Forest Science, Vol. 35, No. 3, pp. 789–800.

Regression Estimators for Late-Instar Gypsy Moth Larvae at Low Population Densities

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ABSTRACT. Two regression estimators were developed for determining densities of late-instar gypsy moth, *Lymantria dispar* (Lepidoptera: Lymantriidae), larvae from burlap band and pyrethrin spray counts on oak trees in Vermont, Massachusetts, Connecticut, and New York. Studies were conducted by marking larvae on individual burlap-banded trees within 15-m diameter plots and recapturing them with pyrethrin sprays to tree crowns at night. Both estimators are based on data that are relatively easy and inexpensive to gather in the field. The estimator for individual trees may be useful in determining relative densities, but the plot estimator, which had an R^2 of 0.99, can be used with a high degree of confidence for determining absolute densities in plots containing several oak trees. Validation of the plot density estimator at five sites in Maryland demonstrated its utility for sampling late-instar gypsy moth. Both estimators were valid only when previous years' egg-mass densities were $\leq$75/ha and decreased in efficiency when prior year egg masses were $\geq$495/ha. These estimates are best suited for density estimates in sparse or building gypsy moth populations in which other procedures are especially difficult to use or evaluate. FOR. SCI. 35(3):789–800.

ADDITIONAL KEY WORDS. Sampling, burlap bands, density estimates, late-instar larvae.

ESTIMATION OF THE NUMBER of gypsy moths, *Lymantria dispar* L., is a problem for both scientists and forest pest managers who rely on detection and monitoring of the insect for formulating, implementing, and modifying research or control procedures. Gypsy moth populations traditionally have been estimated by counting egg masses in fixed or variable plots (Wilson and Fontaine 1978) and more recently by frass pellet counts (Liebhold and Elkinton 1988). Both procedures can be both labor-intensive and time-consuming. Since current suppression strategies and research are aimed at latent and increasing density populations, the need for density estimates on a routine basis to detect change at low population levels is crucial. Survival of late instars was the most important factor for predicting trends in sparse gypsy moth populations (Campbell 1967). Therefore, an accurate estimate of late-instar larval densities could be used to predict pupal and subsequent egg-mass densities.

Use of artificial bark flaps, which capitalize on gypsy moth diurnal behavior, verifies larval presence (Bess et al. 1947, Campbell and Sloan 1977,

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McManus and Smith 1984), although their accuracy in quantifying populations is unknown. In this study, we were interested in determining the potential of using burlap bands on trees to estimate population density. If a consistent relationship exists between the larval population density on a tree and the number of larvae seen at the burlap bands, then simple band counts could be converted to estimates of absolute density by developing appropriate regression models.

Many factors affect the efficiency of burlap bands. In studying sparse gypsy moth populations, Wallner (1983) found little larval movement between burlap-banded trees yet burlap bands are known to attract larvae from nearby unbanded trees (Liebhold et al. 1986). The proportion of larvae using bands is a function of development, which is related to temperature and host type (Hough and Pimentel 1978). Structural features on a tree, which provide natural larval resting locations, can be used to classify forest sites as being susceptible or resistant to gypsy moth defoliation (Houston and Valentine 1977). Yet, the presence of gypsy moth on various host species is related to food preference (Lance and Barbosa 1981, Lechowicz 1983). *Quercus* species are the most preferred host type. Less favored hosts include species of *Carya, Acer, Cornus,* and *Betula.* Consequently, data gathered from burlap bands on preferred host species may provide more information about trends in larval densities than those on less preferred hosts.

Many statistical techniques are available for estimating population densities (Southwood 1966; Seber 1973); but none of these procedures provide the high degree of reliability for the forest manager to assess gypsy moth larval populations. What is needed is a simple, cost-effective procedure requiring little equipment and limited preparation time. Here we report on a method that meets these criteria; the development of two regression estimators for predicting late-instar gypsy moth population densities from larval counts at burlap bands on oak trees.

MATERIALS AND METHODS

Field Methodology

Sample plots were chosen at four locations in the northeastern United States: Pachaug State Forest, North Stonington, CT; Harvard's Black Rock Forest, Cornwall, NY; Bryant Mountain, Salisbury, VT; and Massachusetts Military Reservation, Cape Cod, MA. The New York and Vermont sites have susceptible ridgetop forests composed mainly of chestnut oak (*Quercus prinus* L.) and adjacent resistant valley forests consisting of mixed hardwood stands (Houston and Valentine 1977). Tree species diversity was limited at the Massachusetts site; sandy soil with homogeneous, flat topography yielded stands of predominantly white oak (*Quercus alba* L.), black oak (*Quercus velutina* Lam.), and red oak (*Quercus rubra* L.), and some pitch pine (*Pinus rigida* Mill.). The Connecticut site consisted of mixed hardwoods in a rolling terrain studded with wetlands. In 1984 and 1985, a different fixed-area plot (177 m^2) was chosen within susceptible and resistant sites in New York and Vermont. In Massachusetts and Connecticut, sites were chosen that lacked susceptible-resistant physiography; there, two plots of 177 m^2 were randomly selected. Species composition and diameter breast height (dbh) for these plots are given in Table 1.

At least 1 week before spray sampling, all trees with dbh greater than 7.0 cm in the plots were banded completely around the bole at breast height with 15-cm-wide burlap flaps. The bands were checked for the next 6 days, and larvae present were counted and marked with a dot of Accent® acrylic

TABLE 1. Tree species composition and dbh on the four sample locations each consisting of 354 m^2.

Location	Spray date (growing degree days)		Tree species	Number of stems ≥7.0 cm	Mean dbh (in.)	Percent of larvae per tree species[1]	
	1984	1985				1984	1985
CT	June 19–21	June 15–16	*Quercus alba*	6	9.1	52	55
	(1254–1307)	(1339–1364)	*Quercus velutina*	4	4.8	14	4
			Carya tomentoso	7	5.5	12	17
			Carya glabra	1	8.2	1	2
			Acer rubrum	3	6.5	3	9
			Populus grandidentata	1	9.2	15	4
			Hammamelis virginiana	1	2.3	1	6
			Cornus florida	4	3.5	0	1
				27			
MA	June 28–29	June 30–	*Quercus alba*	8	3.6	16	20
		July 1	*Quercus velutina*	18	4.7	82	60
	(1359–1390)	(1442–1470)	*Pinus rigida*	27	4.1	2	19
				53			
NY *S*[2]	June 23	June 18	*Quercus prinus*	18	5.6	74	4
	(1521)	(1762)	*Quercus alba*	1	7.1	8	0
R	June 22	June 17	*Quercus rubra*	4	11.0	14	61
	(1462)	(1730)	*Acer rubrun*	7	9.6	1	25
			Tilia americana	1	14.4	3	9
				31			
VT *S*	June 25	June 25	*Quercus prinus*	14	6.0	36	56
	(1214)	(1304)	*Quercus rubra*	5	6.0	18	18
			Acer rubrum	5	4.9	18	9
R	June 26	June 26	*Quercus rubra*	10	9.8	21	13
	(1236)	(1316)	*Acer rubrum*	10	4.0	4	0
			Acer saccharum	3	8.7	0	2
			Betula papyrifera	1	6.2	0	0
			Fagus grandifolia	1	3.3	0	0
				49			

[1] Calculated from $\hat{N}_m$ in equation 1.

[2] *S* and *R* represent susceptible and resistant stands, respectively.

waterbase paint. We had determined earlier, in the laboratory, that Accent® paint did not alter behavior, molting, or survival. The purpose of checking bands for 1 week prior to sampling was to verify insect development; only the number of larvae beneath bands immediately prior to spray-sampling was used in model development. Spray-sampling was done when larvae were predominantly in the fifth or sixth instar. The rate of insect development, as a function of time and temperature, varied between sites. These differences are reflected in the growing degree days computed as Tmax-Tmin-5°C based on weather records from the nearest weather reporting station (Table 1). Molting larvae remain under bands for 1–2 days and do not move to the canopy at night until the molt is completed. Immediately before the canopy was sprayed, each band was examined for molting larvae, and these larvae were discounted from the mark/recapture computation as well as the 24-hour postspray counts of larvae under the bands.

Trees were sprayed in a manner similar to that employed by Wallner (1971), with a Pratt-Miller Red Arrow® spray diluted to 0.005% pyrethrin and a Soloport® −423 backpack mistblower. Trees >10 m in height were sprayed from a 10.5-m truck-mounted hydraulic ladder; trees ≤22 m in height could be sampled by this method. Trees were sprayed individually, starting with those in the understory and proceeding upward to the overstory. Plastic tarpaulins, 7.5 and 10 m in diameter, were spread beneath the entire tree crowns to collect all larvae dislodged by the spray. Marked and unmarked larvae were counted and their instar recorded. One hour was allowed for all sprayed insects to drop onto the tarps. This spray sampling was done at night between 2100 and 0400 hours with the aid of a gasoline-powered generator and floodlights. Twelve hours after the trees were sampled with pyrethrin spray, the bands were reexamined for the presence of marked and unmarked larvae.

STATISTICAL METHODOLOGY

Density Estimators

The regression estimator may be based on either a tree basis or a plot basis where regression techniques are used to fit an appropriate model of absolute larval density as a function of band counts. However, since the absolute densities were unobtainable because total counts of instars were impossible, we utilized a mark and recapture sampling design to estimate the absolute densities, and these were used in regression model development.

First, an obvious estimator for the number of larvae per tree is simply the sum of all unmarked individuals observed in the three sampling phases, defined as:

$$\hat{N}_m = \sum_{i=1}^{d} b_i + S_u + b_{d+1} \tag{1}$$

where

$\hat{N}_m$ = estimator for the number of larvae per oak tree $\geqslant$7.0 cm

d = number of days of band sampling before spray sampling

b_i = number of unmarked larvae seen at the band on day i, $i = 1, 2, \ldots, d + 1$

S_u = number of unmarked larvae obtained in the spray sample

This estimator, which yields the minimum number of larvae per tree over $d + 1$ days, is a monotonically increasing function of the band and spray efficiencies, to be discussed later. How well it approaches the true density is unknown; variances and coefficients of variation cannot be found and confidence intervals cannot be constructed. Hence, its reliability cannot be quantified.

Alternatively, an estimator that is applicable for an entire plot can be developed from the traditional Petersen estimator which is a two-sample mark-recapture technique. Generally, the methodology consists of marking individuals in one sample and then, after allowing the marked animals to randomly mix in the population, taking a second sample and recording the number previously marked. For our applications, we restricted our plot estimator to oaks greater than 7.0 cm and used band counts from only the day immediately before the spray sample. Thus, the variables for the Petersen estimator are:

$\hat{N}$ = Petersen estimator for the number of larvae on all oak trees $\geqslant$ 7.0 cm in a plot

n_1 = number of larvae found at the bands on all oak trees $\geqslant$7.0 cm in a plot on the day immediately before spray sampling

n_2 = total number of larvae obtained in the spray sample and

$m_2 = n_2 - S_u$ = number of recaptured marked larvae in the spray sample

The assumptions required for the Petersen estimator to be valid are: (a) the population size N is constant over the course of the sampling period; (b) all animals have the same probability of being caught in the first sample; (c) catching and marking does not affect future recapture; (d) the second sample is a simple random sample; (e) the animals do not lose their marks during the course of the sampling period; and (f) all marks are recognized and reported on recovery in the second sample.

Since sampling was conducted over a short time period (2 days), we believe that little instar mortality and migration took place, resulting in acceptance of the population closure assumption (a). In addition, the short sampling period and use of Accent® acrylic waterbase paint for marking allowed us to accept assumptions (e) and (f). The Petersen estimator is also sensitive to the degree of randomness of the sample distribution as revealed in assumptions (b), (c), and (d) and poor estimates may result with typical trap-addicted or trap-shy populations (Zarnoch 1979, Zarnoch and Burkhart 1980). However, when different sampling methods, namely banding and spraying trees, are used for each of the two samples, n_1 and n_2, as employed in this study, these assumptions are more likely to be satisfied since any biases in departure from randomness for each should be independent, resulting in a valid estimator.

Although the traditional Petersen estimator was derived as a maximum likelihood estimator based on the conditional hypergeometric distribution, it is biased. The Chapman modification (Chapman 1951) defined as

$$\hat{N} = \frac{(n_1 + 1)(n_2 + 1)}{(m_2 + 1)} - 1 \qquad (2)$$

is preferred since it is unbiased if $n_1 + n_2 \geqslant N$ and has a smaller expected mean square error in practical applications. All Petersen estimates calculated herein will use the Chapman modification [Equation (2)]. An approximate variance of $\hat{N}$ according to Seber (1970) is:

$$V(\hat{N}) \sim \frac{(n_1 + 1)(n_2 + 1)(n_1 - m_2)(n_2 - m_2)}{(m_2 + 1)^2(m_2 + 2)} \qquad (3)$$

which is also unbiased if $n_1 + n_2 \geqslant N$. An estimate of the coefficient of variation is

$$C(\hat{N}) \sim \frac{1}{\sqrt{m_2}} \qquad (4)$$

which indicates that the precision of $\hat{N}$ depends almost totally on the number of recaptures (Seber 1973). From a practical viewpoint, at least 10 recaptures may be required for fieldwork if a reasonable coefficient of variation is desired. This is not an unreasonable number of recaptures on an entire plot but often is on a single tree especially at sparse population levels. Thus, the Petersen estimator is not useful for absolute density estimates on an individual tree basis but is useful for plot estimates.

Confidence limits may be obtained by approximations to the Poisson, binomial, and normal distributions as described by Seber (1973). However, for simplicity, we used the normal approximation

$$\hat{N} \pm 1.96\sqrt{V(\hat{N})} \tag{5}$$

for a 95% confidence interval since $\hat{N}$ is asymptotically normally distributed.

The Petersen estimates for each plot, shown in Table 2, reveal a relatively small standard error (square root of $V(\hat{N})$) and, hence, a reliable estimate of absolute density. Since the minimum estimator has no analytical standard error, its reliability is difficult to evaluate. However, a comparison of the minimum estimator versus the Petersen may be made by summing $\hat{N}_m$ for each oak tree ≥7.0 cm on a plot. The results (Figure 1) show that at low density levels both are similar; but as density increases, the minimum tends to achieve considerably lower estimates than the Petersen.

Band and Spray Efficiencies

The reliability of the minimum estimator, $\hat{N}_m$, and the plot density estimator, $\hat{N}$, depends on the band and spray efficiencies. Estimators for the band and spray efficiencies are defined, respectively, as

$$E_b = \frac{m_2}{n_2}$$

and

$$E_s = \frac{m_2}{n_1}$$

Individual-tree band counts exhibit variability between band and spray efficiencies based on tree size and egg-mass density and alone cannot be used as an index of population trend or an estimator of absolute population density. Similarly, spray efficiencies reveal that pyrethrin may not necessarily knock down all late-instar larvae and, hence, cannot be used for population density estimates. However, there is evidence that most of the larvae were killed by the spray since few larvae were found at the band the day after spraying; i.e., b_{d+1} was low.

TABLE 2. Estimates of larval density on oaks ≥7.0 cm for each location based on an area of 354 m^2.

		Petersen		Sum[1]
Location	B_L^2	$\hat{N}$	*SE*	$\hat{N}_m$
CT 1984	254	2639	122.7	1331
CT 1985	47	8871	1437.9	3095
VT 1984	8	28	4.5	22
VT 1985	115	232	5.5	221
NY 1984	223	741	37.6	533
NY 1985	34	98	23.2	70
MA 1984	265	935	44.3	630
MA 1985	1187	8755	146.5	6610

[1] Sum of $\hat{N}_m$ tree estimates for all oaks ≥7.0 cm on each location.

[2] Number of larvae found at burlap bands at each location before spray sampling.

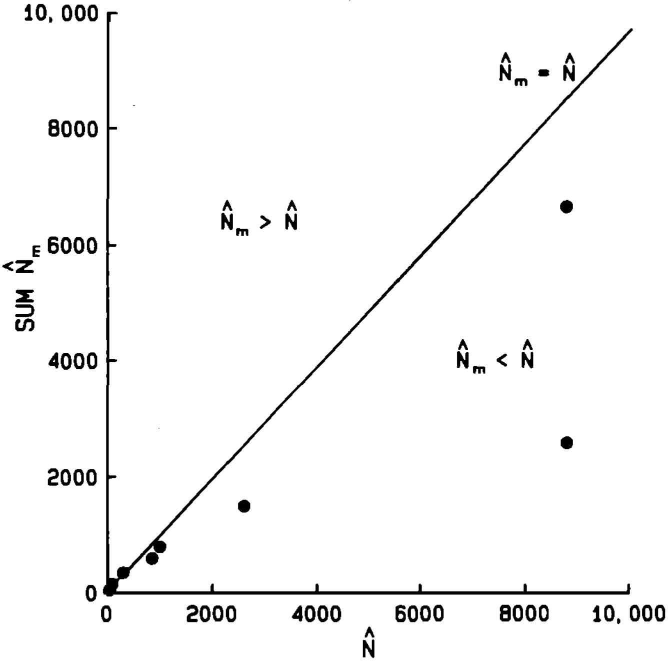

FIGURE 1. Comparison of sum of minimum estimate of unmarked larvae ($\hat{N}_m$) and Petersen estimate of marked and unmarked larvae ($\hat{N}$) on all oaks ≥ 7.0 cm for each location for 1984 and 1985.

RESULTS

INDIVIDUAL-TREE REGRESSION ESTIMATOR

In this study, the entire canopy was sprayed over a given ground area and at the same time the number of larvae falling from each tree was known. Based on the total number of larvae found on each plot by tree species, the greatest percentage of larvae was found on oak (Table 1). Linear regression models of the form $\hat{N}_m^* = b_0 + b_1 B_L$ were developed as individual tree regression estimators for each location and year where B_L is the total number of larvae observed (and marked) at a band during the day immediately before evening spray sampling of an individual oak tree. The data consisted of $\hat{N}_m$ and B_L values for all oak trees used in a specific location-year regression estimator formulation. The * indicates the predicted value of $\hat{N}_m$ from the regression as opposed to the data point. Several initial runs were made using the independent variables $\Sigma_{i=1}^{d} b_i$, and B_L, but since there was little variation in the results, B_L was chosen as the independent variable due to its proximity in time to the spray sample which should satisfy assumptions (a) and (e) more closely. Individual oak trees lacking larval counts for B_L were omitted from the analyses, as were all nonoak tree species. The results (Table 3) indicated consistency in the slopes and intercepts for sites with egg-mass density $\leq$71/ha and variability in intercepts and slopes for the three higher density sites (CT84, CT85, MA85). Overall, the slopes and intercepts appear to increase with egg-mass density. The coefficients of determination, R^2, ranged from 60–100% for plots with egg-mass densities $\leq$71/ha and 26–40% for plots with higher egg-mass densities. Combining the data from the low density ($\leq$71 egg masses per ha) locations (NY84, NY85, VT84, VT85, MA84) yielded the regression model

TABLE 3. *Individual tree regression estimators based on the model* $\hat{N}^*_m = b_0 + b_1 B_L$.

Location	Year	Regression coefficients				Egg mass density/ha[1]
		n	b_0	b_1	R^2	
CT	1984	10	60	2.9	29	495
	1985	7	877	−65	40	1600
MA	1984	25	1.7	2.2	97	39
	1985	25	109	3.3	26	1400
NY	1984	20	5.1	1.9	84	15
	1985	4	4.1	1.6	100	71
VT	1984	6	1.2	1.2	60	21
	1985	22	2.1	1.4	71	51
NY VT MA (egg masses ≤71/ha)		77	0.7	2.2	95	

[1] Egg mass density determined by the Cary Arboretum, Millbrook, NY, in similar sized plots located adjacent to our sample plots. All current year egg masses on rocks, fallen branches, leaf litter, and on tree boles up to a height of 2 m were counted in each 15-m diameter plot.

$$\hat{N}_m{}^* = 0.7 + 2.2\, B_L \tag{6}$$

with $R^2 = 0.95$ and standard error of estimate $SE = 5.95$ based on a sample size of $n = 77$ oak trees. A plot of the residuals revealed no unusual trends. Thus, using standard regression methodology (Draper and Smith 1981), a $100(1\text{-}\alpha)\%$ prediction interval for a new observation at $B_L = X_o$ may be found by

$$\hat{N}^*_m \pm 5.95\, t_{75(1-\alpha)} \sqrt{\frac{78}{77} + \frac{(X_o - 8.2)^2}{10{,}908}} \tag{7}$$

where $t_{75,\,(1\text{-}\alpha)} = 100(1\text{-}\alpha)$ percentage value from t-table with 75 degrees of freedom. The range of application is analogous to the range of B_L, which was 1 to 81 larvae per band.

PLOT REGRESSION ESTIMATOR

An alternative to an individual-tree estimator is the plot estimator based on a regression of the Petersen estimator on total larval counts under burlap bands on all oak trees ≥7.0 cm on the plot for the day before the spray sample. Preliminary larval density estimates at the four locations (Table 3) showed an increasing trend of density with band counts for Vermont, New York, and Massachusetts, but a decreasing trend for Connecticut. In 1984 and 1985, the Connecticut site and the Massachusetts site in 1985, had high defoliating populations. As reported by Liebhold et al. (1986), burlap counts under such conditions are not proportional to population density. Thus, due to this variation, only lower density plots (egg-mass density ≤71/ha) were used. After preliminary modeling and transformations, we decided that the square root of density should be used as the dependent variable since linearity was then achieved. This resulted in the model (Figure 2)

$$\sqrt{\hat{N}^*} = 5.2 + 0.096(B_L) \tag{8}$$

where B_L is the total number of larvae observed (and marked) at bands on all oak trees during the day immediately before the evening spray sampling of

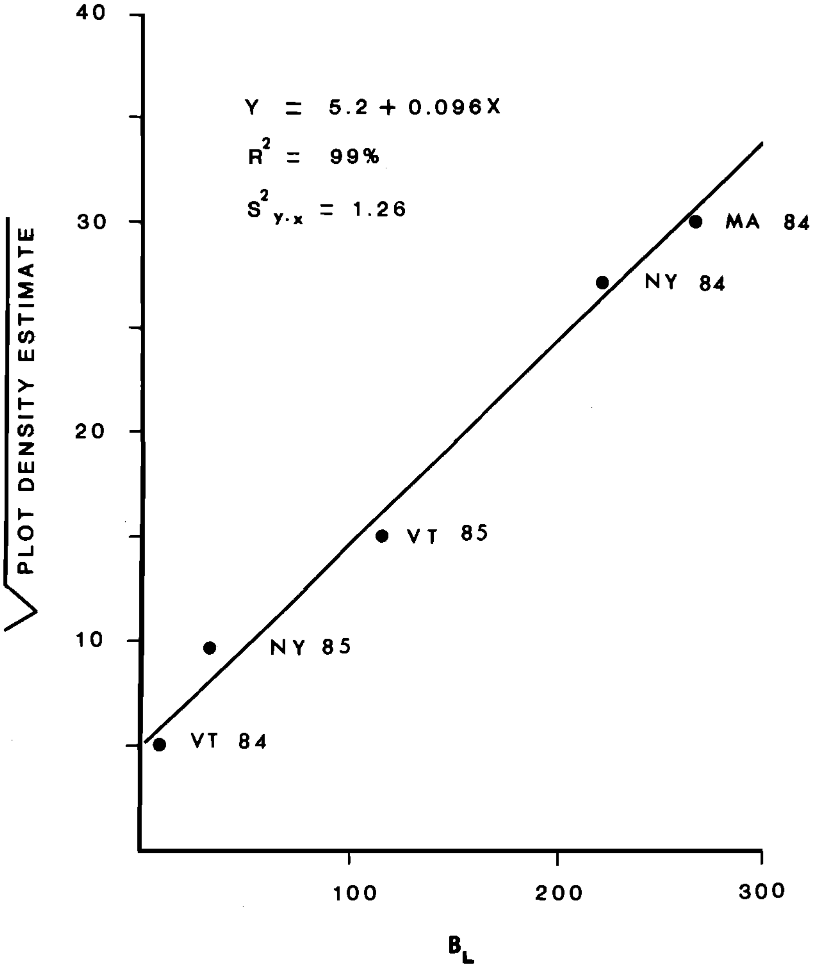

FIGURE 2. Estimates of gypsy moth larvae on all oaks ≥7.0 cm per 354 m² plot area based on larval counts beneath burlap bands *(B_L)* by location for 1984 and 1985.

the plot. The model had an $R^2 = 0.99$, a standard error of estimate $SE = 1.1$, and a sample size $n = 5$. A plot of the residuals revealed no unusual trends. A 100(1-α)% prediction interval for a new observation at a specified $B_L = X_o$ may be found by

$$\hat{N}^* \pm 1.1\, t_{3(1-\alpha)} \sqrt{\frac{6}{5} + \frac{(X_o - 149)^2}{51{,}194}} \tag{9}$$

where $t_{3(1-\alpha)}$ = 100(1-α)% value from *t*-table with 3 degrees of freedom. Squaring the confidence limits will give appropriate limits for density. The range of application of B_L is from 8 to 265.

In 1986, the model was tested by sampling two 15-m diameter plots in the Elk Neck Peninsula in Cecil Co., and three 15-m diameter plots in northeast Harford Co., MD. Procedures identical to those described in the original study were used. The plot-density regression estimator was calculated from Equation (8) and compared with the Petersen estimator, which is based on band and spray sampling and considered to be the "true" density. The results agree with the Petersen estimate except for plot 3, which contained

$\leq$40% oak and a dense larval population on all tree species (Table 4) and indicate the restrictions that apply when using the regression plot estimator in forest stands with a low oak component.

DISCUSSION

This research has resulted in the development of two late-instar larval density regression estimators, applicable on a tree or plot basis when the previous year's fall egg-mass densities are $\leq$71/ha. Initially, it was desirable to formulate an individual-tree estimator but no means were available to determine a good estimate of the true density; only the maximum number of unmarked larvae per tree ($\hat{N}_m$) was available since the larval recapture rate for individual trees was too low to apply the Petersen estimator. Hence, it was necessary to estimate larval numbers on a plot basis using the Petersen estimator applied to band counts on all oaks on the plot (Figure 2). This resulted in sufficient recaptures to achieve a satisfying level of reliability. At the mean larvae/plot beneath burlap band (B_L) level of 149 larvae, the prediction interval at the 95% level for a new observation is 246 to 545. Thus, we accepted the plot estimator as sufficiently precise, and made a comparison by applying the individual-tree estimator to each oak tree in the location and summing, hopefully approaching the plot estimator. Figure 3 illustrates the relationship that the sum of the individual-tree estimators is always less than the plot. This is as expected, because the individual-tree estimator is based on $\hat{N}_m$, a minimum always less than the true density. It is reassuring that the discrepancy is minimal at low densities, and although the plot density increases as B_L approaches 300, the proportional difference appears to be about the same. Hence, the individual-tree estimator may be used to demonstrate relative density, and perhaps absolute density. As a measure of its reliability at the mean tree B_L level of 8.2 larvae, we have $\hat{N}^*_m = 18.7$ and 95% prediction interval for a new observation of 7 to 31. Admittedly, this is a wide range, but it represents the uncertainty in estimating the density on an individual oak tree as compared with a plot of several oak trees.

The trend observed in our Connecticut study site for band counts to decrease with increasing density is attributed to the high gypsy moth density at the site. We have noted in past years that high larval population densities tend to disrupt normal diurnal behavior patterns. During daylight hours, larvae tend to remain in the crown, often close to or on leaves, and have been observed feeding. Bands attract larvae from nearby unbanded trees (Liebhold et al. 1986), a factor we considered in estimating larvae by banding

TABLE 4. Maryland validation for the plot density estimator.

Plot	B_L	Petersen N	Petersen SE	Plot density estimator N^*	Plot density estimator 95% PI	Egg mass density/ha[a]
1	108	250	25.4	242	(137,378)	59
2	47	195	23.1	94	(34,192)	0
3	337	1092	46.2	1410	(1072,1795)	74
4	185	528	49.7	527	(364,720)	74
5	38	124	39.4	78	(22,170)	25

[a] Egg mass density adjacent to sample plots determined by the Maryland Department of Agriculture. All current year egg masses on rocks, fallen branches, leaf litter, and on tree boles up to a height of 2 m were counted in each 15-m diameter plot.

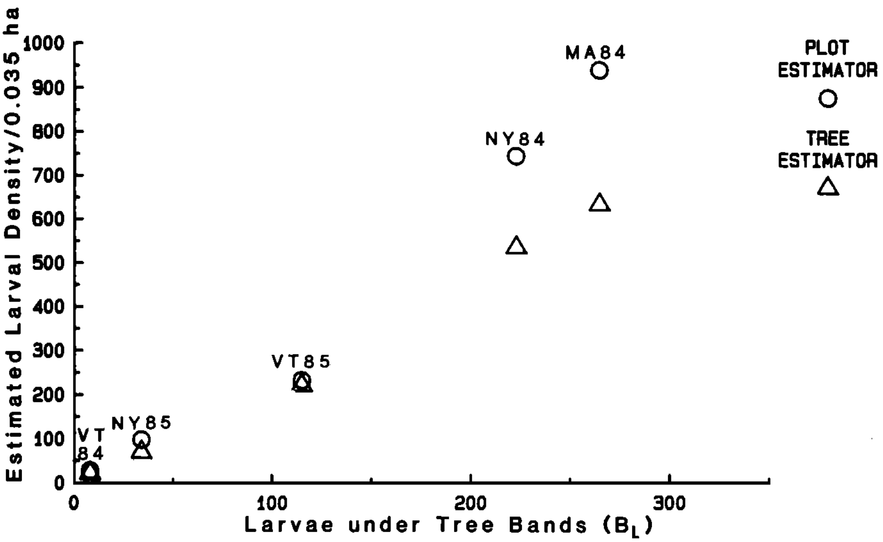

FIGURE 3. Comparison of regression tree estimator and plot estimator for each location.

all trees of one species within a plot. In our studies, the accuracy of counts of larvae beneath bands on individual trees for predicting densities present in an area of forest were unreliable due to low recapture rates. By estimating larval abundance from numbers of larvae beneath burlap bands on all oaks within a plot and applying the Petersen estimator, we achieved a high level of statistical reliability for sampling larvae at low population densities.

Precision diminished with increase in larval density, which may or may not be related to the prior year egg-mass density. For example, in validating the equation in Maryland, plot 3 was within a forest having 74 egg masses/ha, yet larval populations were high (Table 4). Presumably, elevated larval densities occurred through dispersal from a local but dense infestation at a campground about 200 m away. Dispersing and redispersing first instars can occur over a 1-month period (W. E. W. unpublished data); hence, egg-mass counts may be a misleading indicator of subsequent larval density within a discrete area. We made no attempt to ascertain egg-mass counts and subsequent numbers of larvae beneath bands over a range of egg-mass densities, but our data suggest that a reasonable level of precision can be expected at ≤75 egg masses per ha; densities ≥495 egg masses per ha are too high for accurate assessment of late-instar numbers. Burlap-band monitoring of larvae is less labor-intensive than egg-mass sampling or frass traps and may be useful by itself for predicting population trends in sparse populations. Although the regression estimators were developed from plots in the Northeast, we verified by our studies in Maryland that they may be directly applicable elsewhere. However, the estimators should be tested and validated to ascertain performance for predicting the density of late-instar gypsy moth over a broad geographical and ecological range.

LITERATURE CITED

BESS, H. A., H. SPURR, and E. W. LITTLEFIELD. 1947. Forest site conditions and the gypsy moth. Harv. For. Bull. 22.

CAMPBELL, R. W. 1967. The analysis of numerical changes in gypsy moth populations. For. Sci. Monogr. 15.

Campbell, R. W., and R. J. Sloan. 1977. Release of gypsy moth from innocuous levels. Environ. Entomol. 6:323–330.

Chapman, D. G. 1951. Some properties of the hypergeometric distribution with applications to zoological sample censuses. Univ. Calif. Publ. in Stat. 1:131–160.

Draper, N. R., and H. Smith. 1981. Applied regression analysis. Ed. 2. Wiley, New York. 709 p.

Hough, J. A., and D. Pimentel. 1978. Influence of host foliage on development, survival and fecundity of the gypsy moth. Environ. Entomol. 7:97–102.

Houston, D. R., and H. T. Valentine. 1977. Comparing and predicting forest stand susceptibility to gypsy moth. Can. J. For. Res. 7:447–461.

Lance, D. R., and P. Barbosa. 1981. Host tree influences on the dispersal of late instar gypsy moths, *Lymantria dispar*. Oikos 38:1–7.

Lechowicz, M. J. 1983. Leaf quality and the host preferences of gypsy moth in the northern deciduous forest. P. 67–82 *in* Proc. Forest defoliator-host interactions: Comparison between gypsy moth and spruce budworms, R. L. Talerico and M. E. Montgomery (eds.). USDA For. Serv., Northeast. For. Exp. Stn. Gen. Tech. Rep. NE-85. 141 p.

Liebhold, A. M., and J. S. Elkinton. 1988. Techniques for estimating the density of late-instar gypsy moth, *Lymantria dispar* (Lepidoptera: Lymantriidae), populations using frass drop and frass production measurements. Environ. Entomol. 17(2):381–384.

Liebhold, A. M., J. S. Elkinton, and W. E. Wallner. 1986. Effect of burlap bands on between-tree movement of late-instar gypsy moth, *Lymantria dispar* (Lepidoptera: Lymantriidae). Environ. Entomol. 15:373–379.

McManus, M. L., and H. R. Smith. 1984. Effectiveness of artificial bark flaps in mediating migration of late-instar gypsy moth larvae. USDA For. Serv., Northeast. For. Exp. Stn. Res. Note 316.

Seber, G. A. F. 1970. The effects of trap response on tag recapture estimates. Biometrics 26:13–22.

Seber, G. A. F. 1973. The estimation of animal abundance. Hafner Publ., New York. 506 p.

Southwood, T. R. E. 1966. Ecological methods. Metheun, London.

Wallner, W. E. 1971. Suppression of four hardwood defoliators by helicopter application of concentrate and dilute chemical and biological sprays. J. Econ. Entomol. 64:1487–1490.

Wallner, W. E. 1983. Gypsy moth host interactions: A concept of room and board. P. 5–8 *in* Proc. Forest defoliator-host interactions: Comparison between gypsy moth and spruce budworms, R. L. Talerico and M. E. Montgomery (eds.). USDA For. Serv., Northeast. For. Exp. Stn. Gen. Tech. Rep. NE-85. 141 p.

Wilson, R. W., and G. A. Fontaine. 1978. Gypsy moth egg mass sampling with fixed- and variable-radius plots. USDA Agric. Handb. 523. 46 p.

Zarnoch, S. J. 1979. Simulation of effects of learned trap response on three estimators of population size. J. Wildl. Manage. 43:474–483.

Zarnoch, S. J., and H. E. Burkhart. 1980. A simulation model for studying alternatives in mark-recapture experiments. Ecol. Model. 9:33–42.