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Application of Taylor's Power Law to Sample Statistics of *Tylenchulus semipenetrans* in Florida Citrus[1]

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Abstract: Taylor's Power Law was fit to *Tylenchulus semipenetrans* population data obtained from individual trees in a survey of 50 Florida citrus orchards (geographic survey) and to data from individual trees within a single orchard collected at regular intervals for 2 years (temporal survey). No significant differences were detected between slope or intercept values when log variance was regressed against log mean for the geographic and temporal data sets. The geographic survey was divided into two subsets of data according to the perceived size of patches of *T. semipenetrans.* Subsets consisted of orchards which appeared to have numerous small patches of trees infected by the nematode (small patch) and orchards in which most of the trees were infected (large patch). The slope value for the orchards with smaller patches of nematodes was different ($P \leq 0.05$) from that from large-patch orchards. Assuming mean nematode levels of 1,000 juveniles and males/100cm^3 soil, sample sizes (predicted standard error to mean ratio = 0.20) estimated from the relationships of variances to means were 12 trees in the geographic survey and 11 trees in the temporal. Omission of the small-patch data from the geographic survey resulted in a 17% reduction in optimum sample size. Sample size in sporadically infested orchards was estimated to be 69 trees. A data transformation of $x^{0.23}$ was calculated from parameters of Taylor's Power Law fit to the survey data.

Key words: citrus, citrus nematode, population distribution, sampling, Taylor's Power Law, *Tylenchulus semipenetrans.*

Practical applications of the relationship of sample variance to the mean according to Taylor's Power Law (8)

$$\text{variance} = a(\text{mean}^b) \qquad (i)$$

where a is a coefficient affected primarily by sample-size and habitat and b is a species-specific aggregation index, include sample size optimization and derivation of appropriate normalizing transformations (1,3,5,6,9). The Power Law was used to estimate optimum sample size for *Tylenchulus semipenetrans* Cobb in Florida citrus (unpubl.). A significant portion of the deviation of the log of the variance regressed against the log of the mean population counts in that study was found to result from differences between orchards rather than from sample error. Identification of orchard characteristics that influence variance to mean relationships may help define sampling requirements in different situations.

Differences in patch size of *T. semipenetrans* can effect the relationship of the sample variance to the mean, which is particularly evident when variable edaphic or environmental factors effect the nematode carrying capacity of the soil and root. Orchards with low carrying capacities in which all trees are infected by nematodes may have mean population levels similar to orchards with high carrying capacities, but in which fewer trees or smaller groups of trees are infected. The variance to mean ratio of the former orchards would be smaller than those of the latter. Patchily distributed *T. semipenetrans* populations in citrus orchards may result from occasional introductions on contaminated equipment or, if rootstock certification is not employed, when infected trees are used to replace dead or unthrifty trees in uninfested orchards.

This paper considers *T. semipenetrans* sample optimization based on two surveys measuring *T. semipenetrans* population levels in both space and time. A geographic survey measured *T. semipenetrans* population densities in a number of orchards throughout the state during a single sum-

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mer season. The second survey was temporal; population densities were measured in a single orchard at regular intervals for 2 years. The population patch size within orchards is considered as a means to categorize data to improve sample optimization. The suitability of Taylor's Power Law for transformation of data before parametric statistical analysis was also investigated (9).

MATERIALS AND METHODS

In the geographic survey, 10 orchards in five major citrus producing counties in Florida were sampled between June and September 1983 for soil and root stages of *T. semipenetrans.* An 8-ha area was delimited in each orchard and 20 trees were randomly selected for sampling. Samples consisted of soil and roots collected from eight locations around the inner circumference of the dripline of each tree. A shovel was used to obtain soil and roots from a depth of 15–30 cm. The eight samples were combined and mixed, and a 1-liter subsample was analyzed. Second-stage juveniles (J2) and males of the nematode were separated from soil by decanting, density-flotation, and J2 and males hatching from eggs within egg masses on the root samples were obtained by incubation (10). Populations obtained from soil and roots were enumerated separately. Orchards contained mature trees but differed with respect to tree age, scion-rootstock combinations, edaphic conditions, and management practices.

In the temporal survey, samples were obtained from beneath 80 orange (*Citrus sinensis* (L.) Osbeck cv. Valencia) trees growing on sour orange (*Citrus aurantium* L.) rootstock in a bedded, flood-irrigated orchard near Fort Pierce. The orchard was 38 years old when the survey was initiated in July 1985. Trees were sampled at monthly intervals during the first year of the survey and at approximately bimonthly intervals thereafter. Sixteen soil cores (2.3 cm d × 30 cm deep) systematically obtained from a circular, 40.7-m^2 area beneath each tree were composited into a single sample on each sample date. Each sample was mixed, and a 60-cm^3 subsample was processed on a Baermann funnel for 48 hours to recover J2 and male nematodes in the soil.

The mean and variance of nematode counts from soil samples from trees within each orchard in the geographic survey were natural-log transformed. The same transformation was performed on the mean and variance of the counts from the 80 trees for each sample date in the temporal survey. Log variance was regressed against log mean to determine coefficients for Taylor's Power Law according to each survey (8).

The Power Law was also fit to two subsets of data from orchards in the geographic survey. The first subset consisted of data from 19 orchards in which *T. semipenetrans* were detected on 65% or fewer of the trees based on counts from both root and soil samples. The 16 orchards in the second subset of data had detectable nematode populations on at least 90% of the sample trees. It was assumed that the size of nematode patches, or areas with contiguous infected trees, was smaller in the first than the second data subset. Six infested orchards could not be assigned to the above subsets and were not included in the subset analyses. Slope and intercept values from the regression lines were compared with *t*-tests (4).

A transformation procedure to normalize data in order to perform parametric statistics (9) was determined for each of the above data sets according to the formula

$$y = x^{(1 - 0.5b)}. \qquad \text{(ii)}$$

Sample data (unpubl.) obtained on 13 dates from five field experiments were transformed according to the results of equation (ii) before analysis of variance. Samples were not from individual trees but from blocks of four contiguous trees and consisted of 16 composited soil subsamples (2.5 × 30 cm). Experiments were chosen based on a priori reasons (reported nematicide efficacy) for predicting the observed ranks of treatment populations. Thus, there was reason to believe that measurements of treatment population differences were real. Ratios of the largest to the smallest treatment variance estimates of untransformed data, log transformed data, and data transformed according to equation (ii) were compared using Wilcox's signed rank test (7). Mean separation by Duncan's multiple-range test was performed using both log transformed data and data transformed according to equation (ii).

RESULTS

The regression lines of log variance on log mean for the two surveys were not significantly different (Table 1). Slopes of regression lines were 1.57 for the geographic survey and 1.50 for the temporal. Both values differed ($P \leq 0.05$) from values which would indicate from equation (ii) that log (slope = 2.0) or square root (slope = 1.0) data transformations are most appropriate to equalize experimental treatment variances (9).

All trees in the temporal survey had detectable nematode populations at every sample date. Nine of the fifty orchards in the geographic survey had no detectable soil stage populations of *T. semipenetrans.* Nearly half of the *T. semipenetrans*-infested orchards in the geographic survey contained trees beneath which no *T. semipenetrans* was detected. Analysis of the geographic survey data according to perceived patch size resulted in regression slope and intercept values of 1.83 and 8.93, respectively, for orchards with apparent small patches of *T. semipenetrans* (Table 1). Because of the small numbers of trees sampled in an 8-ha area, it was not possible to determine in most cases whether these orchards contained randomly infected trees or clumps of infected trees. The slope and intercept values of the regression of log variance on log mean were 1.59 and 6.29, respectively, for orchards with detectable infestations on all or most sample trees. The regression slope through data from small-patch orchards was greater than that from large-patch orchards ($t = 1.71$; df = 31). Mean population level in the large-patch orchards was 21 times greater than that of the small-patch orchards.

TABLE 1. Coefficients (a and b) of Taylor's Power Law for a geographic and a temporal survey of the population distribution of *Tylenchulus semipenetrans* in Florida citrus.

Survey	a	b	n	r^2
Temporal†	13.73	1.50	18	0.85**
Geographic‡ (total)	9.20	1.57	41	0.95**
Geographic (large patch)	6.29	1.59	16	0.89**
Geographic (small patch)	8.93	1.83	19	0.98**

Subsets of orchards in the geographic survey were selected based on estimated differences in patch size of the nematode. Regression lines fit to large-patch and small-patch data are not parallel ($P \leq 0.05$), based on comparison of slope values.

† Eighty samples obtained from a single orchard, 18 times during a 2-year period.

‡ Twenty samples obtained from each of 50 orchards during a single summer season (June–September). *T. semipenetrans* was detected in 41 of the orchards.

An average slope value (1.54) from the temporal survey and the large-patch orchards of the geographic survey was used in equation (ii), resulting in the normalizing transformation

$$y = x^{0.23}. \tag{iii}$$

Use of equation (iii) did not reduce the largest to smallest variance ratios compared to log transformation in one-third of the cases considered (Table 2). Nevertheless, on the average, the variance ratio values from log transformed data were 62% greater than those of data transformed according to equation (iii). Both transformations reduced ($P \leq 0.01$) variance ratios, relative to untransformed data, and results of mean separation techniques were similar regardless of which transformation was used. However, in one experiment, use of $x^{0.23}$ transformation permitted separation of treatment population levels in which differences were statistically nonsignificant when log-transformed data were used (Table 3).

DISCUSSION

The fit of Taylor's Power Law to data from both the geographic and temporal surveys reflects similar distribution of *T.*

TABLE 2. Comparison of F values from Analysis of Variance and of the ratios of the highest treatment variance to the lowest treatment variance from *Tylenchulus semipenetrans* soil population counts and from transformed counts.†

		F value			Variance ratio		
Sample	df	Log x	$x^{0.23}$	Untransformed	Log x	$x^{0.23}$	Untransformed
1	8	3.60	3.23	2.10	4.33	1.41	8.89
2	10	0.26	0.10	0.70	4.36	3.57	2.76
3	10	16.75	15.80	13.01	11.10	15.01	45.30
4	24	1.08	0.94	0.60	6.16	4.29	2.59
5	32	16.12	15.55	7.74	2.28	1.35	26.83
6	32	1.03	1.20	1.61	1.85	1.57	4.29
7	32	5.05	5.24	5.52	1.50	2.04	7.93
8	32	21.10	20.01	10.05	2.00	1.36	23.42
9	32	2.35	2.00	2.72	1.29	1.33	14.85
10	32	9.07	8.21	3.11	4.98	2.46	38.90
11	32	1.00	0.91	0.78	1.22	1.19	5.93
12	34	10.80	18.37	30.92	49.99	10.19	260.19
13	34	12.73	12.83	10.45	3.70	6.35	93.50

Samples were collected from citrus orchards on 13 occasions and were from five different field experiments.

† Transformation calculated from $y = x^{(1-0.5b)}$ where x is the population count and b is the aggregation index from Taylor's Power Law.

semipenetrans, despite differences in sampling procedures and in the size of the areas sampled (Table 1). For example, the variance to mean relationships in the survey data suggest that to achieve a standard error to mean ratio of 0.20 in sampling an orchard with 1,000 nematodes/100 cm³ soil, 11 trees in a 3-ha area (temporal) or 12 trees in an 8-ha area (geographic) should be randomly sampled (3). Because both sampling techniques obtained soil from reasonably large numbers of sites per tree, they probably were comparable in the precision with which individual trees were sampled. However, depth of sample collection differed between the two sampling methods. Roots and soil from 0–15 cm were not sampled in the geographic survey; since root and nematode abundance are often highest in the shallow soil horizon (2), this reduced the population levels measured.

Analysis of the geographic survey data according to perceived patch size supports the likelihood that identification of certain citrus orchard characteristics permits categorization of data sets to achieve more precise sample estimation using the Power Law (6). The regression of log variance on log mean resulted in higher slope and intercept values for orchards that appear to have small patches of *T. semipenetrans* compared with those in which most trees are infected. Estimated sample size for the latter type of orchard at a population level of 1,000 nematodes/100cm³ soil was reduced by 17% to 10 trees when small-patch orchard data were omitted from the analysis. Conversely, sample size for small-patch orchards with similar population densities requires as many as 69 trees to achieve the same level of precision, nearly a sixfold increase in the sample size estimate described

TABLE 3. Differences in mean separation of *Tylenchulus semipenetrans* juveniles and males/100 cm³ soil according to Duncan's multiple range test on transfomred data.†

Number of comparisons of ordered means	LSR‡		Treatment mean	
	(log x)	($x^{0.23}$)	(log x)	($x^{0.23}$)
2	1.34	1.10	4.85 a	3.01 a
3	1.39	1.13	6.45 b	4.30 b
4	1.41	1.15	6.74 b	4.83 bc
5	1.42	1.17	6.95 b	4.91 bc
6	1.42	1.17	7.57 bc	5.51 c
			8.73 c	7.14 d

Data are from experiment in Table 2, sample 12. Treatments consisted of different application methods of an experimental nematicide.

† Transformation calculated from $y = x^{(1-0.5b)}$ where x is the population count and b is the aggregation index from Taylor's Power Law.

‡ Least significant range ($P \leq 0.05$) for ordered means.

from the total data set. For purposes of management decisions, it is necessary to consider only the case of orchards with large patch size, since sampling a small number of trees in an orchard with small patches of the nematode will almost always result in estimates of mean population levels low enough to preclude management.

Identification of other orchard characteristics that result in variance to mean relationships different from those predicted by the present regression equations is feasible and may result in higher sample precision. Orchards with a great deal of edaphic variability are likely to have greater population variance than predicted by the present equations if the different conditions affect nematode carrying capacity. Variance to mean relationships in such orchards may be higher than in orchards with more uniform edaphic conditions and similar carrying capacity, resulting in differences in optimum sample size. Nevertheless, such conditions must be easily identifiable and relatively consistent in their effect on nematode distribution to be useful in a sample program.

Significant seasonal changes in sample size are indicated by the regressions of log variance on log mean. In the temporal survey, late spring population levels in the range of 2,500–3,000 nematodes/100 cm^3 soil declined to levels between 800 and 1,200 during the summer months. Sample size according to the Power Law is reduced by nearly half for the temporal survey when samples are obtained in mid-May rather than in summer or early autumn. Assuming levels of 800 and 2,500 nematodes/100 cm^3 soil in summer and late spring, respectively, and a standard error to mean ratio of 0.20 results in an estimated sample size of 13 trees in the summer, compared with seven trees in late spring.

Use of the Power Law to transform data for parametric statistical analysis produced similar results, for the most part, to log transformations. Regression of log variance on log mean from orchards with small patches of nematodes resulted in a slope that was not different from 2.0 ($P \leq 0.05$) which indicates the appropriateness of log transformation. Slope values from large-patch orchards were less than 2.0 ($P \leq 0.05$) and an $x^{0.23}$ transformation tended to reduce treatment variance relative to log transformation (Table 2). However, while the former transformation may be useful for mean separation in some experiments (Table 3), log transformation resulted in identical statistical interpretation in the majority of experiments analyzed in this study.

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