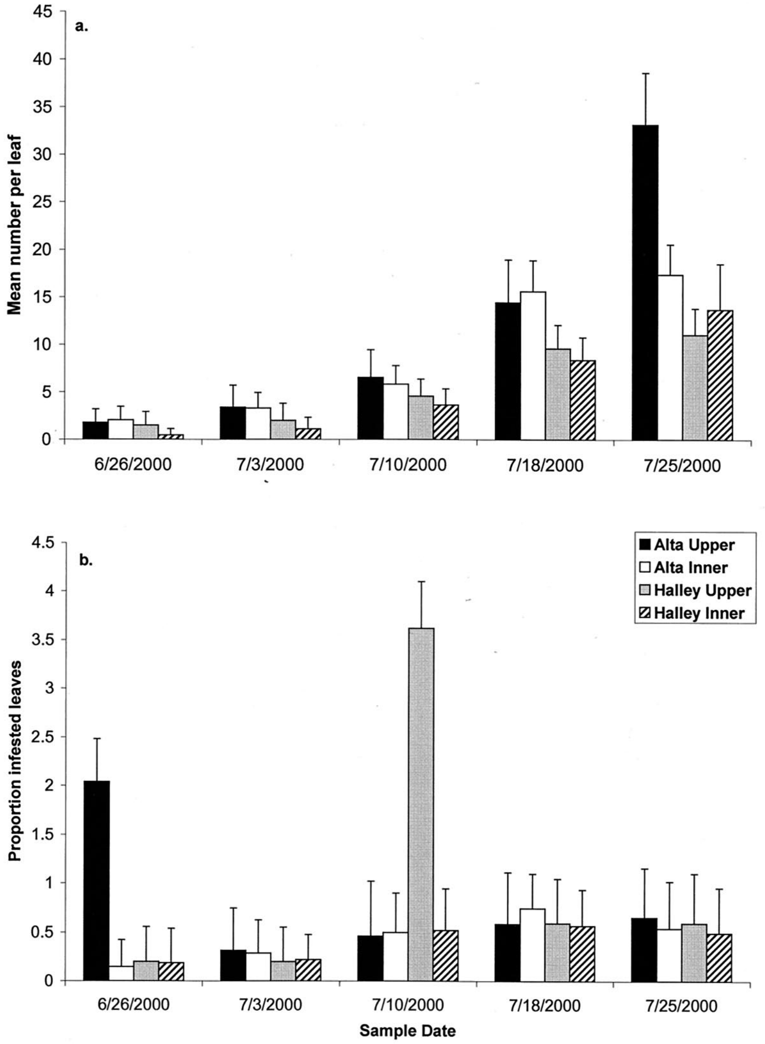

Fig. 3. (A) Mean density ± SE of *M. euphorbiae* per leaf and (B) proportion infested ± SE leaves on 'Alta' and 'Halley' tomato plants, 26 June–25 July 2000.

Taylor's b coefficients in our study ranged from $b = 1.57$ to $b = 1.74$, suggesting a clumped distribution for *M. euphorbiae.* Walker et al. (1984) calculated Taylor's b to be between 1.07 and 1.54, with apterous aphids being significantly more clumped than alates. Most *M. euphorbiae* present in our study were apterae. Wise and Lamb (1995) found Taylor's b for *M. euphorbiae* on oilseed flax, *Linum usitatissimum* L., to be between 1.61 and 1.81. These observations indicate agreement in Taylor's b coefficient for *M. euphorbiae* apterae across plant varieties and families. Once alates infest a field, *M. euphorbiae* distribution likely becomes clumped because of parthenogenic reproduction. This is the time that decision sampling occurs. The damage threshold for processing tomatoes is proposed to be 50–60% infested upper canopy leaves for the susceptible variety 'Alta' (Zalom et al. 2000). This is within the range of values where *M. euphorbiae* infestations can be readily discerned using a binomial sampling procedure.

For purposes of IPM decision-making, our data indicate that binomial sampling for *M. euphorbiae* accurately reflects the mean number of aphids per leaf. Also, because there was no significant relationship between P(I) and sampling position and P(I) on upper leaves reflects P(I) on inner leaves, either leaf could be used. The increase in P(I) and mean number of aphids per leaf over time was independent of variety, suggesting that the use of binomial sampling for *M. euphorbiae* is applicable for the tomato varieties included in this study. Binomial sampling of the upper leaves is more time efficient because the sampling unit is easier to identify, faster to select by a sampler, more consistent, and can be combined with commercial sampling for *H. zea* eggs (Zalom et al. 1990). For these reasons, we propose that the *M. euphorbiae* binomial sampling can be readily implemented in an IPM program (Zalom et al. 2000) with relatively little additional time investment. Developing effective and economical decision rules should allow growers to more efficiently manage *M. euphorbiae.*

Acknowledgments

This research was completed in fulfillment of the Senior Thesis in Animal Biology at the University of California, Davis. We thank S. Keyworth, J. Jackson, and E. Roncoroni for field assistance and C. Hummel for moral support. Funding was provided by the California Tomato Research Institute.

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Received for publication 6 May 2002; accepted 2 October 2003.