Economic Injury Levels and Sequential Sampling Plans for Mexican Bean Beetle (Coleoptera: Coccinellidae) on Dry Beans

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ABSTRACT Field studies were conducted during the growing seasons of 1995 and 1996, in Scottsbluff, Nebraska, to determine yield-loss relationships for Mexican bean beetle (*Epilachna varivestis* Mulsant) on dry bean (*Phaseolus vulgaris* L.). Results of those experiments were combined with data from other studies previously conducted to develop economic injury levels (EILs), economic thresholds (ETs), and a sequential sampling program for Mexican bean beetle. Yield loss was regressed against larvae/row-m, and the slope of the linear regression (113 kg/ha per larvae/row-m) was used as the DI (yield loss/insect density) variable in EIL calculations. The EILs calculated in larvae/row-m were converted to egg masses/row-m and adjusted to reflect average survivorship to the adult stage. An example EIL for esfenvalerate at 0.509 (formulation) liter/ha (0.0453 gal/a) and crop value of \$0.44/kg (\$20/100 lbs) was 17.78 larvae/row-m. The corresponding ET is 1.04 egg masses/row-m, which reflects an average of 54.6 eggs/egg mass and 33% survival rate from egg to injurious stages. Sequential sampling plans were calculated based on a negative binomial distribution using parameter *k* estimated from previous research. Because sampling is based on egg masses, growers can make management decisions and take management actions before significant injury occurs. Also, ETs can be adjusted to include the occurrence of natural mortality in the egg and early instars. Analyses demonstrated that relatively minor variation in ETs has substantial impact on sequential sampling plans, including parameters such as average sample number. An interactive spreadsheet was developed that allows users to input economic and other data specific to their situation to calculate Mexican bean beetle EILs, ETs, and sequential sampling plans.

KEY WORDS *Epilachna varivestis*, *Phaseolus vulgaris*, economic threshold, EIL

THE MEXICAN BEAN BEETLE, *Epilachna varivestis* Mulsant, is an important pest of dry bean, *Phaseolus vulgaris* L., in many production areas of the United States. In western Nebraska, Mexican bean beetle is the most important dry bean insect pest (Hagen 1986). Adults overwinter in and nearby dry bean fields in which larvae developed. After ≈12 d of feeding, overwintered females begin to oviposit, and clusters of 40–60 orange colored eggs are laid on the undersides of the leaves (Bernard and Shepard 1978). Both larvae and adults feed primarily on the undersides of the leaves, removing the epidermal layer and skeletonizing the foliage. Severely injured leaves dry up and drop from the plant (Douglass 1933).

Although the Mexican bean beetle is the primary defoliator of dry beans in the midwestern United States, relatively little is known about how defoliation affects yield of dry beans. Generally, defoliation in vegetative stages of dry bean does not result in significant yield loss, unless the level of defoliation is extreme. Dry bean is more sensitive to defoliation at the flowering and pod fill stages, and yield loss can occur when defoliation exceeds 20% (Fan et al. 1993). Schaafsma and Ablett (1994) found significant yield reduction during the vegetative stages only at defoliation levels above 83%; at flowering and pod fill stages, significant yield reductions were observed when defoliation levels passed 33%. Fan et al. (1993) observed significant yield loss with 28% defoliation at the preflowering stage.

The relationship between defoliation and Mexican bean beetle population density has not been established, so data relating defoliation to yield loss are of limited value in establishing economic injury levels (EILs). Some workers have related larval densities to dry bean yield, but results from these studies are greatly variable. Kabissa and Fronk (1986) observed that 10 larvae per plant did not result in significant yield loss in dry bean. Capinera et al. (1987) indicated that dry beans can tolerate a population of 12–20 Mexican bean beetle larvae per plant without significant yield loss. In contrast, an economic threshold was established by Michels and Burkhardt (1981) at 1–1.5 larvae per plant. Variation observed in yield-loss es-

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timates can be caused by many factors, such as differences in geographical area and climate, cultivars, or crop production practices. Also, differences can be associated with variation in the timing and techniques used to experimentally impose and estimate defoliation (Buntin 1997). This variation is an impediment to establishing EILs and economic thresholds (ETs) (Higley and Pedigo 1997).

Another missing component of an integrated pest management system for dry bean is an adequate sampling procedure for making management decisions. Sampling plans for Mexican bean beetle have been established in soybeans based on mean defoliation level (Bellinger et al. 1981), but defoliation is an inappropriate sampling criterion for decision making because it represents past injury, not an indication of potential injury. More commonly, larval densities are used in thresholds (Higley and Pedigo 1997). Unfortunately, in dry bean, larval sampling for Mexican bean beetle would need to occur at full bloom or later after plants have vined, making sampling difficult. Moreover, movement through the field after full bloom is of concern because pathogens, particularly for common blight, may be disseminated (Schwartz et al. 1996).

An alternative strategy would be to predict injury through monitoring egg mass populations. Sampling egg masses would allow time for insecticidal application before significant injury could occur. Eggs hatch ≈1 wk after laying, and first and second instars typically develop for 1.5–2 wk. Because 87% of the bean foliage consumption by larvae occurs in the third and fourth instars (Kabissa and Fronk 1986), egg sampling provides a wide window of time for making management decisions. Also, egg mass sampling would be conducted before the bean canopy is large and plants start vining, and in this more open canopy the potential for spreading pathogens is reduced. Even though egg masses occur at low densities, they are easy to detect because of their orange coloration, which contrasts with the green of the leaves.

Given that many abiotic and biotic factors affect Mexican bean beetle population dynamics, it would be important to distinguish between populations at the time of sampling and corresponding survivors that would produce injury. This is an issue for all insect sampling, but it is particularly pertinent in using egg mass samples to predict larval injury. Therefore, to use egg masses in making management decisions, the factors affecting Mexican bean beetle population dynamics must be identified and quantified, so that survival at the injurious stage can be estimated and incorporated in the thresholds. Although some work has been done to incorporate survivorship estimates in the calculation of EILs (Ostlie and Pedigo 1987, Pedigo 1997), few thresholds exist that reflect the action of natural enemies and other mortality factors (Peterson 1997).

Our previous research on egg mass sampling (Barrigossi et al. 2001a) and Mexican bean beetle life tables on dry bean (Barrigossi et al. 2001b) established dispersion and survivorship data necessary to use egg mass sampling in Mexican bean beetle management. The remaining data needed to develop EILs, ETs, and associated sampling plans are yield-loss relationships for Mexican bean beetle on dry bean. In this study, we report those yield-loss relationships from field studies over 2 yr, and use these and previously published data to develop EILs, ETs, and a sequential sampling program for Mexican bean beetle.

Materials and Methods

Field experiments were conducted in 1995 and 1996 at the Panhandle Research and Extension Center, Scottsbluff, Nebraska, on Tripp sandy loam soil. The dry bean cultivar Beryl was planted in areas that had been rotated annually with corn (*Zea mays* L.) and sugar beet (*Beta vulgaris* L.). The beans were planted in 0.76-m rows at a depth of 0.03–0.04 m, with a seeding rate of 12–15 seeds per m. Conventional tillage was used, and preplant incorporated herbicides (ethalfluralin and s-ethyl dipropylthiocarbamate each at 2.3 liter [formulation]/ha) were applied 1 wk before planting. Postemergence weeds were eliminated by cultivation and hand weeding. Irrigation was provided to plants as needed.

In 1995, beans were planted on 14 June. The experimental design was a randomized complete block with four replications. Each experimental unit consisted of four rows, 3 m long. To limit larval movement between plots, one bean row was left between plots. Treatments consisted of four larval population levels (0, 33, 67, and 133 larvae/m row). Plots were infested by hand on 3 August, with third instars collected the same day in nearby fields. At the time of infestation, the bean plants were at R4 (mid pod set). Larvae were allowed to feed and develop normally until pupation. Newly emerged adults stayed within the plots for a few days before dispersing, so all plots were sprayed with insecticide (esfenvalerate 300 ml [formulation]/ha) ≈4 d after initial beetle emergence. Check plots were maintained free of beetles with insecticide application.

Measurements were taken from the two central rows. Percent defoliation estimates were taken immediately after all larvae pupated on 22 and 29 August (plant stage R7–8). Plots were harvested by hand on 7 September. From each plot, yield components were determined by hand harvesting and threshing 2.4 m of row from each of the two middle rows of the plot.

In 1996, the experiment was repeated at two locations 8 km apart. The planting dates were 3 and 5 June, and the plots were maintained as described for 1995. The experimental design was a split plot, arranged in randomized complete blocks with eight replications (four in each location). The main plots were infestation times (bean growth stages), and subplots were infestation levels. Each experimental unit was composed of four rows, 3 m long. Measurements were made from the center 2.4-m section of the two middle rows. Five levels of infestation, including a control, were applied using egg masses with neonate larvae. Treatments, established in terms of egg masses, were: 0, 0.7, 1.3, 2.0, and 2.7 egg masses per m row. Egg masses were obtained from field-collected beetles kept in cages with bean plants in the field. Bean leaves containing egg masses were collected and taken to the laboratory, in which leaves were cut in strips and maintained in plastic trays layered with moist paper towels to maintain appropriate humidity until eggs hatched. Plots were infested by stapling leaf strips with new hatched eggs to the underside of bean leaves in the middle of the canopy. This infestation technique was possible because young larvae remained on top of their egg shells for up to 8 h before they started to feed and to spread on the bean leaf.

Infestations were made during each of three bean growth stages, and larvae injured plants for ≈3 wk thereafter. Infestations were made: on 7–10 July at preflowering (V-R1) to produce injury during pot set (R3–R4); on 19–23 July at flowering (R1–R2) to produce injury during seed filling (R5–R6); and on 31 July–2 August at pod set and pod formation (R3–4) to produce injury during late seed fill and pod maturation (R6–R7) (stage descriptions follow Schwartz et al. 1996). Larvae were allowed to feed until they pupated. On 16 August (first two infestations) and ≈29 August (last infestation), after pupation, defoliation estimates were taken, and pupae in the two middle rows were counted. All plants and dropped leaves in the three row-m were inspected. After pupae were counted, plants were sprayed with esfenvalerate (as in 1995) to prevent dispersal of emerging adults. Yield was measured as in 1995.

Yield was regressed against larvae/row-m to provide an estimate of yield-loss rates per insect (the slope of the linear relationship) by the general linear model procedure of SAS (SAS Institute 1990). These data were used to calculate EILs based on the formula: EIL = $C/(DIVK)$, where C = management costs (\$/ha or \$/a), V = commodity value (\$/kg or \$/hundred weight), DI = yield loss per insect density (kg/ha loss per larvae per row-m or hundred weight/a loss per larvae/row-m), and K = the proportion of injury prevented by management (dimensionless) (Higley and Pedigo 1997).

For egg sampling of Mexican bean beetle, the decision occurs long before any significant injury; therefore, the ET in this instance is equal to the EIL (Higley and Pedigo 1997). However, the EIL in larvae/row-m was converted to egg masses/row-m based on an average of 52 eggs per egg mass (Barrigossi et al. 2001b) and adjusted to reflect average survivorship to the adult stage (Barrigossi et al. 2001a).

The sequential sampling plan was based on a negative binomial distribution of egg masses (Barrigossi et al. 2001b) and corresponding formulas from Fowler and Lynch (1987) and Young and Young (1998). Calculations of decision lines, slopes, and Wald's approximations for the operating characteristic curves and average sample number curves were made with an Excel spreadsheet program that we developed based on a spreadsheet by P. Davis in ENSTAT software (Pedigo and Zeiss 1996). Young and Young (1998) discuss the differences between Wald's approximations and exact operating characteristic and average sample number curves (briefly, Wald's formulae assume sampling stops on the boundary; exact calculations account for overshooting the boundary). We used the software (ECOSTAT, available at http://biometry.unl.edu/faculty/linda/lyoung.html) associated with Young and Young's (1998) book to calculate exact operating characteristic and average sample number curves. Although operating characteristic and average sample number curves are typically presented as smooth lines (Fowler and Lynch 1987), these curves are typically developed by calculating a series of points and smoothing a line between them (by a line function) rather than by plotting an equation of the curve (which is difficult or impossible to determine). We present operating characteristic and average sample number curves by plotting a series of calculated points and smoothing by spline between points.

Results and Discussion

Yield Loss and Mexican Bean Beetle Injury. Results of yield-loss experiments in 1995 and 1996 are presented in Table 1. In 1995, larval infestation treatments significantly reduced yield (F = 4.93; df = 3, 9; P = 0.027); however, no significant differences were noted among larval infestation treatments. A common problem arising with artificial infestation as a technique to model yield-loss relationships is that infestation levels may not correspond to final insect densities because of insect mortality in plots (Buntin 1997, 2001). A strong indication that mortality was a problem in 1995 comes from a comparison of yield loss to larval infestation and yield loss to measured defoliation. By linear regression, no significant relationship was observed between yield and larval infestation (F = 2.45; df = 1, 14; P = 0.14); however, a significant linear relationship was observed between yield and percent defoliation (F = 6.84; df = 1, 14; P = 0.0203; r^2 = 0.328). Because percent defoliation is an index of the actual insect populations in plots, a significant linear response to percent defoliation, but not to initial insect densities, implies that final insect densities were different from initial densities.

To address this problem, in 1996, we changed infestation methods and assessment (as outlined in *Materials and Methods*). By using egg mass infestation and sampling pupae, we were able to obtain better estimates of actual (surviving) insect populations in plots. We also added a second field site in 1996 to provide environmental replication of yield responses, and looked at later injury periods (Table 1). No significant field differences were observed (F = 1.74; df = 1, 97; P = 0.1899), so we combined fields for analysis. In 1996, only injury during pod set resulted in significant reductions in yield. The yield to larval infestation relationship was linear (by regression) with yield (kg/ha) = 3109.6–6.91 (kg/ha per larvae/row-m) (F = 14.65; df = 1, 38; P = 0.0005; r^2 = 0.278) or yield (100 lbs/a) = 27.75–0.0616 (100 lbs/a per larvae/row-m). These slopes provide the biological data needed for the DI component of the EIL (Higley and Peterson 1997).

Table 1. Yield and defoliation of dry bean by Mexican bean beetle at Scottsbluff, NE; means (±standard errors) followed by different letters within an injury period are significantly different ($P < 0.05$) by least significant difference

Injury period[a]	Treatment[b] (larvae or egg masses/ 0.3 row-m)	Yield (kg/ha)	Larvae[c] (No./0.3 row-m)	Defoliation (%)
		1995[d]		
Pod set (R4)	0.00	4222.3 ± 260.2a	0.00	0.2 ± 0.02
	10.00	3601.3 ± 232.8b	32.80	16.2 ± 1.6
	20.00	3729.8 ± 159.3b	65.60	22.5 ± 3.9
	40.00	3599.9 ± 227.8b	131.20	35.2 ± 4.1
		1996[e]		
Pod set (R3–R4)	0.00	3071.4 ± 134.5a	0.2 ± 0.1	0.2 ± 0.1
	0.20	2831.9 ± 92.1b	22.1 ± 7.2	9.1 ± 1.3
	0.40	2906.1 ± 92.3b	34.0 ± 10.5	14.4 ± 1.8
	0.60	3045.6 ± 100.3b	41.7 ± 6.8	19.0 ± 1.7
	0.80	2623.6 ± 162.0b	56.8 ± 7.7	24.6 ± 2.0
Seed fill (R5–R6)	0.00	3010.3 ± 117.6a	3.0 ± 0.9	0.3 ± 0.1
	0.20	3181.3 ± 111.7a	7.9 ± 2.1	4.0 ± 1.0
	0.40	3072.4 ± 131.9a	14.0 ± 3.8	7.9 ± 2.6
	0.60	3071.4 ± 120.3a	23.2 ± 6.4	8.9 ± 2.9
	0.80	3045.2 ± 108.8a	29.4 ± 8.6	11.2 ± 3.2
Late seed fill and pod maturity (R6–R7)	0.00	3098.0 ± 145.1a	0.7 ± 0.3	1.0 ± 0.3
	0.20	2952.5 ± 186.3a	11.7 ± 1.6	7.5 ± 0.5
	0.40	3064.0 ± 119.4a	25.0 ± 3.3	13.3 ± 1.5
	0.60	3008.6 ± 99.3a	36.1 ± 6.5	15.6 ± 1.2
	0.80	2894.7 ± 118.8a	50.8 ± 9.2	18.8 ± 2.3

[a] Period of ~90% larval feeding; stages after Schwartz et al. (1996).

[b] In 1995, Mexican bean beetles applied as third instars; 1996, Mexican bean beetles applied as egg masses ~2 wk prior to injury period.

[c] In 1995, larval densities at infestation; 1996, larval densities measured from pupal sampling (to account for mortality) at 16 and 29 August.

[d] $n = 4$; one field.

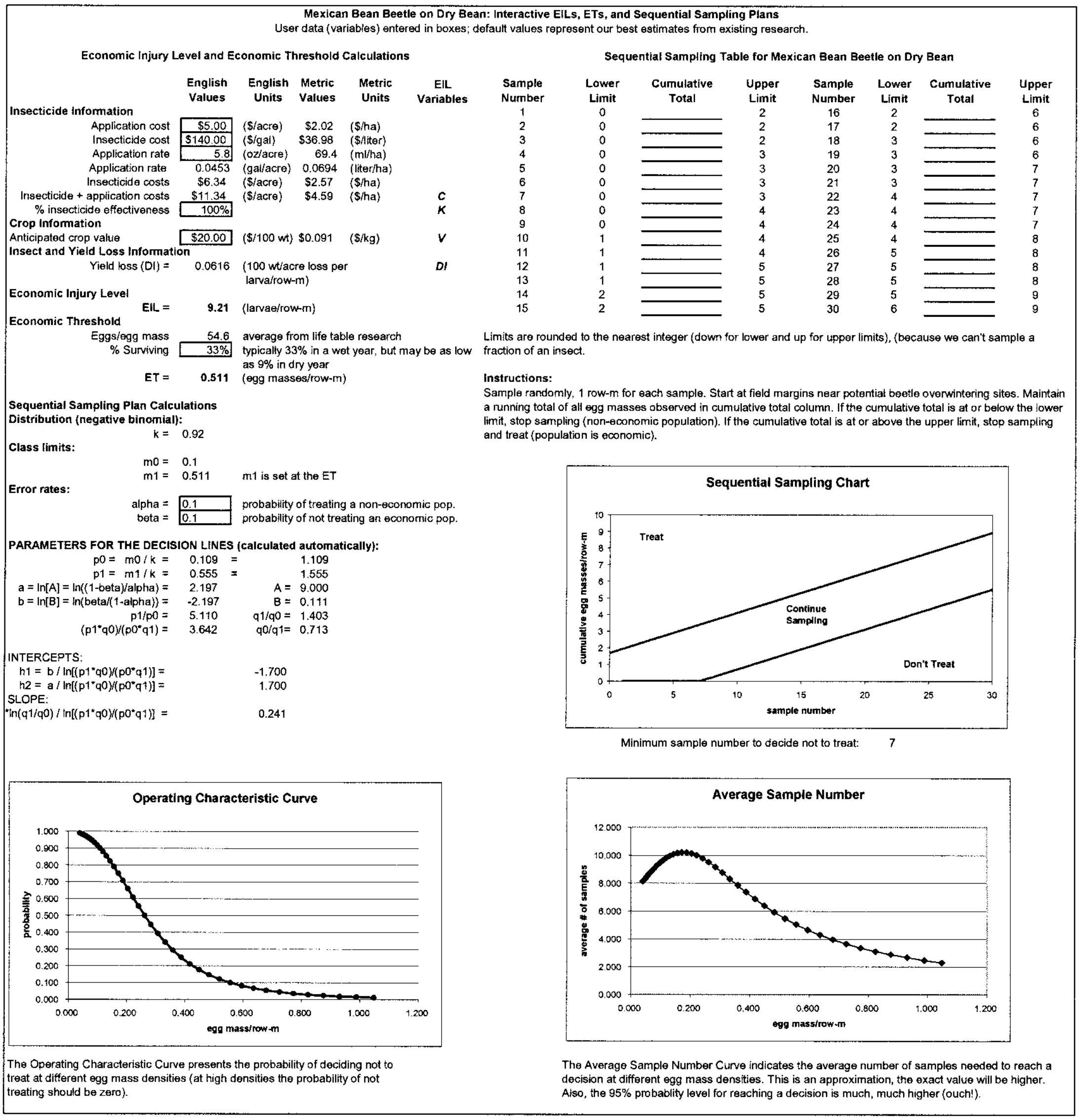
[e] $n = 8$; two fields.

Results in this study generally agree with previous work on defoliation and yield loss in dry bean (Fan et al. 1993, Schaafsma and Ablett 1994), in that yield loss occurred with larval densities sufficient to produce ~20% defoliation from flower to pod fill. However, the same levels of defoliation at later stages did not impact yield. Reduced sensitivity to defoliation at later growth stages is consistent with previous observations on dry bean, and follows the expectation that defoliation during reproductive development is most likely to impact yield (Peterson and Higley 2001). Work in soybean increasingly indicates that the physiological basis of yield loss from defoliation is through reductions in canopy light interception, and therefore, photosynthetic productivity (Higley 2001 reviews this hypothesis). Because reproductive-stage soybean typically tolerates defoliation in excess of 30% without measurable yield loss, it is somewhat unexpected to see yield loss at much lower defoliation levels (≈20%) in dry bean, a related crop species. Differences in canopy size might account for this difference, but the vining growth habit of dry bean during reproductive development might also reduce the efficiency of canopy light interception. Consequently, dry bean genotypes with greater canopy size or improved efficiency of light interception may be more tolerant of defoliation.

A final issue regarding yield loss is the possible impact of adult beetle feeding. Mexican bean beetle adult injury was not included in experimental assessments of injury, because adults could not be confined to individual plots. If adult feeding substantially impacts yield, the calculated yield-loss relationship might underestimate the actual yield loss caused by larvae and adults. However, data from the 1995 and 1996 experiments suggest that at beetle densities below or near the EIL, adult feeding would not greatly impact yield. The 1995 and 1996 field experiments demonstrate that dry bean yield is relatively insensitive to injury after flowering, at defoliation levels ~20%. When eggs are laid during early flowering, the pattern of beetle development is such that most adult beetle feeding occurs after flowering and pod fill, when yields are not greatly affected by defoliation. If this interpretation is correct, then yield-loss relationships for EIL development should focus on larval injury from flowering to pod fill, which we have done in this study.

Economic Injury Levels and Economic Thresholds. The slope of the linear regression of yield loss against larval density provides the *DI* component for Mexican bean beetle injury to dry bean. Other components of the EIL, including insecticide cost (C) and market value (V), are easily determined, so that it is possible to calculate EILs for different insecticides, insecticide rates (which will alter component C), and market values, as illustrated in Fig. 1.

The EIL is the calculated benchmark for assessing pest populations, but the ET is the practical decision guide for taking action against pests. Typically, the ET is set at some level below the EIL to accommodate management delays, although techniques for determining the ET vary from the simple to the complex (Pedigo 1997). Because our sampling program for



Mexican Bean Beetle on Dry Bean: Interactive EILs, ETs, and Sequential Sampling Plans

User data (variables) entered in boxes; default values represent our best estimates from existing research.

Economic Injury Level and Economic Threshold Calculations

	English Values	English Units	Metric Values	Metric Units	EIL Variables
Insecticide Information					
Application cost	$5.00	($/acre)	$2.02	($/ha)	
Insecticide cost	$140.00	($/gal)	$36.98	($/liter)	
Application rate	5.8	(oz/acre)	69.4	(ml/ha)	
Application rate	0.0453	(gal/acre)	0.0694	(liter/ha)	
Insecticide costs	$6.34	($/acre)	$2.57	($/ha)	
Insecticide + application costs	$11.34	($/acre)	$4.59	($/ha)	*C*
% insecticide effectiveness	100%				*K*
Crop Information					
Anticipated crop value	$20.00	($/100 wt)	$0.091	($/kg)	*V*
Insect and Yield Loss Information					
Yield loss (DI) =	0.0616	(100 wt/acre loss per larva/row-m)			*DI*
Economic Injury Level					
EIL =	**9.21**	(larvae/row-m)			
Economic Threshold					
Eggs/egg mass	54.6	average from life table research			
% Surviving	33%	typically 33% in a wet year, but may be as low as 9% in dry year			
ET =	**0.511**	(egg masses/row-m)			

Sequential Sampling Plan Calculations

Distribution (negative binomial):

k = 0.92

Class limits:

m0 = 0.1

m1 = 0.511 m1 is set at the ET

Error rates:

alpha = 0.1 probability of treating a non-economic pop.

beta = 0.1 probability of not treating an economic pop.

PARAMETERS FOR THE DECISION LINES (calculated automatically):

p0 = m0 / k = 0.109 = 1.109

p1 = m1 / k = 0.555 = 1.555

a = ln[A] = ln((1-beta)/alpha) = 2.197 A = 9.000

b = ln[B] = ln(beta/(1-alpha)) = -2.197 B = 0.111

p1/p0 = 5.110 q1/q0 = 1.403

(p1*q0)/(p0*q1) = 3.642 q0/q1= 0.713

INTERCEPTS:

h1 = b / ln[(p1*q0)/(p0*q1)] = -1.700

h2 = a / ln[(p1*q0)/(p0*q1)] = 1.700

SLOPE:

*ln(q1/q0) / ln[(p1*q0)/(p0*q1)] = 0.241

Sequential Sampling Table for Mexican Bean Beetle on Dry Bean

Sample Number	Lower Limit	Cumulative Total	Upper Limit	Sample Number	Lower Limit	Cumulative Total	Upper Limit
1	0	______	2	16	2	______	6
2	0	______	2	17	2	______	6
3	0	______	2	18	3	______	6
4	0	______	3	19	3	______	6
5	0	______	3	20	3	______	7
6	0	______	3	21	3	______	7
7	0	______	3	22	4	______	7
8	0	______	4	23	4	______	7
9	0	______	4	24	4	______	7
10	1	______	4	25	4	______	8
11	1	______	4	26	5	______	8
12	1	______	5	27	5	______	8
13	1	______	5	28	5	______	8
14	2	______	5	29	5	______	9
15	2	______	5	30	6	______	9

Limits are rounded to the nearest integer (down for lower and up for upper limits), (because we can't sample a fraction of an insect.

Instructions:

Sample randomly, 1 row-m for each sample. Start at field margins near potential beetle overwintering sites. Maintain a running total of all egg masses observed in cumulative total column. If the cumulative total is at or below the lower limit, stop sampling (non-economic population). If the cumulative total is at or above the upper limit, stop sampling and treat (population is economic).

Minimum sample number to decide not to treat: 7

The Operating Characteristic Curve presents the probability of deciding not to treat at different egg mass densities (at high densities the probability of not treating should be zero).

The Average Sample Number Curve indicates the average number of samples needed to reach a decision at different egg mass densities. This is an approximation, the exact value will be higher. Also, the 95% probablity level for reaching a decision is much, much higher (ouch!).

Fig. 1. Spreadsheet showing Mexican bean beetle EIL and ET components, thresholds, and sequential sampling information. This example illustrates calculations for high rate (69.4 ml/ha) use of insecticide. User entered variables indicated by boxes; all other values either from research or calculated.

Mexican bean beetles is based on egg mass densities, we must convert the EIL in a larval density to an ET in egg mass density. One crucial observation is that in this instance the EIL and the ET are the same. Usually, the ET is set below the EIL to prevent a growing population from reaching the EIL before action can be taken. But egg mass sampling of Mexican bean beetles will occur from 1 to 3 wk before any significant injury will occur from Mexican bean beetle larvae. So, it is not necessary to set the ET below the EIL (this situation is similar to that of thresholds for weed seedlings, in which the EIL and ET also are the same because action can be taken long before any injury impacting yield occurs) (Montersen and Coble 1997, Pedigo 1997).

Most simply, converting the EIL in larvae/row-m to an ET in egg masses/row-m is just a question of estimating the number of eggs/egg mass and dividing the EIL in larvae/row-m by eggs/egg mass to yield an ET in egg masses/row-m (because one egg corresponds to one larva). From life table studies (Barrigossi et al. 2001a), we sampled 78 total egg masses with an average of 54.6 (SE 0.7) eggs/egg mass. However, not all eggs will survive to produce injurious larvae, so an important refinement is to adjust the ET to account for survivorship.

Despite its potential importance, surprisingly few ETs have been determined that include an assessment of survivorship (Higgins et al. 1986, Ostlie and Pedigo 1987, Calvin et al. 1988, Peterson 1997). Our life table data on Mexican bean beetle indicate that substantial mortality occurs in the egg and early larval stages, so that failing to account for this mortality in determining an egg mass ET would greatly underestimate the real ET. From life tables of eggs through adult in six fields over 2 yr, we observed egg to pupa mean survivorship of ≈9% in dry years and 33% in normal years (Barrigossi et al. 2001a). We also assessed pupal densities after infestation with egg masses in our 1996 yield-loss studies. The average survivorship from egg to pupal stage across two fields in 1996 ($n = 8$) was 32.1% (SE 0.019), which agrees closely with data from separate life table studies (Barrigossi et al. 2001a). Consequently, the ET expressed in egg masses/row-m should be divided by the expected survivorship rate of 33% to provide the most accurate ET.

Sequential Sampling Plans for Mexican Bean Beetle. Where appropriate data are available, a sequential sampling plan can provide significantly improved sampling efficiency. Chief requirements are an estimate of the sample size, the probability distribution best fitting the population, and decision levels for economic and subeconomic populations. Our egg mass sampling studies indicate an appropriate sample unit is one row-m, and a negative binomial probability distribution best fits for Mexican bean beetle egg masses (Barrigossi et al. 2001b). The ET provides an upper decision level (m1), but the lower decision level (m0) is more subjective (Young and Young 1998; see Binns et al. 2000 for alternative arguments on setting m1 and m0). Typically, this lower level is set based on biological understandings of the organism, particularly estimates of potential population increase (Young and Young 1998). We estimated the lower limit at 0.1 egg mass/row-m, but alternative estimates certainly may be justified. It is important to note that greater separation between the lower and upper limits reduces the size of the indecision zone of the sequential sampling program.

Example decision lines for two sequential sampling programs are presented in Fig. 2, based on $k = 0.92$, $m0 = 0.1$, and ETs of 0.368 egg mass/row-m for Asana XL (esfenvalerate) at a low rate (0.0227 gal/a) and an ET of 0.518 egg mass/row-m for Asana XL at a high rate (0.0453 gal/a). Commonly, sequential sampling programs are determined based on a single ET. But as Fig. 2 indicates, failing to calculate the sequential sampling program for the most appropriate ET will reduce the efficiency and accuracy of the sequential sampling program.

The evaluation of sequential sampling plans is generally based on the operating characteristic and average sample number functions. The operating characteristic function is the probability that the null hypothesis (the population mean is below the stated safety level) will be accepted for any given value of the mean. In addition to the operating characteristic and average sample number functions, the parameter $N_{0.95}$ defines where 95% of samples collected will have equal or smaller sample sizes. This parameter is of value in assessing the potential maximum time required to reach a decision for a given sampling plan (Young and Young 1998).

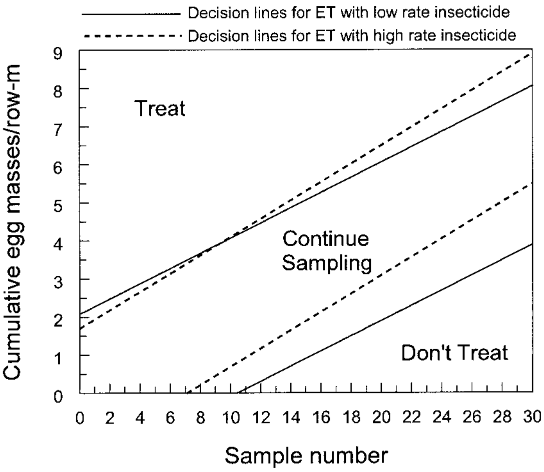


Fig. 2. Decision boundaries for a sequential sampling plan for Mexican bean beetle egg masses on dry bean ($\alpha = 0.1$, $\beta = 0.1$, and safety level [m0] = 0.1 egg mass/row-m): solid lines are boundaries calculated for insecticide at low rate (m1 [ET] = 0.368 egg mass/row-m); dashed lines are boundaries calculated for insecticide at high rate (m1 [ET] = 0.518 egg mass/row-m).

Figs. 3 and 4 present operating characteristic, average sampling number, and 95th percentile ($N_{0.95}$) curves for two sequential sampling plans calculated using Asana XL at high and low rates for determining the ET. The operating characteristic curves show that the probability of making an incorrect decision is very low when the egg mass population mean is below or above the stated levels for both ETs established (Fig. 3). The peak average sample number reduces from 25 to 14 (Wald's) and from 18 to 10 (exact values) when the ET increases from 0.368 to 0.518 egg masses/row-m (Fig. 4). These figures also indicate that the difference between the Wald's approximation and exact values is more significant for average sample number than for operating characteristic function. Fig. 3 also shows the curves for the 95th percentile of sample size ($N_{0.95}$) estimated using ECOSTAT (Young and Young 1998). The $N_{0.95}$ curves indicate that the potential time to reach a decision is much greater than indicated only by the average sample number. The $N_{0.95}$ and average sample number substantially decrease with higher ETs, so efforts to raise the EIL and ET (such as through increasing crop tolerance) both reduce the need for management action and may increase the efficiency of sampling efforts.

An Interactive Management Program for Mexican Bean Beetle. Although EILs, ETs, and sequential sampling plans are presented as static values, or perhaps as a table of selected values, all of these decision-making tools are intrinsically dynamic. Static presentation of dynamic variables is understandable in the past, when computers were not widely available and calculations may have been difficult. But today, we believe dynamic management information such as

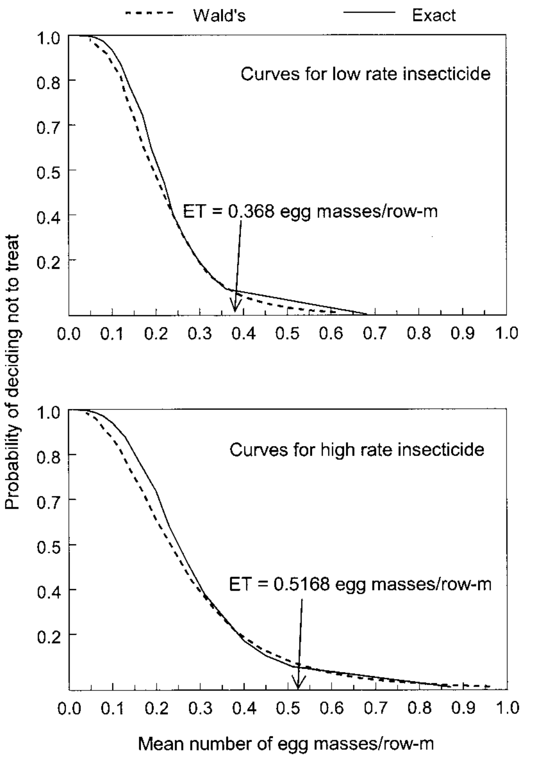


Fig. 3. Operating characteristics curves for sequential sampling plans for Mexican bean beetle egg masses, calculated with ET for low and high rate insecticide. For both plans, $\alpha = 0.1$, $\beta = 0.1$, and the safety level (m0) = 0.1 egg mass/row-m.

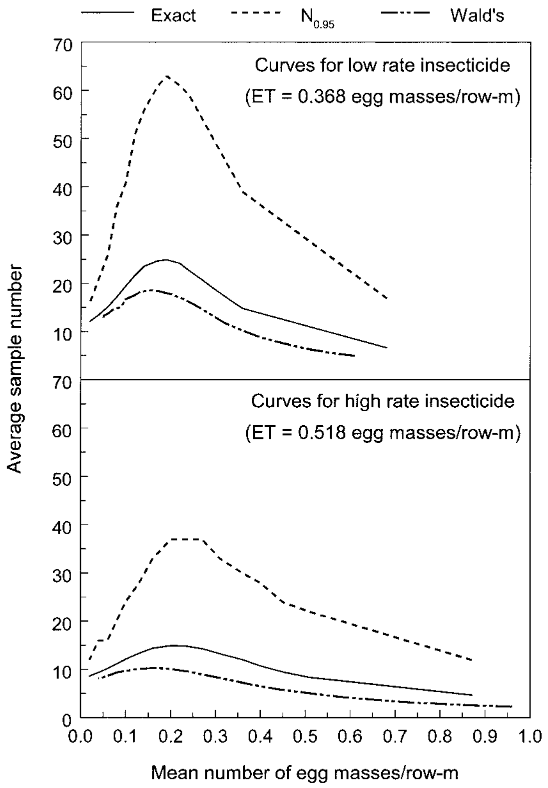


Fig. 4. Comparison of Wald's approximation and exact values of average sample number and the 95th percentile of sample size, $N_{0.95}$, for sequential sampling plans for Mexican bean beetle egg masses. Curves based on sequential sampling plans calculated with ET for low and high rate insecticides. For both plans, $\alpha = 0.1$, $\beta = 0.1$, and the safety level (m0) = 0.1 egg mass/row-m.

thresholds and sequential sampling plans must be interactive to allow users to input the economic and other data specific to their situation. Consequently, we expanded and modified a spreadsheet developed by Paula Davis (in ENTSTAT, Pedigo and Zeiss 1996), to calculate Mexican bean beetle EILs, ETs, and sequential sampling plans. Fig. 1 illustrates spreadsheet calculations, including thresholds, sequential sampling plan (chart and table), and sampling plan analysis charts. Copies of the spreadsheet are available from the authors or at entomology.unl.edu/lgh/ecology/downloads.shtml.

The decision tools reported in this work and illustrated in the interactive spreadsheet have three novel features. First, sampling and decision making are focused on a life stage (egg masses) that occurs well before injury. Sampling a noninjurious stage of the pest allows more time for management action before significant injury occurs. Second, natural mortality is reflected in our decision-making criteria, specifically in the ET calculation. Often, economic thresholds are calculated by assuming 100% survivorship of injurious life stage, ignoring the importance of the natural mortality that often occurs in the field. Our work emphasizes the crucial importance of life table information in developing more comprehensive pest management programs. Third, all management tools, including sequential sampling plans, are dynamic. As examples in this study illustrate, relatively minor variation in ETs has substantial impact on sequential sampling plans, including parameters such as average sample number. Consequently, we believe interactive presentation of thresholds and sampling information should become the standard, not the exception, in pest management.

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