Sampling Plans for the Psocids *Liposcelis entomophila* and *Liposcelis decolor* (Psocoptera: Liposcelididae) in Steel Bins Containing Wheat

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ABSTRACT Psocids are an emerging problem in grain storage, handling, and processing facilities in the United States. We used data from two steel bins each containing 32.6 metric tonnes of wheat, *Triticum aestivum* L., to develop sampling plans for *Liposcelis entomophila* (Enderlein), *Liposcelis decolor* (Pearman) (both Psocoptera: Liposcelididae), and a mixture of the two species. Taylor's coefficients *a* (a sampling factor) and *b* (an index of aggregation) for these pests were calculated and incorporated into sampling protocols to improve accuracy. The optimal binomial sample sizes for estimating populations of these psocids at densities of <25 psocids per refuge were large; therefore, we recommend the use of numerical sampling within this range of densities. Numerical sampling of *L. entomophila* and *L. decolor* at densities of <25 psocids per refuge should not be too laborious given the low psocid numbers involved; we recommend using 10 refuges per bin. For presence-absence sampling of *L. entomophila* or *L. decolor*, 20 refuges per bin should be used at densities of 25–100 psocids per refuge. The sampling plans we have developed based on the use of cardboard refuges are convenient for use in steel bins containing wheat because they are inexpensive, provide a rapid assessment of psocid population incidence, and are easy to implement. These sampling plans can be used to monitor populations of and the efficacy of management strategies used against *L. entomophila* and *L. decolor*.

KEY WORDS cardboard refuges, presence-absence sampling, numerical sampling, booklice, grain storages

Psocids (Psocoptera) in two genera, *Liposcelis* and *Lepinotus*, have been found in large numbers in grain storages in the United States (Throne et al. 2006; Opit et al. 2009a,b). *Lepinotus reticulatus* Enderlein (Psocoptera: Trogiidae), *Liposcelis entomophila* (Enderlein) (Psocoptera: Liposcelididae), and *Liposcelis decolor* (Pearman) have been found infesting wheat in steel bins in Manhattan, KS (Throne et al. 2006; Opit et al. 2009a,b). Arbogast et al. (2000) reported that 88% of insects captured in stored oats (*Avena* spp.), in north central Florida were *L. entomophila.* Psocids seem to be an increasing problem in stored grain in all parts of the world (Nayak 2006). The rise of psocids to prominence as serious pests can be attributed to the weight losses they cause in grain due to germ and endosperm consumption (McFarlane 1982, Kučerová 2002), varied response to management tactics that have been developed for beetle pests, e.g., some psocid species are resistant to residual insecticides and the fumigant phosphine (Nayak et al. 1998, 2002a,b, 2003; Nayak 2006); frequent failure of standard practices of protection and disinfestation to control psocids (Wang et al. 1999, Beckett and Morton 2003, Nayak et al. 2003, Nayak and Daglish 2007); and that in some countries, such as Australia, commodities infested by psocids can be rejected for export (Kučerová 2002, Nayak 2006). Psocid species known to infest grain in North America (Mockford 1993, Lienhard and Smithers 2002) are *L. reticulatus*, *Liposcelis bostrychophila* Badonnel, *Liposcelis brunnea* Motschulsky, *Liposcelis corrodens* (Heymons), *L. decolor, L. entomophila,* and *Liposcelis paeta* Pearman. Of these, *L. bostrychophila, L. decolor, L. entomophila,* and *L. paeta* are the most important as pests of stored products (Rees 2004). Typically, one to three psocid species at a time are found infesting grain storage facilities in the Midwest.

Despite the growing stored-product psocid problem, neither statistically valid sampling methods nor economic thresholds for these pests have been developed. Current industry practice is to control psocids by using tactics and strategies designed for beetle pests, without regard to population density. However, as already stated, psocid species have varied responses

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to these management tactics, and this problem is compounded because multiple psocid species often infest grain storages simultaneously. Currently, it is difficult to determine timing of control treatments or to assess the effectiveness of control methods targeted at psocids due to lack of sampling plans for estimating psocid density in grain.

Several devices have been used to sample psocids in bulk grain (Roesli and Jones 1994; Arbogast et al. 2000; Rees and Starick 2002; Opit et al. 2009a,b). However, sampling plans for psocids were not developed during these studies; we are not aware of any sampling plans that have been developed for psocids in bulk grain.

A sampling procedure that accurately estimates pest populations in a short period is a vital component of any pest management program (Mollet et al. 1984). To be widely adopted, sampling plans also should be as convenient and economical as possible. It is especially important to develop sampling plans that meet these specifications for pests that are difficult to count directly because they are small and typically occur in large population numbers. Such is the case for *Liposcelis* spp., which are major pests in bulk grain storages (Rees 2004). Sampling for psocids by using cardboard refuges (Rees and Starick 2002, Opit et al. 2009b) is particularly attractive because it would be inexpensive and quick, and numbers of psocids in refuges have been shown to be well correlated with those in grain samples (Opit et al. 2009b).

Presence-absence (binomial) sampling, which involves counting the proportion of infested refuges rather than the actual number of psocids in them (numerical sampling), is a relatively simple approach and therefore an approach that potentially can be easily and widely adopted. Development of a presence-absence sampling plan for any psocid species infesting bulk grain requires identification of the sampling unit (here, a cardboard refuge for the reasons stated above), knowledge of the spatial distribution of psocids among refuges, and the relationship between the proportion of psocid-infested refuges and the mean number of psocids in each grain sampling unit. In 2005 and 2006, we sampled two steel bins containing wheat, *Triticum aestivum* L., for psocids (Opit et al. 2009a,b). Our objectives were to use those data to determine the suitability of numerical and binomial sampling for estimating psocid population levels in steel bins containing wheat and to assess whether sampling plans developed for a single species or multiple species of psocids can be used to estimate population levels of other species or species mixtures. The latter objective was investigated because identification of psocid species is difficult and requires highly trained personnel to separate the species. Therefore, development of sampling plans that could be used for different psocid species and species mixtures would be logical because these would be more practical.

Materials and Methods

Storage Situation. Two steel bins at the Grain Marketing and Production Research Center in Manhattan, KS, were filled in July 2005 with newly harvested hard red winter wheat; the grain was infested by natural psocid populations. Both bins were outdoors, in an open area with no shading and no protection from ambient air currents. Bin dimensions were 4.72 m in diameter by 3.35 m in height at the eaves, and each bin was filled with 32.6 metric tonnes (1,200 bushels) of wheat to a depth of 2.4 m.

Sampling Methods. Sampling methods were as described previously (Opit et al. 2009a,b) and are described in brief here. Biweekly sampling was conducted using 20 corrugated cardboard refuges (8.9 by 12.7 cm), which were randomly placed on the surface of the grain in each bin for 1 wk. Placing refuges on the surface of the grain is practical, and Rees and Starick (2002) used the same method to monitor psocid population levels in open-topped 1,600-tonne concrete bins. Psocids were removed from the refuges by knocking them out of the cardboard into a white enamel pan with Fluon (polytetrafluoroethylene; Northern Products, Woonsocket, RI) applied to its walls to prevent psocids from escaping, and then psocids were identified (Mockford 1993) and counted.

In the 2005 sampling study, the steel bins were sampled from August 2005 through March 2006. In the 2006 study, the wheat was fumigated using phosphine in June 2006 and then reused for sampling from July through November 2006. The only psocid species identified in the bins in 2005 and 2006 were *L. entomophila* and *L. decolor*, respectively. In both years, data from the two bins sampled were used for the development of sampling plans.

Binomial Sampling Models for Individual Species. *Taylor's Power Law.* We used Taylor's power law (Taylor 1961) to determine the variance–mean relationship for *L. entomophila* in refuges. This model is described by the equation $S^2 = am^b$, where S^2 is variance; m is mean; and a and b are coefficients, where a is a sampling factor and b is an index of aggregation. The parameters a and b are calculated by regressing the natural logs (ln) of S^2 against ln of m. The values a and b are the antilog of the y-intercept and slope of the linear regression line, respectively. The variance–mean relationship can be incorporated into both numerical and binomial sampling protocols to improve accuracy by taking into account the degree of aggregation (Wilson and Morton 1993).

Equation 1, a binomial model developed by Wilson and Room (1983), shows the relationship between the proportion of pest-infested sampling units (PI) and the mean number of pests per sampling unit (m). It uses the variance–mean relationship that incorporates Taylor's equation (Taylor 1961).

$$PI = 1 - \exp(-m \ln(am^{b-1})/(am^{b-1} - 1)) \quad [1]$$

In a simplified form, this equation can be expressed as follows:

$$\ln(1 - PI) = -m \ln(am^{b-1})/(am^{b-1} - 1) \quad [2]$$

Building the binomial model requires computing the variables m, S^2, and PI from the data for a group of refuges taken from a single steel bin containing wheat on a given sampling date.

Calculating a and b of Taylor's Power Law. Data from each sampling date where at least one psocid was found in the refuges were used to compute values of m and S^2. The natural logs (ln) of all values of m and S^2 were determined, and a linear regression of $\ln(S^2)$ against $\ln(m)$ was performed using TableCurve 2D (Systat Software Inc. 1996) to check whether Taylor's law described the spatial distribution of *L. entomophila* and to calculate the coefficients a and b of Taylor's power law.

Validation of the Binomial Model. The calculated values of a and b were used in the binomial model (equations 1 and 2). However, it is important to check whether the binomial model accurately describes the relationship between m and PI for *L. entomophila* sampled using cardboard refuges. Therefore, the fit of the binomial model was evaluated by regressing the right-hand side of equation 2 against the left-hand side. Tally thresholds of 0, 5, 10, 15, and 20 *L. entomophila* per refuge were tested to determine which threshold resulted in the best fit. For example, if a tally threshold is 5, then at least six individuals must be found in a sampling unit to classify the sampling unit as infested (Jones 1993). Considering zero psocids in a refuge as an absence may result in the model failing to adequately describe the relationship between proportion of infested refuges and mean number of psocids per refuge. Thus, tally thresholds of 5, 10, 15, and 20 were included to determine whether they would produce a better description of the relationship. If the model fits well, then the intercept should be zero and the slope equal to 1. A comparison was made among the five tally thresholds to determine the one with the highest coefficient of determination (R^2) when the right-hand side was regressed against the left-hand side. For the one with the highest R^2, we determined whether the intercept and slope of the regression line were 0 and 1, respectively, by using a two tailed t-test. If both these parameters did not differ from 0 and 1, respectively, then the binomial model could be used without modification (Wilson and Morton 1993, Opit et al. 2003, Alatawi et al. 2005). However, if this was not the case, and one or both of these parameters was or were, different, then the binomial model would need to be modified. The modification was done by incorporating the regression intercept, slope, or both into the model.

Optimal Sample Size. *Numerical Sample Size.* Optimal sample size, n, can be defined as the number of sample units that provides a population density estimate with a specified level of precision (Wilson et al. 1983). Optimal numerical sample size is represented by equation 3 (Karandinos 1976, Ruesink and Kogan 1982):

$$n = Z_{\alpha/2}\, D^{-2}\, a\, m^{b-2} \quad [3]$$

where n is sample size, $Z_{a/2}$ is the is the upper $a/2$ of the standard normal distribution; m is mean; D is a proportion of m (D is a level of precision), where m is expressed in terms of the number of *L. entomophila* found in refuges; and a and b are Taylor coefficients.

During this study and a previous study by Throne et al. (2006), 20 cardboard refuges were placed on the surface of wheat in steel bins to get a general idea about psocid population growth trends and abundance. However, we were interested in determining the effect of using a smaller sample size that would reduce the effort and time spent counting psocids. Numerical sample sizes obtained from the current study suggested that a sample size of 10 refuges would be adequate. Therefore, we compared the effect of using sample sizes of 10 and 20 refuges for estimating psocid population means by comparing the widths of the 95% confidence intervals of the mean for the two scenerios by using *L. entomophila* data from the 2004 study (Throne et al. 2006). As in the current study, data sets in the Throne et al. (2006) study consisted of data from 20 refuges taken from a single bin on a given sampling date. Confidence intervals were obtained for each mean by sampling with replacement to randomly select 10 or 20 values and then computing the mean of these values (Blank et al. 2001). This procedure was iterated 200 times, and the means were arranged in ascending order (Blank et al. 2001). The fifth and 195th values represented the lower and upper bounds of the 95% confidence interval, respectively.

Binomial Sample Size. Equation 3 is inappropriate when using presence-absence sampling but can be changed into a usable form as shown in equation 4 (Karandinos 1976, Gutierrez 1996):

$$n = Z_{a/2}\, D^{-2}\, p^{-1}\, q \quad [4]$$

where p is the proportion of the sampling units infested, q is the proportion not infested, $D = CI/2p$ is the level of precision, and CI is the width of the confidence interval.

To obtain binomial sample size curves for *L. entomophila,* upper and lower bounds of the CI were computed for each value of m using $D = CI/2m$ (as in equation 3). Subsequently, the PI values were determined for both the upper and lower CI by using equation 1 (Nowierski and Gutierrez 1986). A presence-absence sampling plan for estimating *L. decolor* populations in steel bins containing wheat was developed using protocols described for *L. entomophila* described above.

A Binomial Sampling Model for a Mixture of *L. entomophila* and *L. decolor*. Using only July through November data for 2005 and 2006 and protocols described for *L. entomophila* describe above, a presence-absence sampling plan for estimating psocid populations in a mixed infestation of *L. entomophila* and *L. decolor,* in steel bins containing wheat, was developed. This was done because it is common that more than one species of *Liposcelis* is found infesting grain storages. Only data for July through November were used because this is the period sampling was done in 2006, and we wanted to ensure that data used for developing the binomial sampling plan was from the same period of each year. This is also the normal storage period for wheat in the United States.

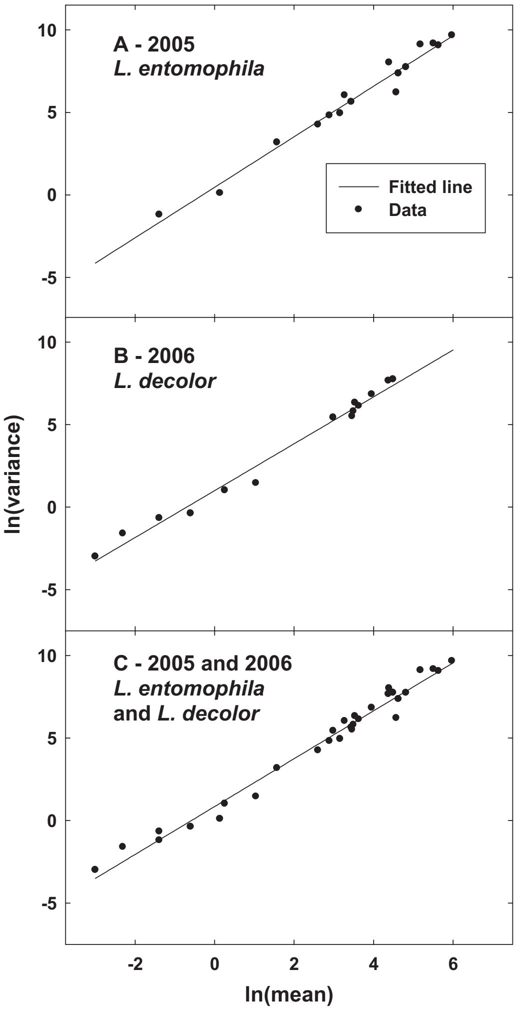

Fig. 1. Relationship between the variance and the mean in (A) 2005, (B) 2006, and (C) 2005 and 2006.

We checked how well the modified binomial models for *L. entomophila*, *L. decolor*, and a mixture of the two species predicted the mean numbers of *L. entomophila* in refuges by using data from a separate sampling study conducted in steel bins containing wheat in 2004 (Throne et al. 2006). Using 2005 and 2006 data, we also tested how well the binomial model for *L. entomophila* predicted the mean numbers of *L. decolor* in refuges, and vice versa. In each case, the proportion of refuges infested was calculated based on data sets of 20 refuges that were taken from a single bin on a given sampling date, and a tally threshold of 15 was used. Only data where the density of psocids was >25 per refuge were used because sample sizes involved were smaller and therefore more practical. Statistical Analysis System software (SAS Institute 2001) was used to conduct chi-square tests to determine whether observed and predicted means differed ($\alpha = 0.05$).

Table 1. Parameters for the linear equation y = a + bx, where y is the ln(variance) and x is ln(mean)

Species (yr)	y-intercept (SE, *t*-value)	Slope (SE, *t*-value)	*N*	R^2
L. entomophila (2005)	0.46 (0.27, 1.7)	1.53 (0.07, 22.7)	16	0.97
L. decolor (2006)	1.00 (0.15, 6.52)	1.42 (0.05, 28.1)	14	0.99
L. entomophila (2005) and *L. decolor* (2006)	0.85 (0.14, 6.0)	1.45 (0.04, 37.1)	30	0.98

In all *t*-tests for y-intercepts and slopes, $P < 0.001$, except *t*-test for y-intercept for *L. entomophila* (2005), $P = 0.113$.

Results

Binomial Sampling Models. The relationship between the mean number of psocids per refuge and the variance, predicted by Taylor's power law, was significant ($P < 0.01$) in all cases: for *L. entomophila*, *L. decolor*, and a mixture of the two species (Fig. 1; Table 1). In all cases, the slope was significantly >1, suggesting that the psocid populations have an aggregated distribution. The high R^2 values of the regressions (Table 1) indicate that the distribution of psocids in all cases is well described by Taylor's power law and that the variance–mean relationship can be incorporated into a sampling protocol in each case to improve accuracy by taking into account the aggregated distribution of the psocids.

The slope of the regression line in each case (Table 1) is equal to the coefficient *b*, and the antilog of the *y*-intercept is equal to the coefficient *a*. Therefore, the values of *a* for *L. entomophila*, *L. decolor*, and a mixture of the two species were 1.58, 2.72, and 2.34, respectively.

Validation of the Binomial Model. Among tally thresholds of 0, 5, 10, 15, and 20, tally thresholds of 15 and 20, 15 and 20, and 10, 15, and 20 resulted in the highest R^2 values for *L. entomophila*, *L. decolor*, and a mixture of the two, respectively (Table 2). A tally

Table 2. Parameters for the linear equation y = a + bx, where y and x are the right- and left-hand side, respectively, of the simplified binomial model

Species (yr)	Tally threshold	R^2	y-intercept (SE, *t*-value)	Slope (SE, *t*-value)
L. entomophila (2005)	0	0.35		
	10	0.70		
	15	0.75	−2.04 (2.46, −0.8)	4.79 (0.75, 6.4)
	20	0.74		
L. decolor (2006)	0	0.76		
	5	0.78		
	10	0.85		
	15	0.96	−0.44 (0.42, −1.1)	5.23 (0.31, 17.1)
	20	0.94		
L. entomophila (2005) and *L. decolor* (2006)	0	0.36		
	5	0.53		
	10	0.74		
	15	0.79	−0.96 (1.28, −0.8)	5.13 (0.5, 10.3)
	20	0.79		

In all regressions, $P < 0.02$. In all *t*-tests for y-intercepts, $P > 0.1$; except for a tally threshold of 20, for *L. entomophila* and *L. decolor*, $P = 0.03$. Degrees of freedom for *L. entomophila* (2005), *L. decolor* (2006), and a combination of the two species (2005 and 2006) were 1, 14; 1, 12; and 1, 28, respectively.

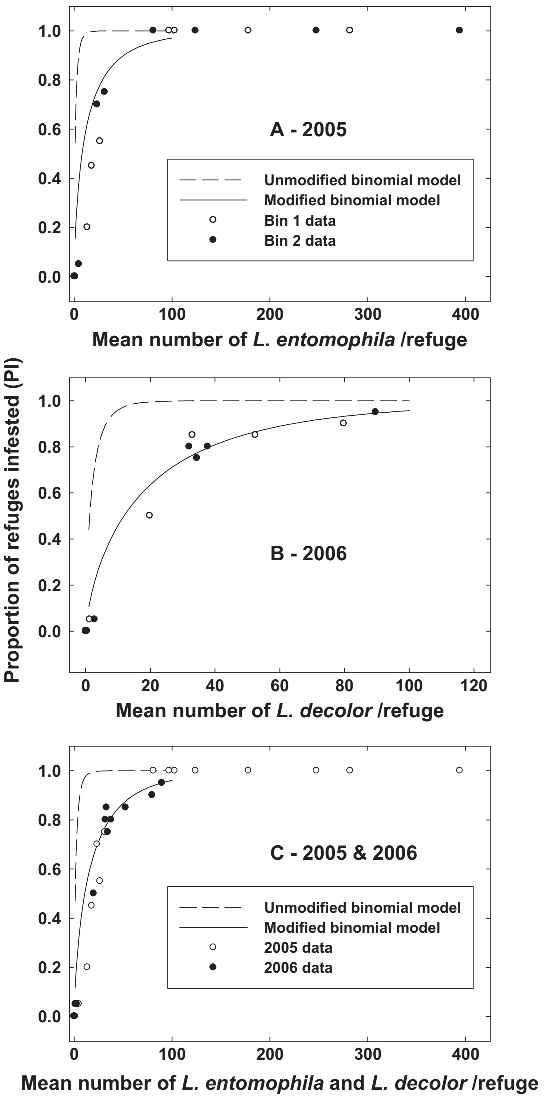

Fig. 2. Relationship between mean number of psocids per refuge and the proportion of refuges infested with psocids in (A) 2005, (B) 2006, and (C) 2005 and 2006.

threshold of 15 was chosen for the development of a binomial model in each case. For each species and a mixture of the species, the intercepts were not significantly different from 0, but the slopes were significantly different from 1, indicating that the model (equation 1 could be improved by incorporation of the regression slope). For *L. entomophila,* the modified equation is (Fig. 2A) as follows:

$$4.79 \ln(1 - PI) = -m \ln(1.58m^{0.53}) / (1.58m^{0.53} - 1) \quad [5]$$

which can be rewritten as equation 6:

$$PI = 1 - 2.72 \exp\{(-m \ln(1.58m^{0.53}) / (1.58m^{0.53} - 1)) / 4.79\} \quad [6]$$

For *L. decolor,* the modified equation is (Fig. 2B) as follows:

$$5.23 \ln(1 - PI) = -m \ln(2.72m^{0.42}) / (2.72m^{0.42} - 1) \quad [7]$$

which can be rewritten as equation 8:

$$PI = 1 - 2.72 \exp\{(-m \ln(2.72m^{0.42}) / (2.72m^{0.42} - 1)) / 5.23\} \quad [8]$$

For a mixture of the species, the modified equation is (Fig. 2C) as follows:

$$5.13 \ln(1 - PI) = m \ln(2.34m^{0.45}) / (2.34m^{0.45} - 1) \quad [9]$$

which can be rewritten as equation 10:

$$PI = 1 - 2.72 \exp\{(-m \ln(2.34m^{0.45}) / (2.34m^{0.45} - 1)) / 5.13\} \quad [10]$$

In each case, a visual comparison of the plots shows that the modified binomial model describes the relationship between m and PI better than the unmodified binomial model (Fig. 2).

The mean numbers of *L. entomophila* in refuges in 2004 were accurately predicted using the *L. entomophila* binomial model developed from 2005 data ($\chi^2 = 8.02$, df = 6, $P = 0.24$; Fig. 3A) but not by the *L. decolor* binomial model developed from 2006 data ($\chi^2 = 22.1$, df = 6, $P = 0.001$; Fig. 3B) nor the *L. entomophila* and *L. decolor* binomial model developed from 2005 and 2006 data ($\chi^2 = 16.9$, df = 6, $P = 0.01$; Fig. 3C). The binomial model for *L. entomophila* (developed from 2005 data) incorrectly estimated the mean numbers of *L. decolor* in refuges in 2006 ($\chi^2 = 15.0$, df = 7, $P = 0.04$; Fig. 4A); the converse also produced the same result ($\chi^2 = 22.9$, df = 3, $P < 0.001$; Fig. 4B).

Optimal Sample Size. Optimal numerical sample sizes required for the estimation of *L. entomophila, L. decolor,* and a mixture of *L. entomophila* and *L. decolor* population levels are smaller than the required binomial sample sizes (Figs. 5–7; Table 3). The number of refuges required for the estimation of *L. entomophila, L. decolor,* and a mixture of *L. entomophila* and *L. decolor* at densities of <25psocids per refuge using binomial sampling ($D = 0.5$) are >66, 91, and 83, respectively (Table 3). Sample sizes required for the estimation of the same psocid levels by using numerical sampling are <12, 21, and 18, respectively (Table 3)—psocid numbers usually increase rapidly once grain gets infested and mean densities of one to two psocids per refuge are rare. At densities of ≥25 psocids per refuge, only three refuges could be used for estimating psocid numbers in each case, by using numerical sampling. Compared with using a sample size of 20 refuges for estimating psocid levels using numerical sampling, a sample size of 10 increased the width of the 95% confidence interval of the mean by 29.9 ± 4.6% (SE) and 41.0 ± 3.7% for means <25 and >25, respectively. Using a sample size of three for estimating

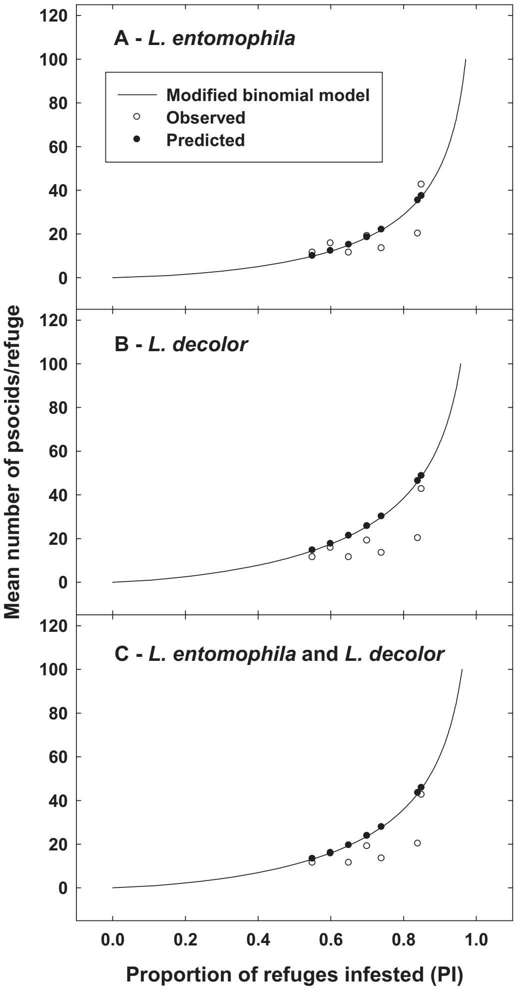

Fig. 3. Using modified binomial models developed from (A) 2005, (B) 2006, and (C) 2005 and 2006 data to predict densities of *L. entomophila* from 2004 data.

means >25 increased the width of the 95% confidence interval by 142.1 ± 7.7%.

Information on seasonal fluctuation of psocid densities in refuges and the effects of abiotic conditions on temporospatial distribution of psocids in grain during this study are reported in Opit et al. (2009a), and correlations between psocid densities in refuges and grain samples are reported in Opit et al. (2009b).

Discussion

Both *L. entomophila* and *L. decolor* may have a clumped population distribution. The binomial and numerical sampling plans we developed showed that for both *L. entomophila* and *L. decolor*, optimal numerical sample sizes required for the estimation of their population levels are smaller than the required presence-absence sample sizes. Using presence-absence sampling ($D = 0.5$), the number of refuges required for the estimation of *L. entomophila, L. de-*

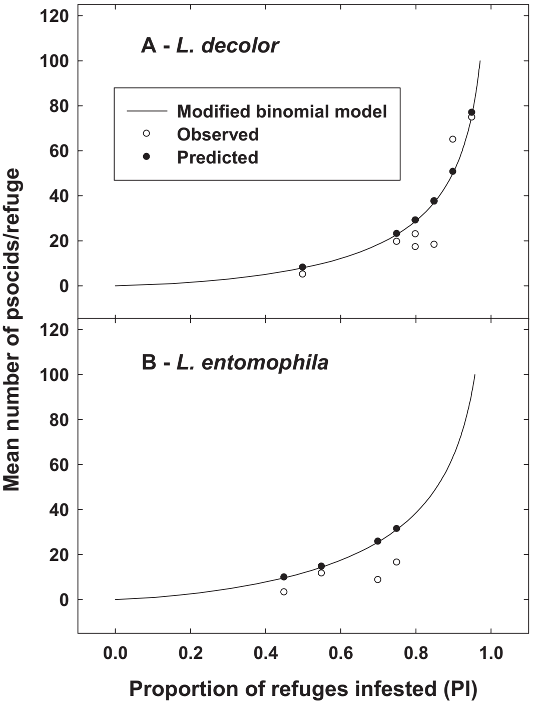

Fig. 4. Using modified binomial models developed using (A) 2005 *L. entomophila* data to predict densities of *L. decolor* from 2006 data and (B) 2006 *L. decolor* data to predict densities of *L. entomophila* from 2005 data.

color, and a mixture of *L. entomophila* and *L. decolor* at densities of <25 psocids per refuge by using binomial sampling are >66, 91, and 83, respectively (Table 3). Sample sizes required for the estimation of these psocid densities by using numerical sampling are <12, 21, and 18, respectively. The presence-absence sample sizes required for estimating mean densities of *L. entomophila, L. decolor,* and a mixture of the two species at densities of <25 per refuge may not be practical. Therefore, numerical sampling should be used for densities of <25 per refuge. Psocid numbers increase rapidly once grain gets infested and mean densities of one to two psocids per refuge are rare; therefore, 10 refuges per bin could be used for numerical sampling at densities of <25 per refuge. Sampling using 10 refuges, for densities <25 per refuge, increases the width of the 95% confidence interval of the mean by 29.9 ± 4.6% (SE) compared with using 20 refuges. For the purpose of quickly getting a general idea of psocid population growth trends and abundance, this tradeoff between accuracy and sample size (time spent counting) is justified. According to our numerical sample size models, densities of ≥25 psocids per refuge can be estimated using only three refuges, but this would increase the width of the 95% interval of the mean by 142.1 ± 7.7%; however, using a sample size of 10 would increase the width of the confidence interval by 41.0 ± 3.7%.

Sample sizes for the estimation of psocid levels at densities of >25 psocids per refuge using presence-

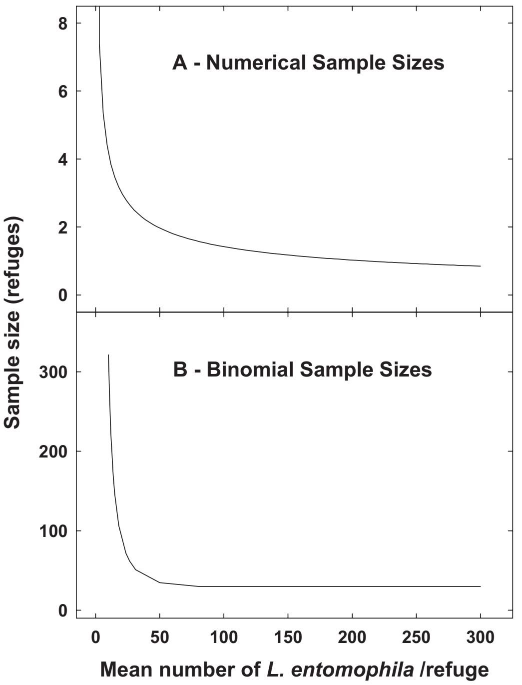

Fig. 5. Optimal (A) numerical and (B) binomial sample sizes for *L. entomophila* (2005); $D = 0.5$ and $\alpha = 0.05$ in both cases.

absence sampling are not too large. Therefore, binomial sampling can be used to estimate psocid populations at these levels. We were able to accurately estimate the mean number of *L. entomophila* in refuges in 2004 by using the *L. entomophila* presence-absence model developed using 2005 data (*L. entomophila* data). The models for *L. decolor* (developed using 2006 data) and a mixture of the two species (developed using 2005 and 2006 data) failed to accurately estimate numbers of *L. entomophila* in refuges in the 2004 data. Using the 2005 *L. entomophila* data and 2006 *L. decolor* data, we found that using the presence-absence model for *L. ento-*

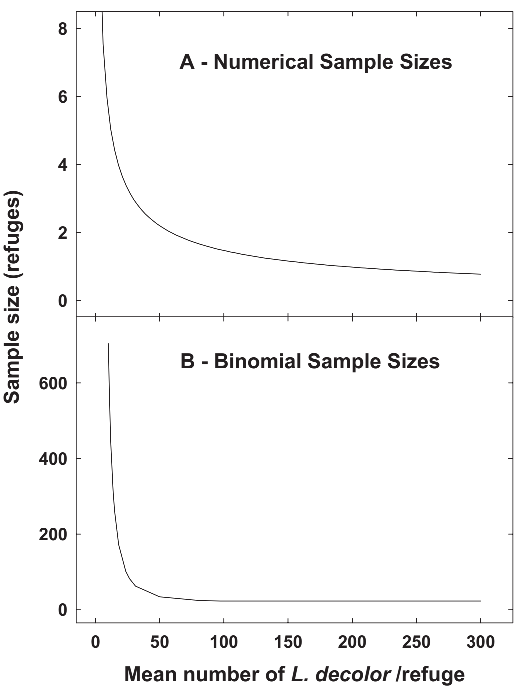

Fig. 6. Optimal (A) numerical and (B) binomial sample sizes for *L. decolor* (2006); $D = 0.5$ and $\alpha = 0.05$ in both cases.

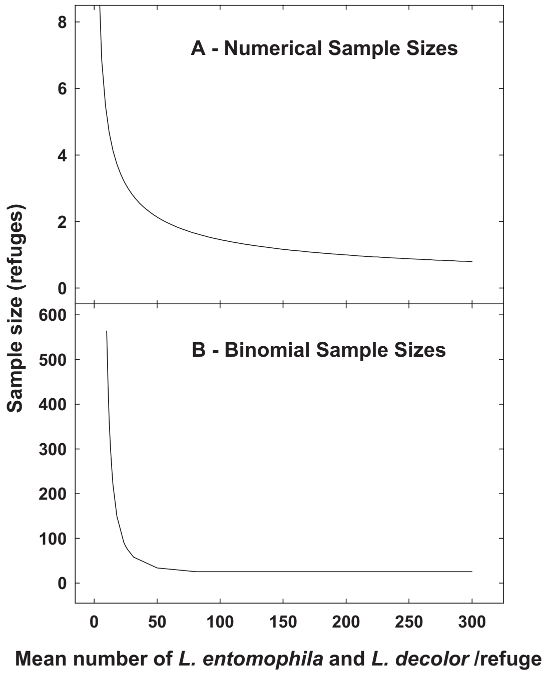

Fig. 7. Optimal (A) numerical and (B) binomial sample sizes for *L. entomophila* and *L. decolor* (2005 and 2006); $D = 0.5$ and $\alpha = 0.05$ in both cases.

Table 3. Optimal numerical and binomial sample sizes for estimating mean numbers of psocids

Species (yr)	Mean	Numerical sample size	Binomial sample size	Binomial sample size[a]
L. entomophila (2005)	1	12		
	10	4	321	98
	15	4	146	42
	25	3	66	17
	50	2	34	7
L. decolor (2006)	1	21		
	10	6	704	232
	15	4	261	82
	25	3	91	26
	50	2	34	8
L. entomophila (2005) and *L. decolor* (2006)	1	18		
	10	5	563	183
	15	4	220	68
	25	3	83	23
	50	2	34	7

[a] Binomial sample sizes estimated using $D = 0.8$; the rest were estimated using $D = 0.5$.

mophila to estimate the mean numbers of *L. decolor* does not give accurate estimates of *L. decolor* population levels; the converse also gave the same result. These results seem to suggest that presence-absence models developed for one psocid species may be good for estimating the population levels of that species alone and not other species or a mixture of species. Research needs to be conducted to investigate whether in a mixed infestation where one species is numerically dominant, sampling plans developed for the predominant species could be used to estimate population levels of the mixture of species. If this were found to be the case, it would eliminate the need for sampling plans for individual species.

If the purpose of presence-absence sampling is to get a general idea about psocid population growth trends and abundance, sample sizes required for the estimation of population levels could be reduced by lowering the level of precision to $D = 0.8$ (Table 3). If this lower level of precision is used, we recommend that 20 refuges per bin be used for presence-absence sampling at densities of 25–100 psocids per refuge. At psocid densities >100 per refuge, the proportion of refuges infested equals 1, and the estimation of population levels becomes difficult.

Hagstrum et al. (1985), also found that the number of sampling units (0.5-kg samples) required for detection or estimation of stored-product insects in wheat stored in steel bins was inversely related to insect density. They found the number of samples required for estimating mean total insect levels by using numerical and presence-absence sampling, for insect densities of 0.001–10 per 0.5-kg samples, were 186–20 and 2,997–1, respectively. Ignoring the type of sampling unit and insect species involved, numerical and presence-absence sample sizes for estimating insect population levels in the current study were smaller and larger, respectively, than in the Hagstrum et al. (1985) study.

The numerical and presence-absence sampling plans we developed for evaluating *L. entomophila* and *L. decolor* in steel bins containing wheat are a quantitative measure of psocid density. When economic thresholds for the control of *L. entomophila* and *L. decolor* are developed, they will be based on numbers of psocids of these species per kg of grain. Therefore, for wheat stored in steel bins, it will then be possible to use such thresholds because the mean number of *L. entomophila* and *L. decolor* can be estimated by counting the number of psocids in refuges or using the proportion of infested refuges. The sampling plans we have developed based on the use of cardboard refuges are convenient for use in steel bins containing wheat because they are inexpensive, provide a rapid assessment of psocid population incidence, and are easy to implement. These sampling plans can be used to monitor populations, time psocid management, and assess the efficacy of management strategies used against *L. entomophila* and *L. decolor*.

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