Binomial Sampling of Western Flower Thrips Infesting Flowering Greenhouse Crops Using Incidence-Mean Models

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Environ. Entomol. 40(2): 381–390 (2011); DOI: 10.1603/EN10085

ABSTRACT Accurate assessments of thrips density are important for effective thrips management programs. Complicating the development of sampling plans for western flower thrips (WFT) *Frankliniella occidentalis* (Pergande) in greenhouse crops are the facts that they are small, difficult to detect, and attack a variety of crops, which may be grown concurrently within the same greenhouse. Binomial sampling was evaluated as an alternative to sampling plans based on complete enumeration. This work included comparison of incidence-mean models across diverse plant species (impatiens, cucumber, and marigold) to determine the possibility of using a generic model for sampling WFT in mixed crops. Data from laboratory-processed flower samples revealed that infestation rates calculated using a tally threshold of three thrips per flower provided the best estimates of thrips population densities in each tested crop and in the combined crops (composite data set). Distributions of thrips populations were similar across the three plant species, indicating potential for development of a generic sampling plan for mixed floral crops. Practical sampling methods for simple and complex flowers tested in the greenhouse (in situ) were evaluated via construction of binomial count operating characteristic functions. In the case of simple flowers (impatiens), visual inspections provided adequate estimates of thrips infestation rates at a low tally threshold, which ultimately enabled accurate estimation of thrips densities. However, visual inspection and tap-sampling of complex flowers (marigold) provided unreliable results. These findings indicate that use of binomial sampling methods in mixed floral crops will require development of more accurate sampling techniques.

KEY WORDS binomial sampling, flower taps, visual inspection, classification sampling, operating characteristic

Western flower thrips, *Frankliniella occidentalis* Pergande, are a polyphagous species (Yudin et al. 1986) with a host range of over 250 plant species (Bryan and Smith 1956, Haselwood 1983), which contributes to its status as a key pest in numerous greenhouse-grown vegetable and floriculture crops around the world (Steiner 1990, Higgins 1992, Seaton et al. 1997). Abundance of *F. occidentalis* in crops can be highly variable and as a result, assessment of thrips density is important for effective management.

Sampling procedures for thrips have been developed for many outdoor crops including apple (*Malus domestica* Borkh.), cotton (*Gossypium* spp.), soybeans [*Glycine max* (L.) Merr.], onions (*Allium* spp.), tomatoes (*Solanum Lycopersicum* L.), and nectarines [*Prunus persica* (L.) Batsch] (Lewis 1973, Chander and Verma 1978, Irwin and Yeargan 1980, Edelson 1985, Terry and DeGrandi-Hoffman 1988, Pearsall and Myers 2000, Boll et al. 2007), and for some greenhouse crops including cucumbers (*Cucumis sativus* L.), sweet pepper (*Capsicum annuum* L.), chrysanthemum (*Chrysanthemum* spp.), *Cyclamen* spp., and garden impatiens (*Impatiens* spp.) (Steiner 1990, Shipp and Zariffa 1991, Taylor et al. 1998, De Courcy Williams 2001, Wang and Shipp 2001, Ugine et al. 2006). The two most common thrips sampling techniques are sticky cards (Steiner 1990, Shipp and Zariffa 1991, Taylor et al. 1998), which are placed directly above or within the crop canopy, and direct observation of thrips on plant material (i.e., leaves or flowers) (Henneberry et al. 1964, Terry and DeGrandi-Hoffman 1988, Rosenheim et al. 1990, Wang and Shipp 2001, Williams 2001, Ugine et al. 2006). In crops of greenhouse cucumber and sweet pepper, sticky card catch can predict thrips density in the crop (Yudin et al. 1987, Shipp and Zariffa 1991) and has historically been the recommended method of assessment (Steiner 1990, Gillespie and Vernon 1990). Sticky traps have the added benefit of detecting small populations of thrips before they can be easily found on the various types of plant samples and before certain types of plant samples are available (i.e., before flowering). However, the relationship between sticky card catch and thrips density

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0046-225X/11/0381–0390$04.00/0

on foliage is often highly variable and can be dependent on the host plant (Higgins 1992, Jacobson 1997, Lewis 1997, Pearsall and Myers 2000, Rhainds and Shipp 2003).

Taylor et al. (1998) in a study of five independent data sets collected from sticky cards placed directly above the canopies of greenhouse cucumbers, sweet peppers, chrysanthemums, garden impatiens [*Impatiens wallerana* (Hook) F], and mixed potted plants, determined that the spatial aggregation of thrips as measured by Taylor's power law (Taylor 1961) was the same across all plant species tested. It was suggested that a sampling scheme using set parameters for Taylor's law "is probably the best practical approach to pest management decision-making for *F. occidentalis* in the greenhouse." However, in only one of the five data sets analyzed Shipp and Zariffa (1991), is there any measure of the correlation between trap catch and thrips density.

Flowers are often attractive to thrips (Gonzalez et al. 1982, Gonzalez and Wilson 1982, Pickett et al. 1988), and sampling flowers is a common method of assessing both thrips presence and density. It has been used in apples (Terry and DeGrandi-Hoffman 1988), cucumber (Rosenheim et al. 1990, Wang and Shipp 2001) cyclamen (Williams 2001), and roses (*Rosa* spp.) (Henneberry et al. 1964) and may be a better estimator of thrips density compared with sticky trap catch; immature and adult thrips can be observed in flower samples, whereas only adult thrips (flying) can be sampled with stick cards. One drawback of sampling flowers is that there is a period of time in the production of most crops in which no flowers are present, making sticky traps the only practical method of thrips detection.

Because thrips are small and difficult to count, binomial count sampling is preferred to complete enumeration. Binomial sampling relates, via statistical models, the proportion of sample units with more than a threshold count, T, to the mean density. The underlying statistical models are known as incidence-mean models. Complicating the development of such sampling plans for thrips in floriculture production is the fact that numerous crop species are often grown concurrently within the same greenhouse. It is impractical and not cost effective to develop and use a different incidence/mean model and associated sampling plan for all the different types of greenhouse floriculture crops. This suggests that there is a need for a generic model and sampling plan. Greenhouse floriculture crops generally fall into two distinct categories, those that have simple flowers and those with composite flowers, implying that there may be a need for two generic sampling plans. Our objectives in this study were to determine 1) whether incidence-mean models describe the relationship between incidence of *F. occidentalis*-infested flowers and mean thrips density, and if this relationship is affected by plant species; and 2) what thrips sampling technique provides the best relationship (minimizes sampling uncertainty) between incidence of infested flowers and mean thrips density for composite and simple flowers in situ. Because of our extensive experience with thrips infesting both garden impatiens and marigolds (*Tagetes patula* L.), we choose these flowering plants as our model simple and complex flowers, respectively. In addition, for comparison with our floriculture crops, we included a data set from a commonly grown greenhouse vegetable, English cucumber *Cucumis sativus* L.

Materials and Methods

Our work broadly consisted of two steps. First, we estimated incidence-mean models for counts of *F. occidentalis* from the three crops and determined whether the crop from which samples were collected influenced the parameters of the estimated models. We found that crop did not have such an effect and proceeded to the second step, which entailed evaluations of practical sampling techniques that could be used in situ.

We developed sampling techniques and corresponding incidence-mean models for simple and composite flowers, and assessed how use of the sampling techniques affected binomial count sampling plan performance. Sampling plan performance was measured via operating characteristic (OC) functions for classification and via variances for estimated mean density. In both cases, fixed sample size procedures were used because they are simple yet allow for the same conclusions as if more complicated sequential procedures were used.

Greenhouses, Plants, and Insects. Three different greenhouse arrangements were used to collect data from impatiens and marigolds. The first consisted of three adjacent glass greenhouses ($\approx$3 m $\times$ 5m) with 9 m^2 of bench space per house. These were filled with 350–400 potted garden impatiens plants, variety 'SuperElfin; white' as described in Ugine et al. (2006). All data from these greenhouses were used exclusively in the model validation aspect of these studies (see below). The second arrangement, used in the investigation of incidence-mean models and approximately half of the plants used in the test of operational sampling techniques (in situ) of complex flowers were grown in a set of five plastic-covered greenhouses with dimensions of 5 $\times$ 4 m. The final experimental arrangement was a single large glass greenhouse that was subdivided with dividing walls into three bays (10.4 m $\times$ 8 m), each with independent environmental controls. Each subdivision contained two sets of four rolling benches (1.5 m $\times$ 2.7 m) situated to maximize the distance between plots of plants. Impatiens plants used in the test of operational sampling techniques (in situ) were grown and maintained in the subdivided greenhouse as described in Ugine et al. 2007. Marigolds, variety 'Bonanza Bolero,' were grown from seed purchased from Park Seed Wholesale, Inc. (Greenwood, SC). All of the marigold plants used in the remaining half of the operational sampling technique tests were maintained in the 3-bay glass greenhouses described above, under similar conditions. Plots of marigolds and impatiens in both the small plastic-covered greenhouse and the three-bay greenhouse

contained 25 flats of plants arranged on benches to form a contiguous plot of 3.7 m^2. The growing conditions for cucumber plants (cultivar 'Flamingo') and methods for insect rearing and release are described by Shipp and Zariffa (1991). Plants were either naturally infested with thrips migrating into the greenhouses or were infested with a small number of thrips (≈20) from a laboratory colony (Ugine et al. 2006). In each instance, the distribution of plants and thrips within plants closely represented distributions that a scout or grower would likely encounter upon entering any thrips-infested greenhouse.

Influence of Plant Species on Incidence-Mean Models. Fully-opened, nonsenescent impatiens, marigold and cucumber flowers were chosen from arbitrarily selected locations throughout the plant canopy, excised, and immediately placed individually into 20-ml scintillation vials or 100-ml snap-cap polycarbonate vials containing 70% EtOH. Flowers were dissected in the laboratory under alcohol in a 100-mm glass petri dish using a stereomicroscope, and the numbers of adult and immature thrips were recorded for each sample. Thrips that were obviously dead before being placed into alcohol (i.e., dry and shriveled in appearance) were rare and were not quantified. One hundred and seventeen, 67, and 20 sample collections of impatiens, marigolds, and cucumbers were made, respectively, and $n = 21–60$, $n = 10–60$, and $n = 20–60$ flowers were collected from each crop for each bout, respectively. Counts of thrips in cucumber flowers were made in research greenhouses at the Greenhouse and Processing Crops Research Center, Harrow, Ontario, Canada from 1996 to 1998. Counts of thrips in impatiens flowers were made in research greenhouses at Cornell University from 1999 to 2003, as were counts of thrips in marigolds from 2005 to 2006.

Operational Sampling Techniques (In Situ).

Composite flower (marigold). In practice, in situ counts of thrips are more feasible than the examination of flowers in a laboratory after collection. Two techniques were tested to determine the utility of in situ counts of thrips with respect to incidence-mean models; flower tapping and visual inspection. Twenty fully-expanded, nonsenescent marigold flowers were arbitrarily selected by each of two samplers from all areas of the plot including edges and the center, to test the two sampling techniques ($n = 10$ flowers per sampler per technique). The flower tapping technique involved picking and holding the flower head at its base and then subjecting the flower head to five vigorous flicks with the middle finger over a single sheet of 21 × 28-cm white paper. The visual enumeration technique entailed picking a flower and searching for thrips among and within the inflorescences and developing seeds. All in situ thrips enumeration was conducted with the unaided eye and a maximum of five thrips were counted before moving to the next flower. All flower samples were ultimately placed into a 100-ml snap-cap vial filled with 70% ethanol, brought into the laboratory and the actual number of thrips per flower assessed with the aid of a microscope by destructive sampling; these samples are referred to later as complete counts. Laboratory counts of thrips were paired with in situ counts of thrips to estimate bias for each thrips sampling technique and for use in generating incidence-mean models. Sampling was performed weekly on five separate dates in 3, 3, 2, 1, and 1 greenhouse(s) per date, respectively, for 20 sampling bouts in total.

Simple Flower (Impatiens). Because thrips are easier to locate in simple flowers, a single technique, visual inspection, was tested to determine the utility of in situ counts in incidence-mean models. Forty-six samples of $n = 30$ impatiens flowers were made in three replicate greenhouses over a 21-d period by five samplers. The total time required to complete a sampling bout was recorded for each sampling bout to determine if there was a relationship between sampling duration and the degree of bias in in situ estimates. A single impatiens flower was picked from an arbitrary location within the plot (we sampled flowers from the center and the edges of the plot) and the number of thrips up to a maximum of five, was determined by visual inspection. After visual inspection, flowers were immediately placed individually into 20 ml scintillation vials filled with 70% EtOH. All flowers were ultimately brought back into the laboratory and the number of thrips per flower counted under a dissecting microscope. Laboratory counts of thrips were paired with in situ counts of thrips to estimate the rate of bias for this thrips sampling technique and for use in generating incidence-mean models.

Influence of Incidence-Mean Models on Sampling Performance. While incidence-mean models serve as the foundation for binomial sampling plans and to a large extent determine the performance of these plans, these models alone do not provide interpretable measures of sampling plan performance. Instead, one must examine OC functions when classification sampling is used and when parameter estimation is the objective, a measure of precision of the parameter estimate. In classification sampling, the objective is to place a population parameter into one of two or more categories (e.g., above or below an action threshold). Classification sampling, in a management context, provides explicit considerations of the likelihood of potential actions. If the objective is to classify a population as above or below some critical density (CD), the OC provides the probability of a below CD classification given any true density (Binns et al. 2000). There are several ways that estimation sampling plans can be evaluated, but a simple one is to determine the variance of the estimated parameter, which can in turn be used to construct confidence intervals (Binns et al. 2000). We calculated OC functions and confidence intervals for estimated means for candidate sampling plans and compared those to gauge the effects of the underlying incidence-mean models.

Classification Sampling. A critical density of two thrips per flower (Wang and Shipp 2001) was used to construct binomial count classification sampling plans based on 25 samples. Generation of OC functions requires a critical pest density, and while a critical thrips density has not yet been experimentally deter-

Table 1. Regression parameters of laboratory-based counts of thrips for the incidence mean models for impatiens, marigolds, cucumbers and a composite model at six tally thresholds

p_T	Crop	R^2	MSE	F-value	*P* value	df	Ln intercept ± SE	Slope ± SE
T = 0	Impatiens	0.69	0.20	241.3	<0.0001	1,106	1.00 ± 0.07	0.60 ± 0.04
T = 1	Impatiens	0.77	0.15	356.4	<0.0001	1,106	1.38 ± 0.04	0.64 ± 0.03
T = 2	Impatiens	0.84	0.10	555.3	<0.0001	1,106	1.64 ± 0.03	0.63 ± 0.03
T = 3	Impatiens	0.91	0.06	1076.2	<0.0001	1,106	1.86 ± 0.02	0.66 ± 0.02
T = 4	Impatiens	0.92	0.05	1278.2	<0.0001	1,106	2.03 ± 0.02	0.63 ± 0.02
T = 5	Impatiens	0.95	0.03	1915.8	<0.0001	1,105	2.19 ± 0.02	0.62 ± 0.01
T = 0	Marigold	0.75	0.38	267.3	<0.0001	1,91	0.79 ± 0.07	0.70 ± 0.04
T = 1	Marigold	0.76	0.24	271.7	<0.0001	1,88	1.30 ± 0.05	0.57 ± 0.03
T = 2	Marigold	0.86	0.14	523.9	<0.0001	1,88	1.59 ± 0.04	0.64 ± 0.03
T = 3	Marigold	0.88	0.12	650.5	<0.0001	1,88	1.76 ± 0.04	0.63 ± 0.02
T = 4	Marigold	0.87	0.12	560.3	<0.0001	1,86	1.89 ± 0.04	0.61 ± 0.03
T = 5	Marigold	0.85	0.13	473.4	<0.0001	1,83	2.10 ± 0.05	0.65 ± 0.03
T = 0	Cucumber	0.72	0.28	43.2	<0.0001	1,17	0.79 ± 0.19	0.72 ± 0.11
T = 1	Cucumber	0.78	0.21	60.5	<0.0001	1,17	1.34 ± 0.12	0.80 ± 0.10
T = 2	Cucumber	0.87	0.13	112.2	<0.0001	1,17	1.61 ± 0.08	0.76 ± 0.72
T = 3	Cucumber	0.93	0.07	229.0	<0.0001	1,17	1.90 ± 0.06	0.70 ± 0.05
T = 4	Cucumber	0.93	0.06	239.1	<0.0001	1,17	2.07 ± 0.06	0.61 ± 0.04
T = 5	Cucumber	0.98	0.02	699.5	<0.0001	1,15	2.27 ± 0.03	0.63 ± 0.02
T = 0	Composite model	0.74	0.28	566.9	<0.0001	1,216	0.87 ± 0.06	0.66 ± 0.03
	Crop effect			0.82	0.44	2,216		
T = 1	Composite model	0.76	0.19	663.2	<0.0001	1,213	1.37 ± 0.04	0.61 ± 0.02
	Crop effect			2.17	0.12	2,213		
T = 2	Composite model	0.85	0.12	1194.9	<0.0001	1,213	1.62 ± 0.03	0.65 ± 0.02
	Crop effect			0.59	0.56	2,213		
T = 3	Composite model	0.90	0.08	1847.0	<0.0001	1,213	1.84 ± 0.03	0.64 ± 0.02
	Crop effect			2.6	0.08	2,213		
T = 4	Composite model	0.90	0.08	1849.2	<0.0001	1,211	2.00 ± 0.03	0.62 ± 0.01
	Crop effect			6.4	0.002	2,211		
T = 5	Composite model	0.90	0.07	1892.2	<0.0001	1,205	2.18 ± 0.03	0.63 ± 0.01
	Crop effect			5.9	0.003	2,205		

mined for cucumbers, marigolds or impatiens, we chose a critical pest density of two thrips per flower as this represents a level of infestation considered intolerable by many growers for a variety of crops. Binomial-count sample plans make use of a tally threshold (T) that is used to define which sample observations are scored as infested or occupied and which are not. For example if T = 0 then samples having one or more organisms will be scored as occupied. In general, the precision of incidence-mean models, as measured by model mean squared error (MSE), increases with increasing tally threshold up to some limit and then precision declines with further increase in T (Binns et al. 2000). Often binomial sampling becomes more difficult as T becomes larger. Operating characteristic functions were calculated using the methods described by Binns et al. (2000).

Statistical Analysis. For each sample bout for each crop tested, we calculated the proportion of sample observations with >0 through five thrips (e.g., T = 0 through 5) and the mean number of thrips per flower. Linear regression was used to relate the proportion of infested flowers for each tally threshold (P_T) to the mean number of thrips per flower (m) (e.g., an incidence-mean model). The model was fit for each level of T within a crop using the equation $\ln(m) = a + b*\ln(-\ln[1-p_T])$, as well as for a composite data set comprised of all the crops that included crop as a factor to determine if plant species affected the incidence-mean relationship. Sample bouts with means in excess of 25 thrips per flower were omitted from all data sets to minimize the effect of the leverage of these high means on the fit of the line to the incidence-mean model. The proportion of infested flowers that was equal to 1, was replaced with 0.999999 as the natural log of one is 0. This served to keep these data points in the statistical model.

Incidence-mean models were fit for the different in situ sampling techniques tested for impatiens and marigolds as above. Operating characteristic functions were generated using the methods described by Binns et al. (2000) for binomial count sample plans as well as for plans that used complete enumeration. In general, binomial count sampling plans perform poorer than those based on complete enumeration because complete enumeration provides greater information about each sample observation. Estimates of variance of the sample mean for complete counts were determined using Taylor's Power Law and complete count 95% confidence intervals were calculated using these estimates. Binomial count (BC) 95% confidence intervals were estimated using variances generated as per Schaalje et al. (2001), which includes a combination of biological, prediction and sampling variance.

Results

Test of Incidence-Mean Model Fit as a Function of Crop Species. The results of incidence-mean modeling of laboratory-based counts of thrips in flowers are presented in Table 1. Generally, the range of incidences (proportion of infested flowers) for each tally

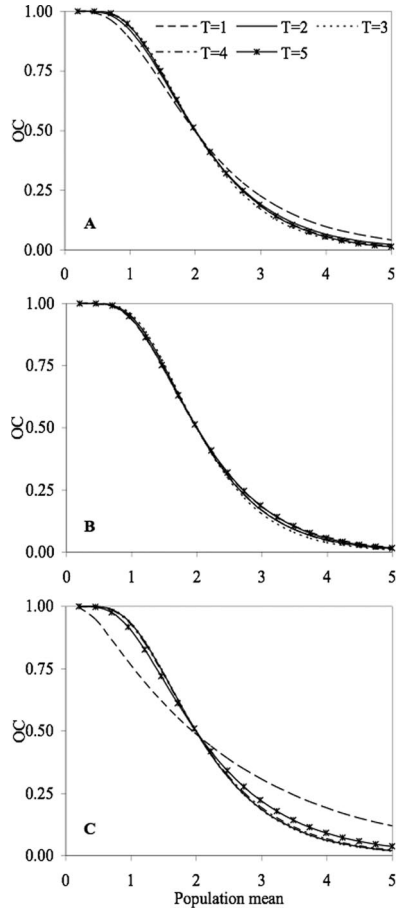

Fig. 1. Operating characteristic functions at tally thresholds (T) 1–5 for laboratory-based binomial counts of thrips in a) cucumber, b) impatiens, and c) marigold flowers.

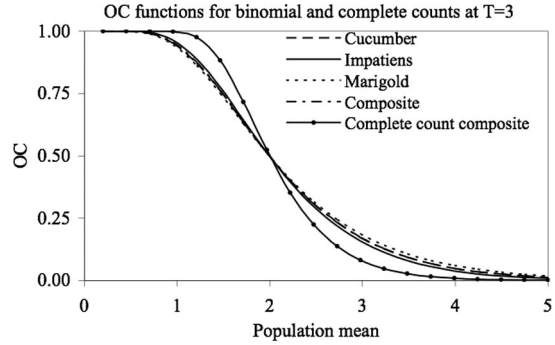

Fig. 2. Operating characteristic function at a tally threshold of three (T = 3) for laboratory-based binomial counts of thrips in cucumber, marigold, and impatiens flowers and a composite data set comprised of counts from all three plant species.

threshold covered >90% of the possible range (i.e., from 0 to 1.0). In only one instance did the range of incidences cover <50% of the possible range; this occurred for cucumbers at T = 0 (e.g., saturation of incidence in the model). As expected, the relationship between incidence of infested flowers and mean thrips per flower improved as T increased, as indicated by lower mean squared errors (MSE); this was true for all three crops as well as for the composite model, which was fit across plant species. MSE was relatively stable at T = 3, T = 4 and T = 5 for all three crops and the composite model. Because thrips can be difficult to count, we would like to choose the level of T that balances the number of thrips needing to be counted while maximizing sample precision. We judged this to occur at T = 3 for each crop based on the steepness of the OC functions (Fig. 1) as this takes into account the intercept, the slope and variation about the incidence-mean model. When the composite model was fit for T = 3, there was not a significant effect of crop on the relationship between incidence of infested flowers and mean thrips per flower ($F_{[2,213]} = 2.6$, $P = 0.08$); however, at T = 4 and T = 5 there was a significant crop effect (Table 1).

The OC functions for the three crops and the composite model at T = 3 (Fig. 2) are nearly identical indicating that use of the composite model when sampling thrips for classification in impatiens, marigold or cucumber would not affect sample outcomes. Maximizing information from each sample by counting all of the thrips results in improved sample plan performance as reflected in the OC function for complete counts with a composite model (Fig. 2). However, the difference between binomial and complete counts does not preclude use of binomial count sampling. Although we chose an unconfirmed critical density (i.e., not related to actual damage) informed only by the opinions of growers and scouts, this will not appreciably affect the inferences drawn regarding the influence of plant species (flower type) on sample plan performance.

Ninety five percent binomial and complete count confidence intervals of thrips abundance predicted from the composite incidence-mean model are also not substantially different from those for the crop-specific models (Fig. 3) especially in the area of interest (0–5 thrips per flower). Taylor's power law (TPL) regressions yielded similar slopes for impatiens, marigolds and the composite model (1.25, 1.20 and 1.24, respectively) whereas the slope for cucumbers was slightly higher at 1.52. The TPL regression for the composite model was not affected by crop ($F_{[2,216]} = 1.6$, $P = 0.21$).

Operational Sampling Techniques (In Situ). The results of incidence-mean modeling of in situ-counts of thrips in simple and complex flowers using different sampling techniques are presented in Table 2. Several of the ranges of incidences within a crop and sampling technique were not large, covering only ≈50% of the possible range (i.e., impatiens visual T = 5, marigold tap T = 4, T = 5, marigold visual T's = 2–5). As the tally threshold of thrips per flower increased from 0 to 5, the relationship between the proportion of flowers classified as infested and the mean number of thrips im-

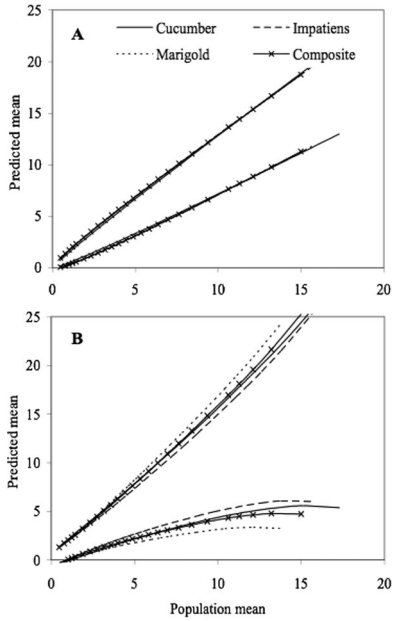

Fig. 3. Plots of a) 95% complete count confidence limits and b) 95% binomial count confidence limits for laboratory-based counts of thrips in cucumber, marigold, and impatiens flowers and a composite data set comprised of counts from all three plant species at a tally threshold of three thrips per flower (T = 3).

proved when marigolds were sampled but was variable for impatiens. The tally thresholds for the two sampling methods by flower type combinations that provided the best relationship between incidence and mean as measured by the steepness of the OC functions were T = 1, T = 0, and T = 1 for impatiens visual inspections, marigold visual inspections and marigold flower taps, respectively (Fig. 4). Visual binomial counts of thrips on impatiens in situ (T = 1) compared with estimates of laboratory-based incidence estimates of thrips in impatiens flowers showed that in situ counts are biased, underestimating actual thrips abundance (Fig. 5a). The in situ OC function and the laboratory-based binomial count OC function were nearly identical (Fig. 5b). The difference between plots of binomial and complete count OC functions represent the added variability associated with using binomial count models versus complete count models, which are always more precise (Fig. 5b).

A very pronounced difference was found in the effectiveness of the two sampling methods tested for marigold flowers in situ. Inspection of the relationship between in situ incidence and laboratory-determined incidence reveals that using counts of thrips from flower taps to determine the incidence of infested marigold flowers provided a less biased estimate of actual thrips density compared with visual inspections (Fig. 6a). The shape of the binomial count OC functions for the two sampling methods (Fig. 6b) shows a much flatter OC function for visual inspection of marigolds compared with flower tapping and laboratory-based count models. Thus, visual inspection of marigolds will lead to increased erroneous classification compared with tapping. All binomial count procedures were less precise than making complete counts of thrips (Fig. 6b).

Discussion

Because thrips are small and can be difficult to count, binomial count sampling is preferred to complete enumeration. Complicating the development of such a sampling plan is the fact that numerous crop species are often grown concurrently within the same greenhouse. It is impractical to use a different incidence mean model and hence sampling plans for each crop; a generic sampling plan would be much more useful. We compared incidence-mean models for thrips in flowers from three different greenhouse crops, garden impatiens, fresh market cucumber and

Table 2. Regression parameters of in situ counts of thrips infesting impatiens and marigolds and the effect of tally threshold and sampling method

p_T	Crop	Sampling method	R^2	MSE	F-value	*P* value	df	Ln intercept ± SE	Slope ± SE
T = 0	Impatiens	Visual	0.74	0.14	124.8	<0.0001	1,44	1.37 ± 0.06	1.10 ± 0.10
T = 1	Impatiens	Visual	0.81	0.11	185.7	<0.0001	1,44	1.83 ± 0.07	0.80 ± 0.06
T = 2	Impatiens	Visual	0.70	0.14	102.7	<0.0001	1,43	2.05 ± 0.10	0.64 ± 0.06
T = 3	Impatiens	Visual	0.64	0.17	73.7	<0.0001	1,42	2.17 ± 0.12	0.54 ± 0.06
T = 4	Impatiens	Visual	0.63	0.18	67.3	<0.0001	1,39	2.34 ± 0.14	0.57 ± 0.07
T = 5	Impatiens	Visual	0.52	0.24	9.7	0.01	1,9	2.52 ± 0.36	0.49 ± 0.16
T = 0	Marigold	Visual	0.67	0.52	85.9	<0.0001	1,43	2.34 ± 0.16	0.95 ± 0.10
T = 1	Marigold	Visual	0.47	0.50	28.9	<0.0001	1,32	2.92 ± 0.26	0.75 ± 0.14
T = 2	Marigold	Visual	0.34	0.33	11.7	0.002	1,23	2.94 ± 0.29	0.51 ± 0.15
T = 3	Marigold	Visual	0.66	0.14	29.7	<0.0001	1,15	3.89 ± 0.33	0.87 ± 0.16
T = 4	Marigold	Visual	0.54	0.17	15.2	0.002	1,13	3.82 ± 0.43	0.77 ± 0.20
T = 5	Marigold	Visual				Insufficient samples			
T = 0	Marigold	Tap	0.84	0.28	255.6	<0.0001	1,49	1.61 ± 0.08	1.07 ± 0.07
T = 1	Marigold	Tap	0.73	0.19	103.0	<0.0001	1,38	2.15 ± 0.09	0.73 ± 0.07
T = 2	Marigold	Tap	0.67	0.20	70.0	<0.0001	1,35	2.51 ± 0.13	0.73 ± 0.09
T = 3	Marigold	Tap	0.54	0.29	38.8	<0.0001	1,33	2.61 ± 0.17	0.62 ± 0.10
T = 4	Marigold	Tap	0.47	0.35	23.6	<0.0001	1,27	2.85 ± 0.24	0.64 ± 0.13
T = 5	Marigold	Tap	0.69	0.10	45.9	<0.0001	1,21	3.07 ± 0.17	0.57 ± 0.08

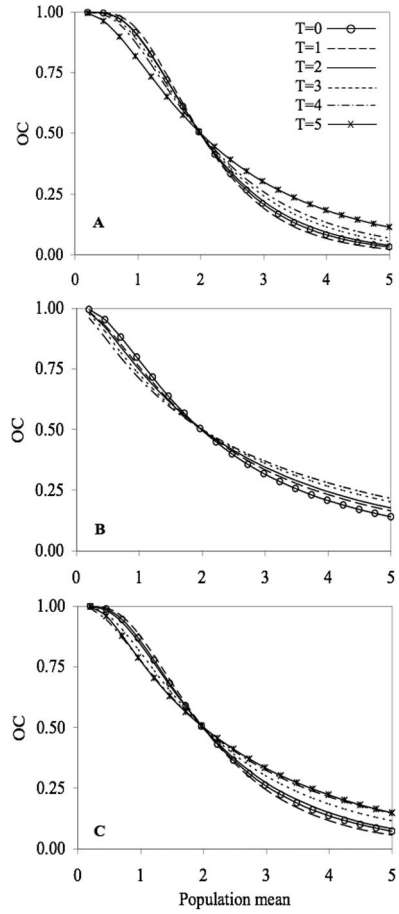

Fig. 4. Operating characteristic functions at tally thresholds (T) raging from 0 to five for greenhouse-based a) visual inspections of impatiens, b) visual inspections of marigold flowers, and c) marigold flower taps.

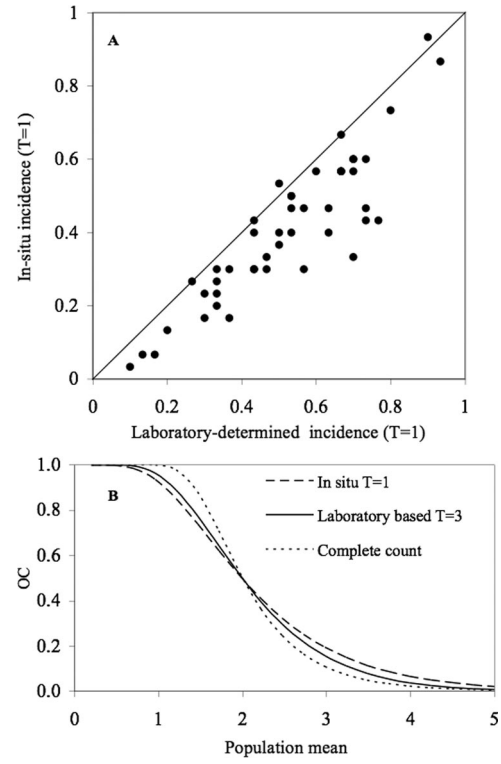

Fig. 5. A) Scatter plot of incidences generated from binomial counts of thrips conducted in situ versus the laboratory, and b) binomial count and complete count operating characteristics of in situ, laboratory-based and complete counts of thrips in impatiens. The diagonal line represents the zero bias line.

marigolds, to evaluate the possibility of using a generic model for sampling thrips. As a first step toward the development of a sampling plan for *F. occidentalis* infesting flowering greenhouses crops, it was first necessary to determine whether or not incidence-mean models precisely described the relationship between the proportion of flowers infested and mean thrips abundance. This relationship was determined for tally thresholds of thrips per flower ranging from >0–5 to determine which tally threshold best described the relationship. All counts of thrips were conducted in the laboratory and we determined that proportions of infested flowers calculated using a tally threshold of three thrips per flower was best for each crop tested as well as for a composite data set, suggesting that a generic sampling plan may be possible for multiple flowering plant species.

Because it is impractical for growers and or scouts to collect flowers and count thrips with the aid of a microscope, it became necessary to develop sampling techniques for use in greenhouses. Given that there are two distinct flower architectures, simple versus composite, we decided to test sampling techniques for both flower types to determine if a single sampling technique could be used across flower types. We discovered that in our complex flower (marigolds) counts of thrips made by visual inspection were not good predictors of mean thrips abundance. Visual inspections were difficult to conduct and immature thrips, which range in color from white to yellow to orange, were exceptionally difficult to discriminate against the marigold flower petals, which range in color from yellow to dark-orange. Additionally, the architecture of marigold flowers is such that the total surface area needing inspection is large and irregular, and immature thrips moved quickly among the achenes, ray and disk flowers adding to the difficulty of quantification. This led to an underestimate of incidence, and when our in situ counts were confirmed in the laboratory, we discovered a large degree of bias in our counts. The OC curve for binomial counts of thrips in marigold flowers as determined via visual inspection was much flatter than flower taps and that of the complete count (laboratory confirmation) OC function. Visual inspections of fully opened, nonsenescent impatiens flowers, while easier than visual inspection of thrips in marigolds, presented a few minor problems; specifically, quantification of first in-

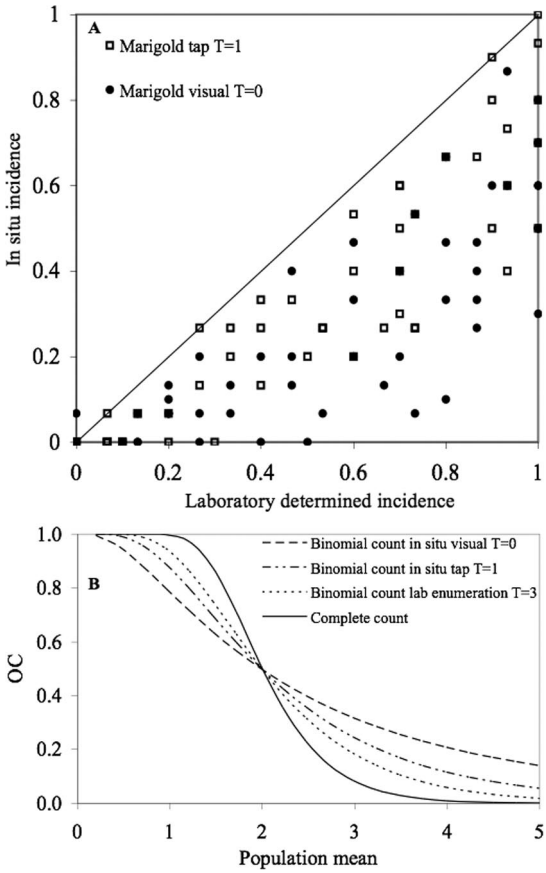

Fig. 6. A) Scatter plot of incidences of in situ binomial counts versus laboratory-based binomial counts of incidence, and b) binomial count operating characteristic functions calculated from visual, tapping and laboratory assessments of thrips per flower and laboratory determined complete count OC functions. The diagonal line represents the zero bias line.

stars. White impatiens were used in this study, and first instars range in color from a translucent white to light yellow making it difficult to detect them on the flower petals. While we did not categorize any of our in situ counts of thrips into groups of adults and immatures, we did split our laboratory-based counts. Generally, immature thrips in crops of both marigolds and impatiens comprised 70–80% of the total population on average across the entire cropping cycle (data not shown), indicating that the largest amount of bias associated with in situ counts occurs in the quantification of immature thrips. Presumably bias could be decreased by improving the training of scouts, and by providing an inexpensive, easy to use OptiVISOR (Donegan Optical Company Inc., Lenexa, KS) or hand lenses, which were not used in this study.

An important criterion of a well-designed sampling plan is practicality and time efficiency (Binns et al. 2000). In this study, samplers were asked to sample 10 marigold flowers, or 30 impatiens flowers using the in situ methods previously described with a stop boundary of six thrips/flower (i.e., stop counting if you reach a tally of six thrips/flower). Time per sample bout was recorded to provide estimates of time per sample. Generally, visual inspection of impatiens flowers was the most time efficient (30 s/flower), followed by marigold flower taps (44 s/flower) and visual inspections of marigolds (1.2 min/flower). Given that 1) marigold flower taps were more effective than visual inspection of marigold flowers, 2) we used a stop boundary of six thrips per flower and 3) that for marigold flower taps and visual inspection of impatiens flowers a tally threshold of $T = 1$ provided the best relationship between incidence of infested flowers and mean thrips abundance, the estimates of time actually required to conduct a sampling bout/time per flower are overestimated as a stop boundary of $T = 1$ has been deemed most appropriate.

One of the limitations of this study is that it is specific for *F. occidentalis*, whereas thrips infestations in greenhouses may be mixed species. While this is true, the spatial aggregation pattern of some of the most common flower thrips species occurring in greenhouses (e.g., *F. tritici* [Fitch]) have been shown to be aggregated within flowers (Salguero Navas et al. 1994). The spatial distribution of an organism as measured by Taylor's power law has been demonstrated to be remarkably robust when the sampling technique/unit is the same across distribution areas (e.g., thrips in flowers, thrips on sticky traps) (Taylor et al. 1998) suggesting that this sampling plan may be useful for additional thrips species, however, this would need to be verified.

When counts of thrips are made with virtually no observer bias, as in laboratory-based counts, binomial count sampling using a composite incidence-mean model provides nearly equal classification precision as compared with making complete counts. In situ counts of thrips from simple flowers were able to produce acceptable classification precision when using binomial count sampling as seen in the nearly identical OC functions for in situ-binomial and complete count data. However, in situ counts of composite flowers lead to an unacceptable level of observer bias, which in turn decreases classification precision resulting in OC functions for binomial count sampling that are likely unacceptable. This problem could be remedied by the development of in situ thrips sampling procedures that minimizes observer bias. Additionally, given that the in situ counts of thrips in simple flowers produced acceptable levels of classification precision, it may be possible to use these counts to estimate the level of thrips infestation within a greenhouse, including complex flowers. However, a suitable indicator plant would need to be at least as attractive to thrips as production plants, must be located throughout a greenhouse, and must give true indications of thrips abundance. Given the complicated nature of greenhouse operations, staggered cropping cycles, frequent moving of plants between greenhouses as they require greater spacing, and a host of other factors, this may prove difficult. The alternative to assessing thrips population densities in mixed floral

crops that include both simple and complex flowers is to use the current industry standard, sticky cards.

Acknowledgments

This research was funded in part through a Specific Cooperative Agreement between the USDA-ARS Biological Integrated Pest Management Research Unit and the Cornell University Department of Entomology, Ithaca, NY (Specific Cooperative Agreement 58-1907-4-447) funded by the USDA-ARS, as part of the Floriculture and Nursery Research Initiative.

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Received 9 April 2010; accepted 11 January 2011.