

EGG MASS SAMPLING PLANS FOR GYPSY MOTH MANAGEMENT PROGRAMS

by

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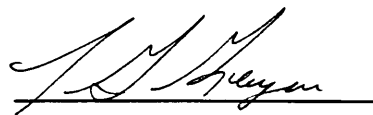


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(ABSTRACT)

The goal of this research was to develop gypsy moth egg mass sampling plans that reflect the influence of habitat, changes in egg mass distribution, and provide populations densities or density categories for making control decisions.

Sequential egg mass sampling plans for gypsy moth management programs in urban and suburban habitats were developed from 0.01 ha fixed-radius plot samples collected in Loudoun, Fairfax, and Arlington Counties, Virginia. The sampling plans were developed from Wald's sequential probability ratio test and is based on a negative binomial distribution. Operating characteristic and average sample number curves were used to determine the acceptability of the sampling plans. Three sampling plans were developed for the action thresholds of 618, 1,236, and 2,471 egg masses/ha.

The use of binomial sampling for low density (<618 egg masses/ha) gypsy moth populations in continuously forested habitats was examined. Fixed- and variable-radius plot egg mass samples were collected in 28 study areas in Virginia, Maryland, and Massachusetts. The relationship between egg mass density and the proportion of trees with zero egg masses was developed. Binomial sampling resulted in a higher relative variability and lower relative efficiency than the fixed- and variable-radius plot sampling method. Binomial sampling was determined not to be an effective sampling method for gypsy moth populations below 618 egg masses/ha.

Fixed- and variable-radius plot egg mass samples were taken when leaves were present (summer) and absent (winter) in 136 sample sites in Virginia. A significant difference between summer and winter counts was determined. The relationship between summer and winter counts was quantified using nonparametric statistics. Winter egg mass counts were found to be 14 to 34 percent higher than summer egg mass counts. The probability of a summer egg mass count exceeding an action threshold was constructed by fitting a logistic curve to empirical data for the action thresholds of 618

and 1,236 egg masses/ha. Egg mass counts need to compensate for differences between summer and winter counts. Alternatively, the probability of a summer egg mass count exceeding an action threshold should be utilized.

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Chapter 1

Introduction

History and Distribution. The gypsy moth (Lepidoptera: Lymantriidae) Lymantria dispar, is a native pest of European and Asian countries and an introduced pest of eastern forests in the United States (Fig. 1). The gypsy moth's habitat is primarily in temperate regions of the World. This includes central and southern Europe, northern Africa, and central and southern Asia, including Japan and Ceylon (Forbush & Fernald 1896). The gypsy moth's range extends from a latitude of 20° N in southeastern Asia to about 58° N in Sweden, Norway and Eastern Russia (Leonard 1974). In this region there are two strains of the gypsy moth, the Asian and European, which are closely related.

The gypsy moth was intentionally imported to the United States by Leopold Trouvelot, an astronomer and naturalist. Trouvelot was attempting to cross the gypsy moth with the silkworm moth to develop a hardy strain of silk-producing insects for a commercial silk industry. In 1869, an unknown number of gypsy moth larvae escaped from Trouvelot's home in Medford, Massachusetts. The gypsy moth went relatively undetected for the first twenty years after its release until the first extensive outbreak occurred in 1889 in Medford. Since that time the biology and spread of the gypsy moth has been well studied and documented (Fernald & Fernald 1896, Bess 1961, Doane & McManus 1981, Elkinton & Liebhold 1990).

Over the last 120 years, the distribution of the gypsy moth has expanded from Massachusetts throughout the northeastern states, south to North Carolina, and west to Wisconsin. The gypsy moth has expanded north into Canada and spot infestations have been found throughout the United States including Washington, Oregon, California, Iowa, and Utah (Fig. 2). In 1991, a population of the Asian gypsy moth strain was identified in Washington, Oregon, and Vancouver, BC. The potential for the Asian gypsy moth to become a serious pest to western forests has not yet been determined but eradication of the Asian gypsy moth is being attempted.

Biology and Ecology. The gypsy moth is a univoltine insect. First instar larvae hatch in mid-April to mid-May usually coinciding with bud break (Fig. 3). The larvae will feed on over 300 species of trees and shrubs (Lechowicz and Mauffette 1986). Preferred species include all oak species (Quercus spp.), aspen (Populus spp.), birch,

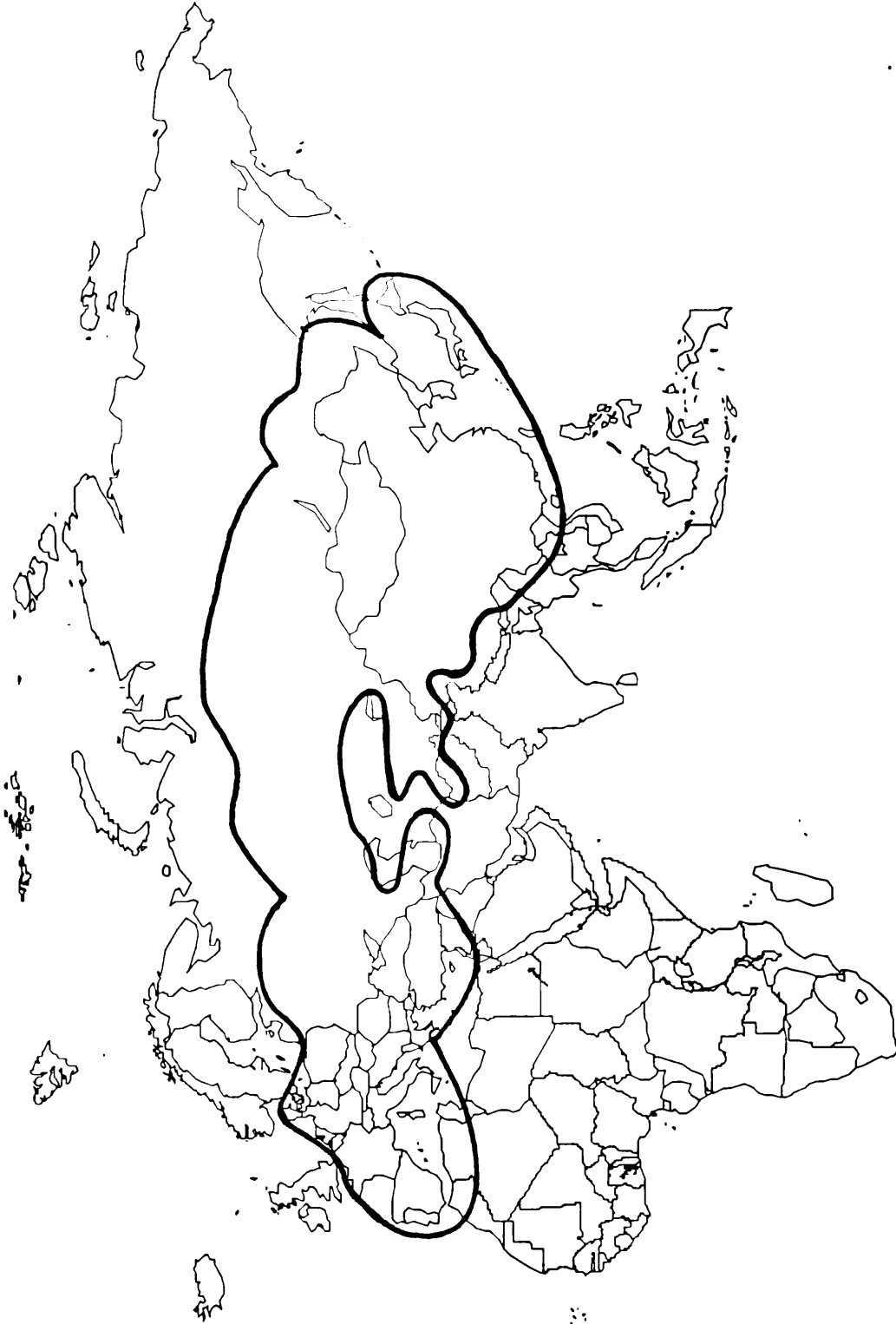
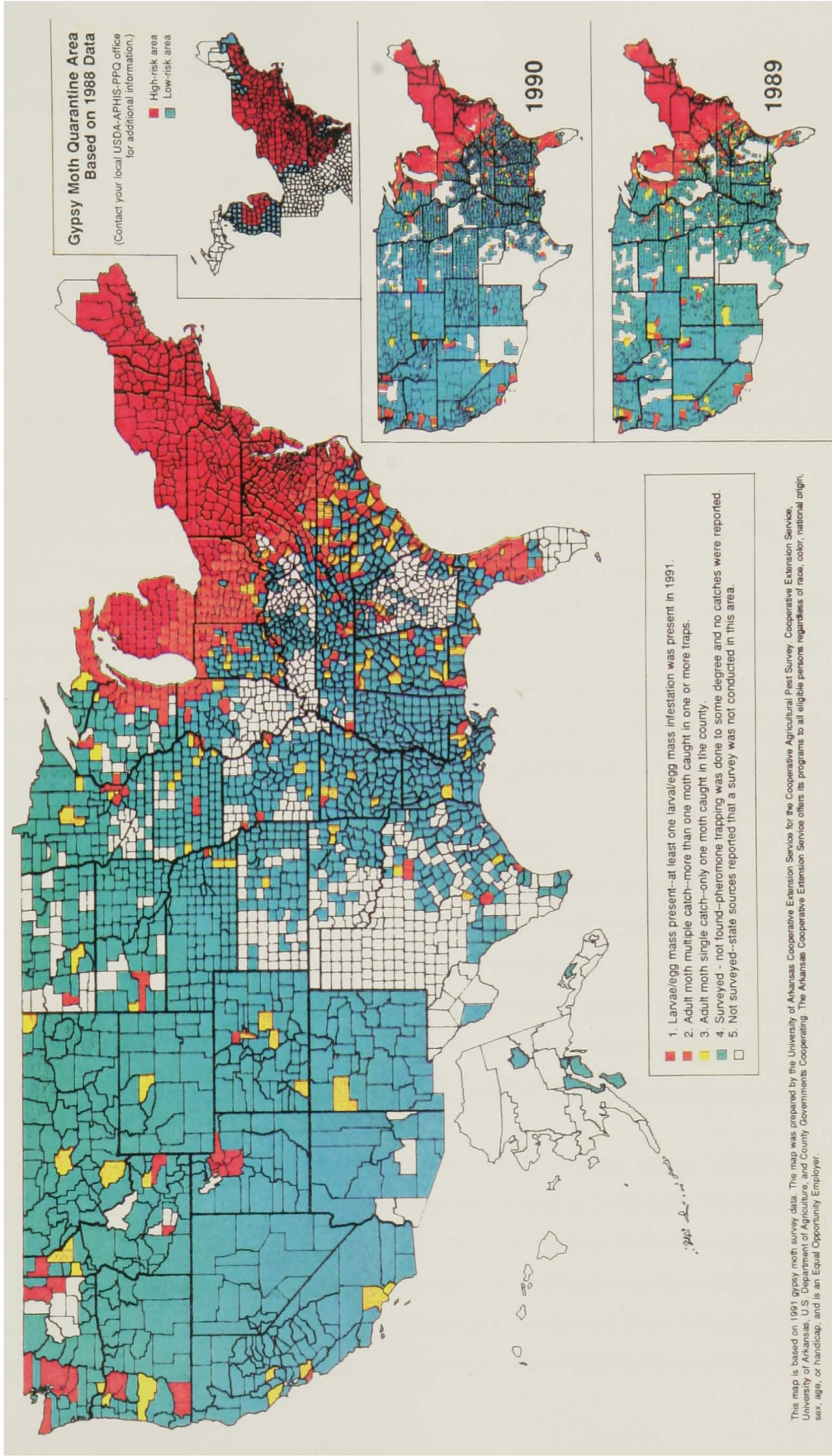


Fig. 1. Range of gypsy moth distribution which includes central Europe, northern Africa, and southern Asia, including Japan and Ceylon. Gypsy moth range is enclosed within the black lines (Anon. 1953).

Gypsy Moth Survey - 1991



(*Betula* spp.) or apple (*Malus* spp.) which often become defoliated during population outbreaks (Table 1).

Table 1. European Gypsy moth host plant preferences (Mason 1987).

Class I: Species that are favored for all life-stages

Overstory: apple, basswood, bigtooth aspen, quaking aspen, gray, paper, and river birch, boxelder, larch, American mountain-ash, all oak species, lombardy poplar, sweet gum, willow.

Understory: alder, hawthorn, hazelnut, eastern hophornbeam, serviceberry, all sumac species, witch-hazel.

Class II: Preferred species fed upon for 4th instars and older.

Overstory: chestnut, eastern hemlock, all pine species, all spruce species.

Class III: Nonpreferred species fed upon by 4th instars and older.

Overstory: American beech, black and yellow birch, blackgum (tupelo), Ohio and yellow buckeye, butternut, sweet and black cherry, eastern cottonwood, cucumbertree, American and slippery elm, hackberry, all hickory species, Norway, red silver, and sugar maple, pear, silver poplar, sassafras, black walnut.

Understory: blueberries, pin and choke cherry, American hornbeam, paw paw, persimmon, redbud, sourwood, sweetfern.

Class IV: Nonpreferred species that are rarely fed upon.

Overstory: all ash species, baldcypress, *Catalpa*, eastern redcedar, balsam and fraser fir, American holly, horsechestnut, Kentucky coffee-tree, black and honey locust, mulberry, sycamore, tulip-tree (yellow poplar).

Understory: all *Azalea* species, dogwood, elderberry, grape, greenbrier, juniper, mountain and striped maple, *Rhododendron*, all *Rubus* species, sheep and mountain laurel, spicebush, sarsparilla, all *Viburnum* species.

Male larvae typically have five instars and females have six instars but an additional molt is common for both sexes. The larvae will pupate beginning in mid-June continuing through mid-July. Pupae remain in cocoons for about two weeks before emerging as adults. The main difference between sexes becomes apparent during the adult stage. The adult male is typically a mottled brown color, emerges one to two days before females, and is capable of flight. The adult female is a whitish color with black markings and

although she has fully formed wings, is incapable of flight in the European strain. Females emit a pheromone to attract males for mating which occurs soon after emergence. The eggs are laid in an oval shaped egg mass which is covered with buff-colored hairs from the female's abdomen. Oviposition occurs from late June to mid-August. Each egg mass contains from 100 to over 1500 eggs (Carter 1991). Egg masses are generally laid in protected areas such as the underside of tree limbs, bark cervices, under rocks, or on man-made objects. Eggs develop into a pharate first instar larvae before overwintering.

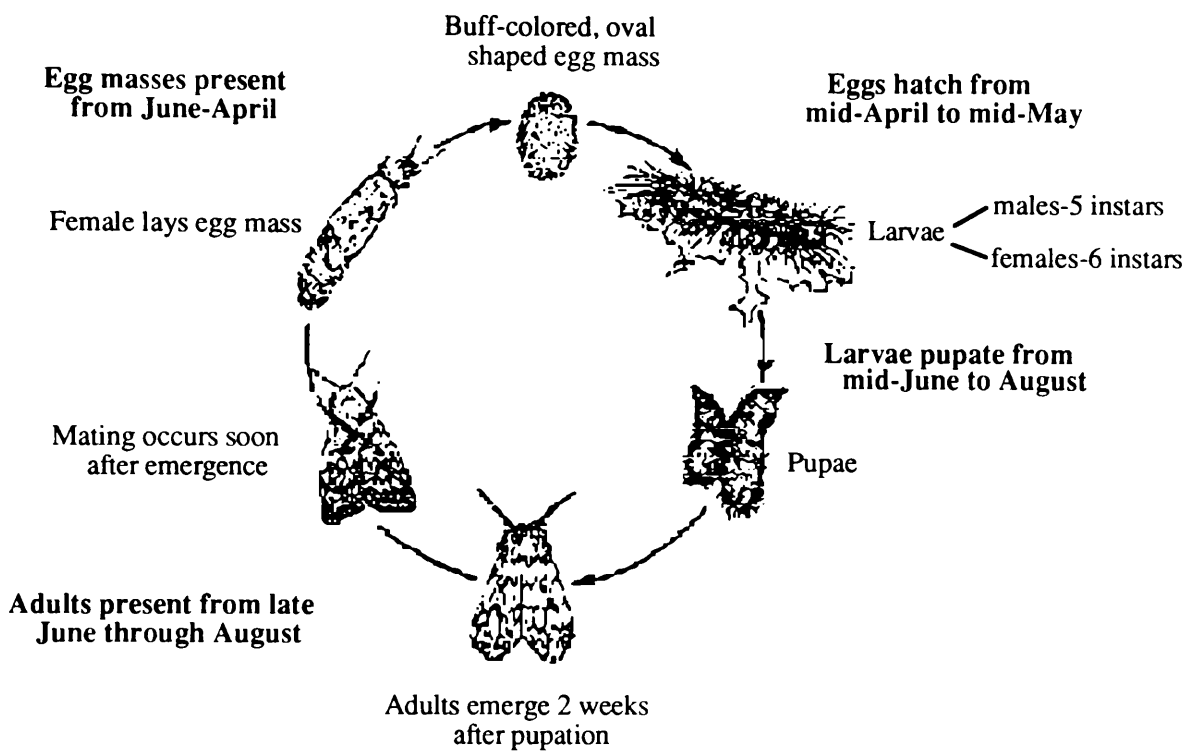


Fig. 3. Gypsy moth life cycle indicating time of occurrence of various life stages

Gypsy moth populations in Northern America have been described as numerically bimodal and have four distinct population phases. Campbell and Sloan (1978) described the four phases as innocuous, release, outbreak, and decline. In areas where the gypsy moth has established populations, the innocuous and outbreak phases are relatively stable phases while the release and decline are considered transient phases. The innocuous phase is characterized by populations remaining at relatively low densities over many

years (2 to 25,000 fourth-instar larvae per hectare). These populations may experience a rapid increase in density (release phase) resulting in outbreaks. An areawide outbreak is characterized by fourth-instar larval densities of 250,000 to 2,500,000 larvae per hectare and results in extensive defoliation. Outbreak populations begin to decline after several years. Population decline is hypothesized to be a result of overpopulation leading to increased disease, reduced fecundity, and starvation. In leading edge areas¹ the population dynamics vary from established populations and outbreaks often occur only two to three years after initial infestation.

Gypsy Moth Management. In 1891, Massachusetts appropriated money to eradicate the gypsy moth. Over the next nine years eradication efforts in Massachusetts resulted in successfully reducing the infestation. Early eradication efforts involved applying creosote or acid to egg masses, burning infested trees and shrubs, hand removal of larvae and egg masses, trapping larvae with burlap or sticky bands on trees, and applying arsenical poisons such as Paris green (Forbush & Fernald 1896, Kirkland 1905, Burgess 1930). By 1900 Massachusetts ceased eradication efforts thus allowing gypsy moth populations to begin to increase and spread again.

In 1912, the federal government enacted a domestic quarantine against the gypsy moth to help reduce the spread and prevent infestation of new areas. A barrier zone was established from Canada to Long Island, NY in 1923. Although all infestations within and west of the zone were to be eradicated, the barrier zone was generally infested by 1939. Despite increased efforts to find effective natural enemies, the use of DDT and other chemical controls, it was realized that attempts to eradicate the gypsy moth were futile (McManus and McIntyre 1981).

In the 1970's emphasis was placed on developing management techniques to minimize the effects of the gypsy moth and reduce its spread. Additional research on monitoring techniques, population dynamics, and addition control methods were conducted to develop effective management programs. Control tactics for the gypsy moth includes natural enemies, synthetic insecticides, and microbial insecticides. Parasitoid and predator research has been ongoing since the early 1900's and is reported by Forbush & Fernald 1896, Howard & Fiske 1911, Stefanov & Keremidchiev 1961, and Leonard 1974. Imported natural enemies of larvae, pupae, and eggs have been successful

¹The leading edge is defined as areas newly invaded by the gypsy moth but contiguous with generally infested areas to the north and east. Leading edge areas are experiencing gypsy moth related defoliation for the first time (Carter et al. 1991).

in maintaining low density populations but alone are incapable of preventing outbreaks. Gypsy moth parasites include Ooencyrtus kuvanae (How.) (egg), Parasetigena silvestris (R.D.) (larvae), Compsilura concinnata (Meigen) (larvae), and Brachymeria intermedia (Nees) (pupa). Predators include vertebrates such as birds, the white-footed mouse, short-tailed shrew, and invertebrate predators including several species of Calosma (Leonard 1974). Chemical controls have included lead arsenate, DDT, carbaryl (Sevin[®]), organophosphates, and an insect growth regulator (Dimilin[®]) (White et al. 1981). Microbial controls include Bacillus thuringiensis Berliner (Bt) and the gypsy moth nucleopolyhedrosis virus (NPV) (Dubois 1981). Presently insecticide treatment of infested areas is conducted with either diflubenzuron (Dimilin[®]), Bt, or NPV. Other control tactics include the use of disparlure for mating disruption in low density populations (Cameron 1973), release of sterile males (Mastro et al. 1981), and silvicultural techniques (Gottschalk 1986).

Gypsy moth populations are monitored with larval, pupal, and egg mass samples, pheromone-baited traps, and defoliation surveys (Ravlin et al. 1987). Pheromone-baited traps have been used to determine population densities but a relationship between the number of males captured and population density has not been determined due to changes in trap efficiency as traps fill and become saturated (Elkinton 1987, Bellinger et al. 1990). Egg mass surveys are the primary method used for making control decisions. Prior to 1991, there were few attempts to develop egg mass sampling plans or sample units which has resulted in thirteen different sampling protocols being used in thirty-two management units (Ravlin et al. 1987).

Gypsy moth action thresholds (treatment thresholds) were determined by Etter (1979). Three common action thresholds are 618, 1,236, and 2,471 egg masses/ha (250, 500, and 1,000 egg masses/ac., respectively). These action thresholds were developed based on the relationship between the number of egg masses and the percent of defoliation which occurs (Campbell 1973).

Egg Mass sampling methods. The most common egg mass sampling methods are fixed- and variable-radius plots (Wilson & Fontaine 1978), fixed-radius plots (Kolodny-Hirsch 1986), and timed walks (Eggen & Abrahamson 1983). Fixed- and variable-radius plot sampling involves examining two sample units: first, a variable-radius plot within which trees are selected using an angle gauge or prism with the probability of selection proportional to the tree's basal area, and then, second, a fixed plot of 1/200th acre fixed-radius (radius = 2.53 m) located at the center of the variable-radius

plot. All substrates within both plots are searched for egg masses including trees and the ground. Rocks, fallen limbs, and artificial substrates are carefully examined for egg masses. The objection to fixed- and variable radius sampling is that it is time consuming usually requiring one man-hour per sample (Ravlin 1991).

Fixed-radius sampling involves examining all substrates within a 0.01 ha or 0.04 ha plot. Kolodny-Hirsch (1986) determined that 0.01 ha (1/40th acre) plots were the most efficient sample size and, currently, are more commonly used. A 0.01 ha plot survey is conducted by counting all substrates within a 5.65 m (18.6 feet) radius circle for new egg masses. Fixed-radius sample plots reduce the cost and maintain the same precision as fixed- and variable-radius plots but are still time consuming.

To minimize time and costs, Eggen and Abrahamson (1983) developed timed 5 minute walks. This technique involves two surveyors walking along a straight line for 5 minutes and counting all egg masses seen. At the end of the five minutes the two counts are averaged and a regression relationship is used to relate the counts to an area-wide egg-mass density count. Although timed-walks have the advantage of covering large areas in a short time, variability among agencies, individuals, population density, and habitat prevent the use of this technique over large geographic areas (Fleischer et al. 1991, Liebhold et al. 1991).

Sequential and Binomial Sampling Plans. The need for rapid yet reliable sample methods for pest managers has become increasingly important for implementation of pest management programs. Sequential sampling plans have been found to be very useful in integrated pest management programs because they allow the manager to rapidly classify population densities into broad categories such as low, medium, or high with a minimum number of samples. Sequential sampling was developed during World War II for quality control work in munitions plants (Wald 1945). It was first used for entomological surveys almost ten years later and has since been used for many agricultural and forest insect surveys (Stark 1952, Waters 1955, Harcourt 1966, Allen et al. 1972, Hollingsworth & Gatsonis 1990). Sequential sampling is appealing because the sample size is not fixed but dependent on the relationship between population density and action thresholds. Populations that are sparse or dense require very few samples while populations near action thresholds demand more effort.

Sequential sampling plans require that the action thresholds and the acceptable levels of risk of making a wrong decision be predetermined. Several mathematical models have been devised to develop sequential sampling plans. Probability models can

be used to calculate the probability of observing a particular count given one or more population parameter. The most commonly used probability models include the Poisson and negative binomial. The Poisson model describes counts which have a random distribution where the variance is equal to the mean. The Poisson distribution has a single parameter of the mean, m . The negative binomial model is used to describe populations that are aggregated or clumped resulting in the variance being greater than the mean. The negative binomial distribution has been used to describe many biological populations and is represented by two parameters, the mean and an index of aggregation, k .

Calculation of the index of aggregation. The index of aggregation can be calculated using several methods (Anscombe 1949, 1950, Bliss & Fisher 1953, Debauche 1962). A simple but approximate method is

$$k = \frac{\bar{x}^2}{s^2 - \bar{x}}. \quad [1]$$

Eq. 1 is efficient for low density populations but is not reliable for populations that show a moderate degree of clumping (i.e., a k of 3 or less). A second method is more efficient:

$$\log\left(\frac{N}{n_0}\right) = k \log\left(1 + \frac{\bar{x}}{k}\right). \quad [2]$$

In Eq. 2, N is the total number of samples, n_0 is the number of samples containing no animals ; and k is solved iteratively. This method works well for populations with small means, but for populations with large means this method only works where there is extensive clumping. These two methods should be used as first steps towards the more accurate method of maximum likelihood. The maximum likelihood equation is

$$Z_i = \sum \left(\frac{A_x}{k_i + x} \right) - N \ln \left(1 + \frac{\bar{x}}{k_i} \right) \quad [3]$$

where A_x is the accumulated frequency of sample units containing more than x individuals and k_i are the successive values of k used in the iterative procedure.

Descriptions of these methods and the calculation of a common k can be found in Southwood(1978) and Elliott (1977).

Sequential sampling plans based on a negative binomial distribution include Wald's (1947) sequential probability ratio test (SPRT). The primary objection to sampling plans based on probability models is that parameters do not allow for changes in distribution with changing density. Nyrop and Binns (1991) showed that despite the variability, use of the negative binomial distribution should not be discarded and it is often superior to other methods. The benefits to using probability models is that the

sampling plans developed are often better sampling schemes than empirical models and when attempting to analyze the performance of the sampling plan, probability models allow for simulated sampling by generating random variables from a distribution (Nyrop & Binns 1991).

In contrast to probability models (eg., Poisson or negative binomial), a second group of models are empirical and are used to determine variance -mean relationships. Two commonly used variance-mean models are Taylor's Power Law and Iwao's patchiness regression (Taylor 1961, Iwao 1968, respectively). Taylor's Power Law uses the following equation to relate the variance (s^2) to the mean (m):

$$s^2 = am^b.$$

This relationship has been found to hold over a wide variety of population densities and species. The parameter b is a measure of the degree of clumping in a population and is generally constant for a species. Populations are considered random when $b=1$, are clumped when $b>1$ and uniform when $b<1$. Taylor's power law has generally provided a better fit to data than Iwao's mean crowding (Nyrop & Binns 1991).

Iwao (1986) determined that Lloyd's (1960) mean crowding index was linearly related to mean density. Mean crowding is defined as the mean number of other individuals per individual per quadrant and is calculated as:

$$mc = m + \left(\frac{s^2}{m-1} \right).$$

The parameters of the mean crowding index and the mean are linearly related by

$$mc = a' + b' m$$

where a' and b' have been used to distinguish these parameters from those of Taylor's Power Law. The parameters a' and b' are biologically relevant with a' referring to the basic sample unit of the population and b' describing the spatial pattern of the sample unit (i.e., uniform, random, or clumped).

Once a probability or empirical model has been chosen, sequential sampling plans can be developed using the appropriate stop line formula (Waters 1955, Green 1970, Fowler & Lynch 1987, Iwao 1975). When the purpose of the sample plan is to make a management decision, classification of the population as either above or below an action threshold is justified. Sequential sampling involves using the cumulative number of individuals sampled to determine if sampling should continue or can stop because a decision that the population is above or below an action threshold can be made (Fig. 4).

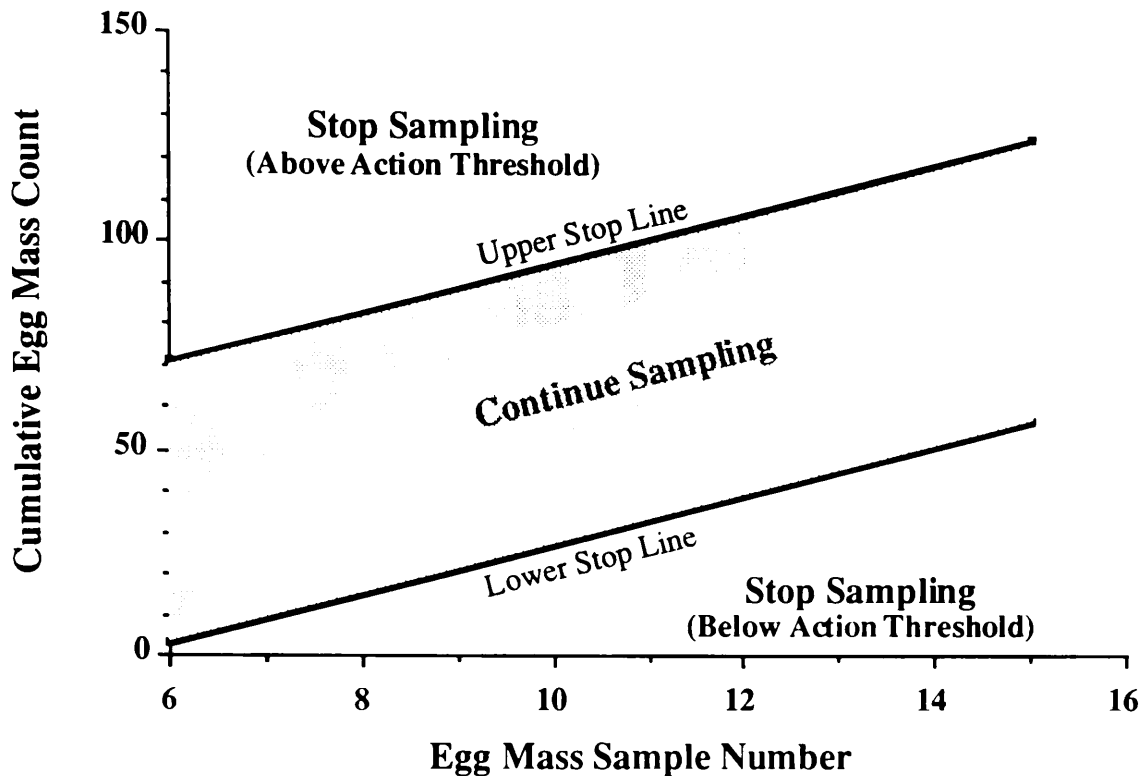


Fig. 4. Sequential sampling plan

If no decision is reached, an additional sample is taken and the count is added to the cumulative number and compared to the stop lines again. Sampling continues until the population is classified as above or below the threshold or a maximum number of samples is taken. Operating characteristic curves and average sample number curves are used to evaluate the performance of the sample plan. The operating characteristic curve is the probability of accepting (whether correctly or not) that the population mean is less than a lower stop line. The average sample number is the average number of observations required to classify a population given any true population density.

Binomial sampling. Binomial sampling is based on the relationship between the density of organisms in a sample unit and the proportion of sample units with more than T organisms, where T is referred to as the tally or cutoff threshold. Binomial sampling is appealing when populations are at very low densities or organisms are very small and abundant, such as mites. Binomial sampling is usually simpler, less time consuming, and less costly but there is increased uncertainty requiring more samples to estimate or categorize a population with a certain degree of precision.

When using a binomial sampling plan the only information retained from the sample unit is if an organism at or below the tally threshold is present or absent in the sample unit. Traditionally a tally threshold of 0 has been used but the use of a different threshold (i.e., tally threshold of 1, 2, 3,...) has been suggested (Binns & Bostanian 1990a). Binomial sample plans have been developed for several agriculture and forest insects (Gerrard & Chiang 1970, Nachman 1984, Lysyk & Sanders 1987, Lysyk & Schaalje 1992, Nyrop et al. 1989).

Binomial sampling plans can be based on either a probability model or an empirical model. Binomial sampling using probability models include the use of the negative binomial distribution (Pielou 1960, Binns and Bostanian 1988, 1990a, Nyrop et al. 1989, Jones 1991). The consequences of using a negative binomial distribution with the parameter k was discussed by Binns and Bostanian (1988, 1990a) who suggested that an appropriate choice of the tally threshold could minimize the effects of a variable k . Empirical models have been used by Kono and Sugino (1958), Gerrard and Chiang (1970), Nachman (1981), Kuno (1986), and Binns and Bostanian (1990b). The empirical model uses two parameters, a and b , which can be estimated from the linear regression of $\ln(\text{mean})$ on $\ln(-\ln(P_T))$. The independent variable, P_T , is defined as the proportion of samples with individuals at or below the tally threshold. Complete descriptions of fixed sample size or sequential binomial sampling using either the negative binomial or empirical models can be found in Kuno (1989), Nyrop and Binns (1991), or Binns and Nyrop (1992).

Gypsy Moth Egg Mass Sequential Sampling Plans. To provide gypsy moth managers with time and thus cost-saving egg mass sampling plans, sequential sampling plans were developed for eastern hardwood forests for integrated pest management programs (Fleischer et al. 1991). Previously, sequential sampling plans based on eastern Maryland forested woodlots were developed but validation and implementation were not considered (Kolodny-Hirsch 1986). Kolodny-Hirsch assumed that egg masses were contagiously distributed and calculated a common k of 1.08. Fleischer et al. (1991) assumed a negative binomial distribution and used a common k of 1.1 to develop sample plans based on three action thresholds. These sample plans require a minimum number of four samples per 1-km² cell and a maximum of ten samples. Fleischer et al. (1991) determined that an average savings of about four samples per 1-km² cell or a savings of about 40% in labor cost could be obtained using the sequential sample plan compared to a fixed sample plan.

Gypsy moth egg mass sampling research needs. The gypsy moth is an urban pest as well as a forest pest. The first outbreaks occurred in urban habitats where the gypsy moth not only caused extensive defoliation but was a great nuisance (Forbush & Fernald 1896). Early reports of the gypsy moth problem were numerous and suggest the extent of the infestation.

"In 1889 the apple-trees in our neighborhood were attacked and stripped by the gypsy-moth caterpillars. They fed on the apple trees until there was nothing more to eat, and then started for the elms on the street. In the morning following the night when they finished on the apple trees they were to be seen crossing the fence in swarms in the direction of the large street elms. They were crawling fast, and were plainly heading for the elms (Miss Helen T. Wild)."

"For several summers the women folks on our street made a regular business of killing caterpillars. We got fairly worn out catching them. I have seen Mrs. Mayo, across the way, sweep the caterpillars up in the gutter in great piles and burn them... Another of our neighbors had the whole front of her house practically covered with caterpillars. One could hardly go outdoors without getting caterpillars on the clothing. You could see them travelling about. When they were thickest we did not pretend to go out the front door at all. We had the front doorsteps torn up, and found underneath a good many nests. There were thousands of eggs and caterpillars under the underpinning of the houses. In 1889 they got into our cellar, and we had it whitewashed. When the caterpillars were very small they would get all over the washing when it was hung out (Mrs. R. Tuttle, Forbush & Fernald 1896)."

Today, the gypsy moth is still a problem in human inhabited areas. County gypsy moth programs are often initiated in infested areas to reduce the effect of this pest. Gypsy moth managers are responsible for monitoring and control of the gypsy moth which requires a substantial budget. In Virginia, a survey of county budgets in infested areas ranged from approximately 100,000 to 1.3 million dollars (Carter, personal communication).

Gypsy moth managers may have a wide range of habitats to sample including forested, suburban, and urban. Sampling techniques should correspond to these different

habitats. Urban and suburban habitats are not the same as forested habitats due to the influence of man and man-made objects which contribute to changes in the spatial distribution of gypsy moth egg masses and to sampling variability among habitats. Alteration of the habitat by man has increased the gypsy moth problem by providing artificial substrates for oviposition such as signs, doghouses, fences, etc. (Leonard 1981). discontinuous tree cover, grassy undercover, and a lower density of trees also contribute to the gypsy moth problem in urban/suburban habitats. The spatial distribution of egg masses has been shown to be influenced by man-made objects and the forest edge which causes the distribution to differ from continuously forested habitats (Campbell & Sloan 1977, Campbell 1981, Bellinger et al. 1989).

Most county programs use egg mass samples to make treatment decisions. Federal and State cooperative suppression programs use an action threshold of 618 egg mass/ha and require that there be at least 1 house per 62 hectares (25 acres) in a spray block. Thorpe et al. (1992) examined egg mass survey methods in urban areas. It was determined that 0.01 ha egg mass surveys were the most efficient and 70% of egg masses were found on trees. As federal, state, and county programs experience increased budget constraints, the need for egg mass sampling plans which minimize the number of samples but are accurate is apparent. Sequential sampling plans would be beneficial but the forested sequential sample plans are not appropriate due to the differences in habitat and effects of man-made objects which influences the distribution of egg masses (Thorpe et al. 1992). For county gypsy moth programs, the need for sampling plans which are habitat specific is apparent. The development of sampling plans for urban and suburban habitats is necessary for managers to have accurate and time saving egg mass sampling plans for all habitats.

In low density populations in forested habitats, egg mass spatial distributions may differ from high density populations. Fleisher et al. (1991) determined that areas which were within a previous year's spray block had a variance much less than the mean. This would suggest that a negative binomial distribution would no longer fit the data and prohibits the use of a sequential sampling plan developed for forests. Kolodny-Hirsch (1986) also stated that sampling low density populations (i.e., <250 egg mass/ha) would be labor intensive using an absolute sampling method and a fixed level of precision $\leq 25\%$. It was estimated that a minimum of five hours of labor would be required to sample a population of 247 egg masses/ha (100 egg mass/acre) and it was suggested that populations should be classified into broad categories for sampling. Egg mass sampling

methods may also not be appropriate for low density populations. Fixed- and variable-radius plot surveys were not recommended for populations below 247 egg mass/ha. Since traditional egg mass sampling methods and plans have been shown to be inappropriate, use of binomial sampling may be an appropriate method which would allow rapid sampling over a large geographic region and provide accurate egg mass densities.

Gypsy moth managers have time restrictions due to state and federal cooperative spray programs. Managers are required to have treatment areas determined by November (D. Twardus, personal communication) which means that egg mass surveying must occur as early as possible. Wilson and Fontaine (1978) reported that the presence of leaves has little effect on egg mass sampling counts so sampling could begin as soon as moth flight had ceased. Since leaves restrict the visibility of the upper canopy of trees it would seem that summer egg mass counts would differ from winter egg mass counts. If egg masses were being overlooked this would cause the egg mass density to be underestimated which could effect control decisions based on these estimates. Gypsy moth managers need to be confident that the populations estimates taken are accurate for proper control decisions to be made so the relationship between egg mass samples taken with leaves present or absent was examined.

Research Objectives

The goal of this research was to develop and validate gypsy moth egg mass sampling plans that optimize allocation of limited resources of labor, time, and money while producing accurate measures of population densities or categories. Specifically, the objectives are to develop egg mass sampling plans that reflect the influence of habitat, changes in egg mass distribution, and provide population densities or density categories for making control decisions and to improve the understanding of the relationship between egg mass sample counts when leaves are present and absent to provide managers with accurate egg mass density estimates. The objectives of the three studies conducted are listed below and the results are presented in the following chapters.

Chapter 2. *Sequential egg mass sampling plans for gypsy moth management.*

The objective of this study was to develop and validate sequential egg mass sampling plans for gypsy moth management decisions in urban and suburban habitats.

Chapter 3. *Binomial egg mass sampling plans for low density gypsy moth populations.* The objective of this study was to develop binomial sampling plans for low density populations (<618 egg masses/ha) to provide accurate population estimates in continuously forested habitats.

Chapter 4. *Relationship between gypsy moth egg mass sample counts when foliage is present or absent.* The objectives of this study were to 1) determine if there is a significant difference between summer and winter egg mass counts, 2) quantify the relationship between summer and winter counts, and 3) determine the probability of exceeding an action threshold when samples are taken in the summer.

REFERENCES CITED

- Allen, J., D. Gonzalez, & D. V. Gokhale. 1972. Sequential sampling plans for the bollworm, *Heliothis zea*. *Environ. Entomol.* 1: 771-789.
- Anscombe, F. J. 1949. The statistical analysis of insect counts based on the negative binomial distribution. *Biometrics* 5: 165-173.
1950. Sampling theory of the negative binomial and log-arithmetic series distributions. *Biometrika* 37: 358-382..
- Bellinger, R. G., F. W. Ravlin, & M. L. McManus. 1990. Predicting egg mass density and fecundity in field populations of the gypsy moth (Lepodoptera: Lymantriidae) using male moth wing length. *Envir. Entomol.* 19: 1024-1028.
- Bess, H. A. 1961. Population ecology of the gypsy moth *Portheria dispar* L. (Lepidoptera: Lymantriidae). New Haven: Conn. Agric. Exp. Sta. Bull. 646. 43pp.
- Binns, M. R. & N. J. Bostanian. 1988. Binomial and censored sampling in estimation and decision making for the binomial distribution. *Biometrics* 44: 473-483.
- 1990a. Robust binomial decision rules for integrated pest management based on the negative binomial distribution. *Am. Entomologist.* Spring: 50-54.
- 1990b. Robustness in empirically based binomial decision rules for integrated pest management. *J. Econ. Entomol.* 83: 420-427.
- Binns, M. R. & J. P. Nyrop. 1992. Sampling insect populations for the purpose of IPM decision making. *Annu. Rev. Entomol.* 37: 427-453.
- Bliss, C. I. & R. A. Fisher. 1953. Fitting the binomial distribution to biological data. *Biometrics* 9: 176-200.
- Burgess, A. F. 1930. Improvements in spraying equipment. *J. Econ. Entomol.* 23: 132-136.
- Cameron, E. A. 1973. Disparlure: A potential tool for gypsy moth populations manipulation. *Bull. Entomol. Soc. Am.* 19: 15-19.
- Campbell, R. W. 1973. Forecasting gypsy moth egg-mass density. USDA For. Serv. Res. Paper NE-268.
1981. Evidence for high fecundity among certain North American gypsy moth populations. *Environ. Entomol.* 10: 663-667.
- Campbell, R. W. & R. J. Sloan. 1977. Release of gypsy moth populations from innocuous levels. *Environ. Entomol.* 6: 323-330.

1978. Numerical bimodality among North American gypsy moth populations. *Environ. Entomol.* 7: 641-646.
- Carter, M. R. 1991. Quantification and use of pheromone-baited milk-carton traps to monitor gypsy moth populations. Ph.D. dissertation, VA. Polytechnic Institute and State Univ., Blacksburg.
- Carter, M. R., F. W. Ravlin, & M. L. McManus. 1991. Changes in gypsy moth (Lepidoptera: Lymantriidae) fecundity and male wing length resulting from defoliation. *Environ. Entomol.* 20: 1042-1047.
- Doane, C. C. & M. L. McManus. 1981. The gypsy moth: research toward integrated pest management. U.S.D.A. For. Serv. Tech. Bull. 1584.
- Debauche, H. R. 1962. The structural analysis of animal communities in the soil. pp 10-25. *In* P.W. Murphy [ed.], *Progress in Soil Zoology*. London.
- Dubois, N. R. 1981. Microbials, pp 445-429. *In* C.C. Doane and M.L. McManus [eds.], *The gypsy moth: research toward integrated pest management*. U.S.D.A. For. Ser. Tech. Bull. 1584.
- Eggen, D. A. & L. P. Abrahamson. 1983. Estimating gypsy moth egg mass densities. School of Forestry ESF 83-002, State University of New York, College of Environmental Science and Forestry, Syracuse, N.Y.
- Elkinton, J. S. 1987. Changes in efficiency of the pheromone-baited milk-carton trap as it fills with male gypsy moths (Lepidoptera: Lymantriidae). *J.Econ. Entomol.* 80: 754-757.
- Elkinton, J. D. & A. M. Liebhold. 1990. Population dynamics of gypsy moth in North America. *Annu. Rev. Entomol.* 35: 571-596.
- Elliot, J. M. 1877. Some methods for the statistical analysis of samples of benthic invertebrates, 2nd ed. Freshwater Biological Association, Scientific Publication 25.
- Etter, D. O., Jr. 1979. Thresholds-Appendix K. Comprehensive gypsy moth pest management system. National Gypsy Moth Management Board.
- Fleischer, S. J., F. W. Ravlin, & R. C. Reardon. 1991. Implementation of sequential sampling plans for gypsy moth (Lepidoptera: Lymantriidae) egg masses in eastern hardwood forests. *J. Econ. Entomol.* 84: 1100-1107.
- Forbush, E. H. and C. H. Fernald. 1896. The gypsy moth, *Porthetria dispar* (Linn.). Wright and Potter Printing Co., Boston.

- Fowler, G. W. and A. M. Lynch. 1987. Sampling plans in insect pest management based on Wald's sequential probability ratio test. *Environ. Entomol.* 16: 345-354.
- Ganser, D. A. and O. W. Herrick. 1985. A method for predicting gypsy moth defoliation from egg mass counts. *North J. Appl. For.* 2: 78-79.
- Gerrard, D. J. & H. C. Chiang. 1970. Density estimation of corn root-worm egg populations based upon frequency of occurrence. *Ecology* 51: 237-45.
- Gottschalk, K. W. 1986. Managing Appalachian hardwood stands to minimize gypsy moth impacts. *SAF Publ.* 86-02. p. 181-207.
- Green, R. H. 1970. On fixed precision level sequential sampling. *Res. Popul. Ecol.* 12: 249-251.
- Harcourt, D. G. 1966. Sequential sampling for the imported cabbageworm, *Pieris rapae* (L.). *Can. Entomol.* 98: 741-746
- Hollingsworth, C. S. & C. A. Gatsonis. 1990. Sequential sampling plans for green peach aphid (Homoptera: Aphididae) on potato. *J. Econ. Entomol.* 83: 1365-1369.
- Howard, L. O. and W. F. Fiske. 1911. The importation into the United States of the parasites of the gypsy moth and the brown-tail moth. U.S. Dep. Agric. Bur. Entomol, Bull 91.
- Iwao, S. 1968. A new regression method for analyzing the aggregation pattern of animal populations. *Res. Popul. Ecol.* 10: 11-20.
1975. A new method of sequential sampling to classify populations relative to a critical density. *Res. Popul. Ecol.* 16: 281-288.
- Jones, V. P. 1991. Binomial sampling plans for tentiform leafminer (Lepidoptera: Gracillariidae) on apple in Utah. *J. Econ. Entomol.* 84: 484-488.
- Kirkland, A. H. 1905. The gypsy moth and brown-tail moth. Bull. 1. Wright and Potter Printing Co., Boston.
- Kolodny-Hirsch, D. M. 1986. Evaluation of methods for sampling gypsy moth (Lepidoptera: Lymantriidae) egg mass populations and development of sequential sampling plans. *Environ. Entomol.* 15: 122-127.
- Kono, T. & T. Sugino. 1958. On the estimation of the density of rice stems infested by the rice stem borer. *Jpn. J. Appl. Entomol. Zool.* 2: 184-188.
- Kuno, E. 1986. Evaluation of statistical precision and design of efficient sampling for the population estimation based on frequency of occurrence. *Res. Popul. Ecol.* 28: 305-319.

- Lechowicz, M. J. & Y. Mauffette. 1986. Host preferences of the gypsy moth in eastern North America versus European forests. *Revue d'Entomologie du Quebec* 31: 43-51.
- Leonard, D. W. 1974. Recent developments in ecology and control of the gypsy moth. *Ann. Rev. Entomol.* 19: 197-229.
1981. Bioecology of the Gypsy Moth, pp 9-29. *In* C.C. Doane and M.L. McManus [eds.], *The gypsy moth: research toward integrated pest management*. U.S.D.A. For. Ser. Tech. Bull. 1584.
- Liebholt, A., D. Twardus, & J. Buonaccorsi. 1991. Evaluation of the timed-walk method of estimating gypsy moth (Lepidoptera: Lymantriidae) egg mass densities. *J. Econ. Entomol.* 84: 1774-1781.
- Lloyd, M. 1960. Mean crowding. *J. Anim. Ecol.* 31: 1-30.
- Lysyk, T. J. & C. J. Sanders. 1987. A method for sampling endemic populations of the spruce budworm (Lepidoptera: Tortricidae) based on proportion of empty sample units. Information Report OX-382. Great Lakes Forestry Centre, Sault Ste. Marie, Ont.
- Lysyk, T. J. & G. B. Schaalje. 1992. Binomial sampling for pest management of stable flies (Diptera: Muscidae) that attack dairy cattle. *J. Econ. Entomol.* 85: 130-136.
- Mason, G. N. 1987. Rating stand susceptibility to gypsy moth defoliation. *In* *Proceeding, Coping with the Gypsy Moth in the New Frontier*. WV University Books, Morgantown.
- Mastro, V. C., C. P. Schwalbe, & T. M. O'Dell. 1981. Sterile-male technique, pp. 669-679. *In* C.C. Doane and M.L. McManus [eds.], *The gypsy moth: research toward integrated pest management*. U.S.D.A. For. Ser. Tech. Bull. 1584.
- McManus, M. L. & T. McIntyre. 1981. Introduction, pp. 1-1. *In* C.C. Doane and M.L. McManus [eds.], *The gypsy moth: research toward integrated pest management*. U.S.D.A. For. Ser. Tech. Bull. 1584.
- Nachman, G. 1981. A mathematical model of the functional relationship between density and spatial distribution of a population. *J. Anim. Ecol.* 50: 453-560.
1984. Estimates of mean population density and spatial distribution of Tetranychus urticae (Acarina: Tetranychidae) and Phytoseiulus persimilis (Acarina: Phytoseiidae) based on the proportion of empty sampling units. *J. Appl. Ecol.* 21: 903-913.

- Nyrop, J. P., A. M. Agnello, J. Kovach, & W. H. Reissig. 1989. Binomial sequential classification sampling plans for European red mite (Acari: Tetranychidae) with special reference to performance criteria. *J. Econ. Entomol.* 82: 483-490.
- Nyrop, J. P. and M. Binns. 1991. Quantitative methods for designing and analyzing sampling programs for use in pest management, pp. 67-132. In D. Pimentel [ed.], *Handbook of pest management*. CRC. Boca Raton, Fl.
- Pielou, D. P. 1960. Contagious distribution in the European red mite, *Panonychus ulmi* (Koch), and method of grading population densities from a count of mite-free leaves. *Can. J. Zool.* 38: 645-653.
- Ravlin, F. W. 1991. Development of monitoring and decision-support systems for integrated pest management of forest defoliators in North America. *Forest Ecology and Management*. 39: 3-13.
- Ravlin, F. W., R. G. Bellinger & E. A. Roberts. 1987. Gypsy moth management programs in the United States: status, evaluation, and recommendations. *Bull. Entomol. Soc. Am.* 33: 90-98.
- Southwood, T. R. E. 1978. *Ecological methods*. Chapman & Hall, London.
- Stark, R. W. 1952. Sequential sampling of the lodgepole needle miner. *For. Chron.* 28: 57-60.
- Stefanov, D. and M. Keremidchiev. 1961. The possibility of using some predators and parasitic insects in the biological control of the gypsy moth (*Lymantria dispar* L.) in Bulgaria (in Bulgarian, English summary). *Nauch. Trud. vis. lesotekh. Inst.* 9: 157-168. (*Rev Appl. Entomol.* 53: 170.)
- Taylor, L. R. 1961. Aggregation, variance and the mean. *Nature* 189: 732-735.
- Thorpe, K. W. & R. L. Ridgway. 1992. Gypsy moth (Lepidoptera: Lymantriidae) egg mass distributions and sampling in a residential setting. *Environ. Entomol.* 21: 722-730.
- Wald, A. 1945. Sequential tests of statistical hypothesis. *Ann. Math. Stat.* 16: 117-186.
1947. *Sequential analysis*. Wiley, New York.
- Waters, W. E. 1955. Sequential sampling in forest insect surveys. *For. Sci.* 1: 68-79.
1974. Sequential sampling applied to forest insect surveys. IUFRO/SAF/SUNY Symposium on Monitoring forest Environment through Successive Sampling. 22p.

- White, W. B, W. H. McLane, & N. F. Schneeberger. 1981. Pesticides, pp. 423-442. In C.C. Doane and M.L. McManus [eds.], The gypsy moth: research toward integrated pest management. U.S.D.A. For. Serv. Tech. Bull. 1584.
- Wilson, R. W., Jr., & G. A. Fontaine. 1978. Gypsy moth handbook: gypsy moth egg-mass sampling with fixed- and variable-radius plots. USDA Agriculture Handbook 523.

Chapter 2

Sequential Egg Mass Sampling Plans for Gypsy Moth Management in Urban and Suburban Habitats

The gypsy moth is one of the most important forest pests in the eastern United States, with monitoring and control costing millions of dollars each year (Ravlin et al. 1987). Accurate and cost effective monitoring programs are essential for proper management. Presently, egg mass density is the primary criterion used to make control decisions against the gypsy moth (Ravlin et al. 1987). Egg mass density is used since egg masses are easier to find and count over a longer period of time than other life stages. Egg mass sampling methods include fixed- and variable- radius plots (Wilson & Fontaine 1978), fixed-radius plots (Kolodny-Hirsch 1986), and timed walks (Eggen & Abrahamson 1983). Fixed-radius plots of 0.01 ha have been shown to be more cost effective and precise than fixed- and variable-radius plots (Kolodny-Hirsch 1986) and timed walks (Fleischer et al. 1991, Liebhold et al. 1991). Action threshold have been established at 618, 1,236, and 2,471 egg mass/ha (250, 500, and 1,000 egg masses/ac respectively) (Etter 1979, Ravlin et al. 1987).

Sequential sampling is another method used in gypsy moth management programs. Sequential sampling is appealing because it minimizes the number of samples that have to be taken and thus time to meet management objectives. When the objective of the sampling plan is to make a control decision, classification of population densities as either above or below some action threshold is appropriate for a sampling plan. Sequential sampling requires that the action thresholds, used for classifying populations, and the risk levels that users are willing to accept be predetermined. A decision is made after each sample to continue or terminate sampling therefore classifying the population as above or below the action threshold. The sample size is not fixed but is dependent upon the values of the samples taken. Sequential sampling is preferred because it is as reliable as fixed sample size methods but on average only require 40 to 60% as many observations and sample size reductions as high as 86% have been reported (Sterling 1975).

Sequential egg mass sampling plans for gypsy moth IPM programs have been developed for forested woodlots and eastern hardwood forests (Kolodny-Hirsch 1986, Fleischer et al. 1991, respectively). Although these plans work well in forest habitats,

Fleischer et al. (1991) did not recommend these plans for areas influenced by the presence of man-made objects such as urban or suburban habitats. It was assumed that the presence of man-made objects would cause the egg mass distribution to differ from forested habitats due to discontinuous habitat, lower tree densities, and artificial substrates that provide oviposition sites. Since gypsy moths are an urban as well as a forest pest, counties in developed areas have initiated management programs to reduce gypsy moth impact. These management programs require sampling plans that are cost and time effective, correctly categorize pest density, and are relevant for the egg mass distributions found in areas with man-made objects. The goal of this study was to develop and validate sequential egg mass sampling plans for gypsy moth management decisions in urban and suburban habitats.

MATERIALS AND METHODS

Study Area. Egg mass sample data were obtained from three adjacent counties (Loudoun, Fairfax, and Arlington) in Virginia in 1989 and 1990 (Fig. 1). Adjacent counties were chosen so egg mass sample data would be over a large geographic region which had experienced relatively homogeneous gypsy moth population trends and management programs. Arlington and Fairfax Counties are completely urbanized but Loudoun County has areas of urban and suburban habitats with some forest habitats. Forest habitat data from Loudoun County were removed from the data set since sequential sampling plans for eastern hardwood forests had previously been developed by Fleischer et al. (1991). All three counties have implemented gypsy moth monitoring and control programs since the mid-1980's.

In accordance with state suppression cooperative agreements, the three counties conducted fixed-radius samples (0.01 ha) and use an action threshold of 618 egg masses/ha (250 egg masses/ac.). Yearly samples were taken usually at or near the same sites using a grid system but there were no set number of samples taken each year. In addition to egg mass density, each county recorded additional data including egg mass size, housing type (single dwelling, multi-dwelling, or green space), and a grid identification number.

Egg mass data from 1989 were used to develop sequential sampling plans. Since each county used a different grid size, data were standardized by creating a new grid system by using Arc/Info[®], a geographic information system, for Loudoun County; the tax map grid system for Fairfax County; and modifying the previous used grid system for

Arlington County. A 2.6-km² (1 mi²) grid was laid over the entire three county region and each egg mass sample was given a identification number corresponding to the new grid. Only grid cells which had at least 10 egg mass samples within them were used to develop the sequential sampling plans.

Statistical Analysis. A mean and variance for egg mass density was calculated for each grid cell. Data were tested for over-dispersion with a chi-square to determine if they fit a negative binomial distribution using a FORTRAN program written by Davies (1971). To develop sampling plans using a negative binomial distribution the mean, variance, and index of aggregation (k) are needed. The maximum likelihood method was used to develop a k for each grid cell (Bliss and Fisher 1953). The maximum likelihood method requires that a k value be determined that reduces Z_i to 0 within a range of ± 0.0001 where:

$$Z_i = \sum \left(\frac{A_x}{k_i + x} \right) - N \ln \left(1 + \frac{\bar{x}}{k_i} \right) \quad [1]$$

In Eq. 1, A_x is the accumulated frequency of sampling units containing more than x individuals and k_i are the successive values of k used in an iterative procedure. A modified FORTRAN program was used to calculate k using the maximum likelihood method (Davies 1971). Analysis of variance was used to determine if there was any difference between the mean k value for each county (PROC GLM, SAS Institute 1989).

Development of Sequential Sampling Plans. Sequential sampling plans were developed using Wald's sequential probability ratio test (SPRT) which requires that data follow a negative binomial distribution (Wald 1947). Stop lines for sequential sampling plans can be developed using predetermined action thresholds and risk levels for making a type I or II error along with the calculated index of aggregation, k . A type I error (α) is the risk of classifying a population as above the threshold when it is actually below and a type II error (β) is the risk of classifying a population as below the threshold when it is actually above. The formulas for the lower intercept (h_1), higher intercept (h_2) and slope of the stop lines are as follows (Fowler and Lynch 1987):

$$h_1 = a / \ln [p_1 * q_0 / p_0 * q_1]$$

$$h_2 = b / \ln [p_1 * q_0 / p_0 * q_1]$$

$$\text{slope} = k * [\ln (q_1 / q_0) / \ln (p_1 * q_0 / p_0 * q_1)]$$

where:

$$a = \ln [(1 - \beta) / \alpha]$$

$$b = \ln [\beta / (1 - \alpha)]$$

$$p_0 = u_0 / k$$

$$p_1 = u_1 / k$$

$$q_0 = 1 - p_0$$

$$q_1 = 1 - p_1.$$

Operating characteristic (OC) and average sample number curves (ASN) were calculated to determine the acceptability of the sampling plans based on SPRT. The sensitivity of the OC and ASN curves to changes in the value of k was conducted. The OC and ASN curves were calculated from 1,000 Monte Carlo simulations for three values of k and plotted.

Three sampling plans based on action thresholds of 618, 1,236, and 2,471 egg mass/ha were developed. Upper (u_0) and lower (u_1) class limits were chosen to bracket the action thresholds. All sampling plans were based on α and β levels of 0.25. The probabilities, α and β , were not considered error rates but rather parameters which can be used to define an acceptable sequential sampling plan (Nyrop et al. 1989, Nyrop and Binns 1991). The maximum number of samples for each action threshold plan was determined by using the maximum ASN calculated from Wald's SPRT (Water 1974).

Validation of Sequential Sampling Plans. The 1990 egg mass data sets from Arlington and Loudoun Counties were used to validate the sampling plans. For each 2.6 km² grid cell, a computer program determined the management decision reached when using the sequential sampling plan and when using the maximum number of samples. Decisions made from the maximum number of samples were assumed to be the "correct" decisions. The two management decisions were compared to determine if the same management decision was reached (Luna et al. 1983, Fleischer et al. 1991).

RESULTS

A total of 111 grid cells were used to develop the sequential sampling plans (61 from Loudoun, 35 from Fairfax, and 15 from Arlington). There was no significant difference between mean k values among counties so the data sets were combined ($F = 0.51$; $df = 2$; $P = 0.6018$). Average egg mass densities ranged from 0 to 254 egg masses/2.6 km² grid. There was no difference between housing types or between urban and suburban habitats so the resulting sequential sampling plans can be used for any urban/suburban habitat. The criterion for determining if an area is urban/suburban is based on housing density. These sampling plans can be used in habitats where the housing density ranges from 0.247 houses/ha to 12.35 houses/ha.

Spatial distribution. The distribution of egg mass counts in all grid cells conformed to a negative binomial distribution. The k values ranged from 0.034 to 2.36 with a mean k of 0.527. A criticism of Wald's SPRT is that only one k can be used although k changes with population density. The use of a common k has been suggested but this does not eliminate the variability in k among cells. Although k is not stable, use of Wald's SPRT is justified if the OC and ASN are acceptable over a range of k values (Nyrop & Binns 1991). A plot of mean egg mass density versus the maximum likelihood estimates of k shows a slight increase in k with increasing densities with a slope equal to 0.0023 and a r^2 of 0.063 (Fig. 2). Since the slope was small, the effect of using one k value should be minimal.

The OC curve is the probability of accepting (whether correctly or not) that the population mean density is less than the lower stop line. The ASN curve is the average number of samples required to classify the population mean density. OC and ASN curves were calculated for the mean k value of 0.527 and an extremely high value of 2.36 and an extreme low value of 0.034 to determine the effect of changes in k on the OC and ASN and hence the acceptability of the sampling plan (Figs. 3 and 4, respectively). By increasing k to 2.36, the OC curve was reduced over a smaller range of densities but at the cost of increasing the average sample number. The effect of decreasing k to 0.034 resulted in spreading the OC curve over a wide range of densities but reducing the average number of samples. The difference between the OC and ASN curves for the mean k value of 0.527 and a k of 2.36 was considered small enough that a sampling plan developed with the mean k would be acceptable to use in populations with a less aggregated population. If the mean k value is used instead of a lower k , the resulting sampling plan may require taking more samples than necessary but would still be acceptable. In low density populations, where lower k values occurred, the sampling objective may change from making control decisions to estimating population density therefore taking more samples would result in a better population estimate. Thus, a k value of 0.527 was chosen for developing the sequential sampling plans.

Validation of Sampling Plans. The sequential sampling plans produced the same treatment decisions as using the maximum number of samples in 100% of the areas for action thresholds of 1,236 and 2,471 egg mass/ha and 90% of the areas for the 618 egg mass/ha threshold (Table 1). It produce incorrect decision in only 6.45% of the areas (2 of the 31 areas validated) and no decision could be made for the remaining areas. The incorrect decisions that resulted were a type I error in which control was suggested when

no control was necessary. Although this causes an increase in cost due to unnecessary treatments, the risk of not treating a potentially damaging population was zero. There was a significant reduction in the number of samples that were taken. The average number of samples ranged from 7.41-8.17 per grid cell which resulted in saving of 31-49% over the maximum number of samples per grid cell (Table 1).

DISCUSSION

Stop lines were developed for three action thresholds (Table 2) based on a 2.6-km² (1 mile²) grid across each county. In each grid cell the minimum number of 0.01 ha fixed-radius samples for a desired action threshold needs to be distributed throughout the grid cell. After the minimum number of samples have been taken, the cumulative number of egg masses counted are compared to the stop lines until a decision can be made that the population is above or below the action threshold or until the maximum sample number is taken (Fig. 5).

Sequential sampling plans for urban/suburban habitats differ from forested habitats due to the increased aggregation of egg masses. The k value for forested areas was determined to be 1.1 (Fleischer et al. 1991) which closely resembled the k (1.08) calculated for woodlots (Kolodny-Hirsch 1986). A k of 0.527 for urban/suburban habitats is almost half that of forested habitats indicating a more aggregated egg mass distribution and the need for different egg mass sampling plans.

Differences in egg mass distribution have also been found to be influenced by the forest edge. Bellinger et al. (1989) found that forest edge trees have 2.4 times more egg masses than interior trees and Campbell et al. (1976) found higher egg masses densities along forest edges that were adjacent to suburban areas. The difference in egg mass distribution shows the need to consider each of these habitat as a separate entity when making management decisions or conducting research. It should not be assumed that relationships which occur in one habitat will remain the same for another. For example, action thresholds have been developed based on the number of egg masses that cause a certain percent of defoliation in a forested habitat. However, these thresholds are used in all habitats although it is not known if the same relationship between egg masses and defoliation occurs. In the future, research for monitoring and controlling the gypsy moth needs to consider where the research is to be used and take into account differences which may occur between habitats.

REFERENCES CITED

- Bellinger, R. G., F. W. Ravlin, & M. L. McManus. 1989. Forest edge effects and their influence on gypsy moth (*Lepidoptera: Lymantriidae*) egg mass distribution. *Environ. Entomol.* 18: 840-843.
- Bliss, C. I. & R. A. Fisher. 1953. Fitting the negative binomial distribution to biological data. *Biometrics* 9: 176-201.
- Campbell, R. W., M. G. Miller, E. J. Duda, C. E. Biazak, & R. J. Sloan. 1976. Man's activities and subsequent gypsy moth egg-mass density along the forest edge. *Environ. Entomol.* 5: 273-276.
- Davies, R. G. 1971. *Computer programming in quantitative biology*. Academic Press, NY.
- Eggen, D. A. & L. P. Abrahamson. 1983. Estimating gypsy moth egg mass densities. School of Forestry ESF 83-002, State University of New York, College of Environmental Science and Forestry, Syracuse, N.Y.
- Etter, D. O., Jr. 1979. Thresholds-Appendix K. Comprehensive gypsy moth pest management system. National Gypsy Moth Management Board.
- Fleischer, S.J. , F. W. Ravlin, & R. C. Reardon. 1991. Implementation of sequential sampling plans for gypsy moth (*Lepidoptera: Lymantriidae*) egg masses in eastern hardwood forests. *J. Econ. Entomol.* 84: 1100-1107.
- Fowler, G. W. & A. M. Lynch. 1987. Sampling plans in insect pest management based on Wald's sequential probability ratio test. *Environ. Entomol.* 16: 345-354.
- Kolodny-Hirsch, D. M. 1986. Evaluation of methods for sampling gypsy moth (*Lepidoptera: Lymantriidae*) egg mass populations and development of sequential sampling plans. *Environ. Entomol.* 15: 122-127.
- Liebhold, A., D. Twardus, & J. Buonaccorsi. 1991. Evaluation of the timed-walk method of estimating gypsy moth (*Lepidoptera: Lymantriidae*) egg mass densities. *J. Econ. Entomol.* 84: 1774-1781.
- Luna, J. M., S. J. Fleischer & W. A. Allen. 1983. Development and validation of sequential sampling plans for potato leafhopper (*Homoptera: Cicadellidae*) in alfalfa. *Environ. Entomol.* 12: 1690-1694.
- Nyrop, J. P., A. M Agnello, J. Kovach, & W. H. Reissig. 1989. Binomial sequential classification sampling plans for European red mite (*Acari: Tetranychidae*) with special reference to performance criteria. *J. Econ. Entomol.* 82: 483-490.
- Nyrop, J. P. & M. Binns. 1991. Quantitative methods for designing and analyzing sampling programs for use in pest management, pp. 67-132. In D. Pimentel [ed.], *Handbook of pest management*. CRC. Boca Raton, Fl.

- Ravlin, F. W., R. G. Bellinger, & E. A. Roberts. 1987. Gypsy moth management programs in the United States: status, evaluation, and recommendations. *Bull. Entomol. Soc. Am.* 33: 90-98.
- SAS Institute. 1989. *SAS user's guide: statistics*. SAS Institute, Cary, N.C.
- Sterling, W. L. 1975. Sequential sampling of cotton insect populations, pp. 133-135. In *Proceedings, Beltwide Cotton Production Research Conference, New Orleans.*
- Wald, A. 1947. *Sequential analysis*. Wiley, New York.
- Waters, W. E. 1974. Sequential sampling applied to forest insect surveys. IUFRO/SAF/SUNY Symposium on Monitoring forest Environment through Successive Sampling. p22.
- Wilson, R. W., Jr., & G. A. Fontaine. 1978. Gypsy moth handbook: gypsy moth egg-mass sampling with fixed- and variable-radius plots. *USDA Agriculture Handbook* 523.

Table 1. Management decisions reached using fixed sample size plans compared to sequential sampling plans and the average number of samples taken using the sequential sample plan for three action thresholds.

Action threshold (Egg Masses/ha)	Total Number of 2.6-km ² cells		Decision reached by sequential plan (% of 2.6-km ² grids) ^b				Average Number Sampled ^d	Maximum Number Sampled ^e
	Below threshold ^a	Above threshold ^a	Correct	No decision	Type I	Type II		
618	25	6	90.32	3.23	6.45	0	7.41	15
1,236	16	1	100	0	0	0	8.17	22
2,471	15	1	100	0	0	0	7.62	24

^a Categorization of a grid as above or below a management threshold based on a fixed sample size of the maximum number for that management threshold (Table 2)

^b Categorization of cell as above or below a management threshold using the sequential sample plan compared with the decision made using a fixed sample size plan

^c A type I error occurs when the sequential sampling plan concluded the cell was above the threshold when it was actual below the threshold. A type II error occurs when the sequential sampling plans concluded the cell was below the threshold when it was actual above the threshold.

^dWhen using a sequential sampling plan

^eWhen using a fixed sample size plan

Table 2. Sequential sample parameters for 0.01 ha fixed-radius sample plots based on a negative binomial distribution using a $k = 0.527$ for three action thresholds.

Action threshold (egg masses/ha)	Lower	Upper	Minimum sample number	Maximum sample number	Stop Line	
	limit(egg masses/ 0.01 ha)	limit (egg masses/ 0.01 ha)			Intercept ^a	Slope
618	5.0	7.5	6	15	34.013	6.089
1,236	10.0	14.0	7	22	76.258	11.781
2,471	21.0	29.0	7	24	162.128	24.576

^a The positive value of the intercept gives the upper stop line and the negative value gives the lower stop line

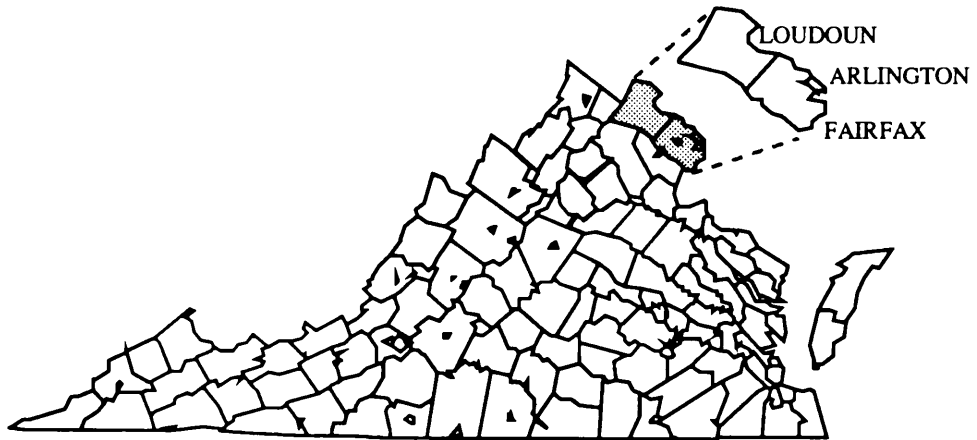
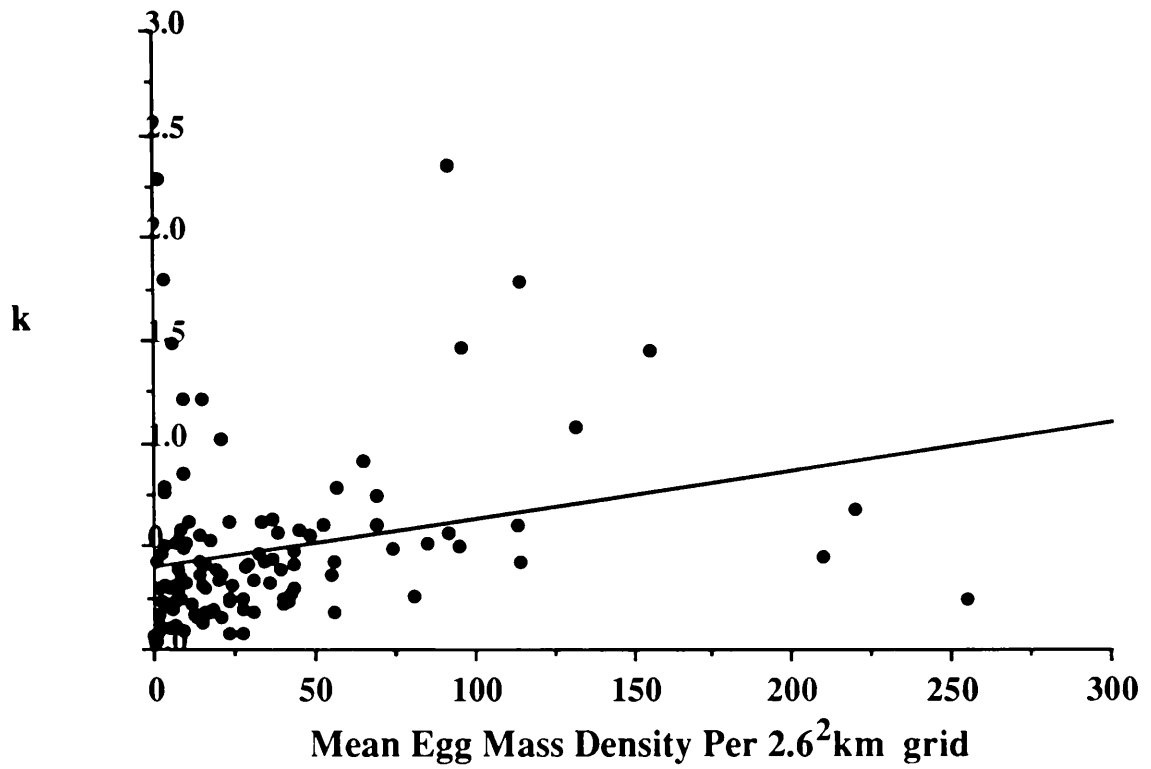


Fig. 1. Study areas of Loudoun, Fairfax, and Arlington counties, Virginia where 0.01 ha fixed-radius egg mass samples were collected in 1989 and 1990.



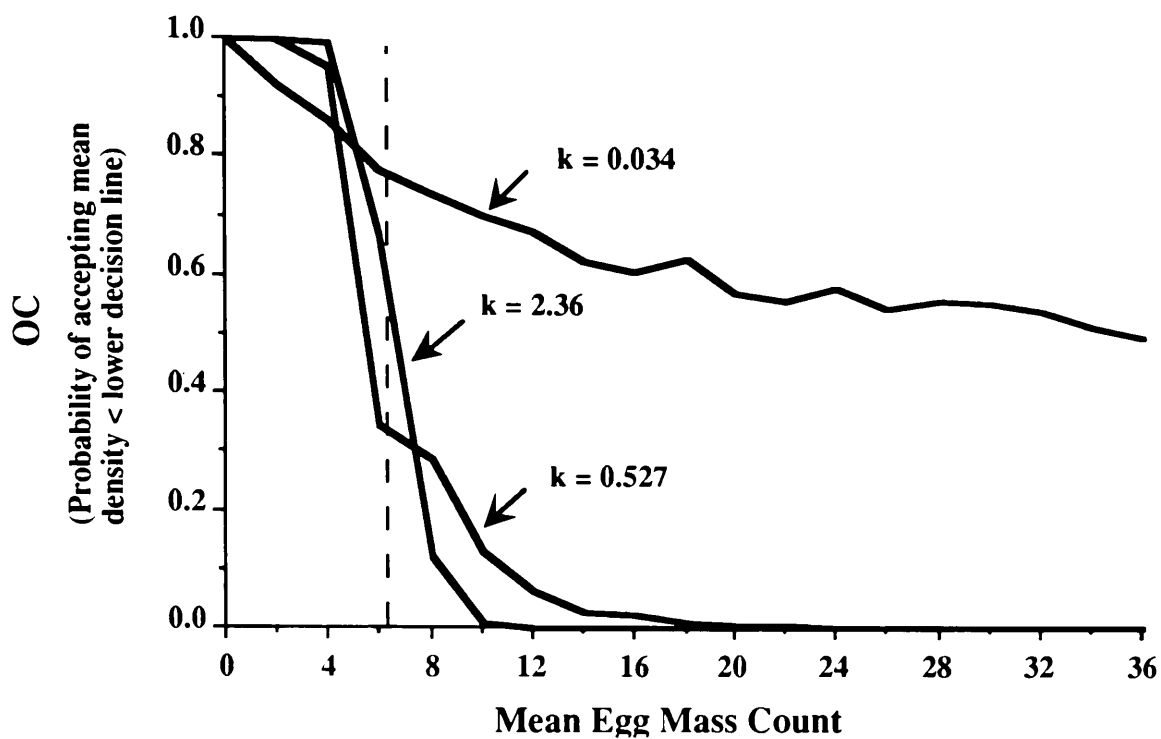


Fig. 3. Operating characteristic curve for a mean k of 0.527 and a high k of 2.36 and a low k of 0.034 to show the effect of changes in k on the OC function for Wald's SPRT based on a negative binomial distribution. Hashed vertical line references the action threshold of 6.25 egg masses/ha for a 0.01 ha fixed-radius plot.

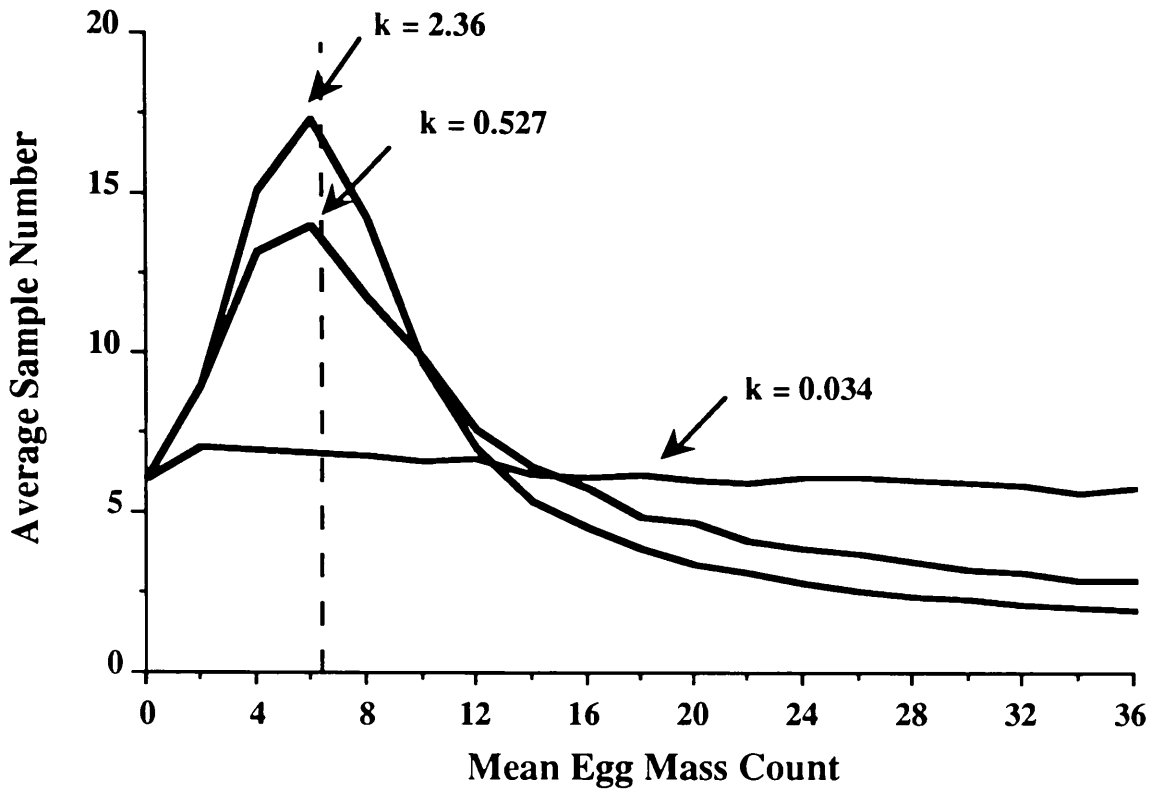


Fig. 4. Average sample number for a mean k of 0.527 and a high k of 2.36 and a low k of 0.034 to show the effect of changes in k on the ASN function for Wald's SPRT based on a negative binomial distribution. Hashed vertical line references the action threshold of 6.25 egg masses/ha for a 0.01ha fixed-radius plot.

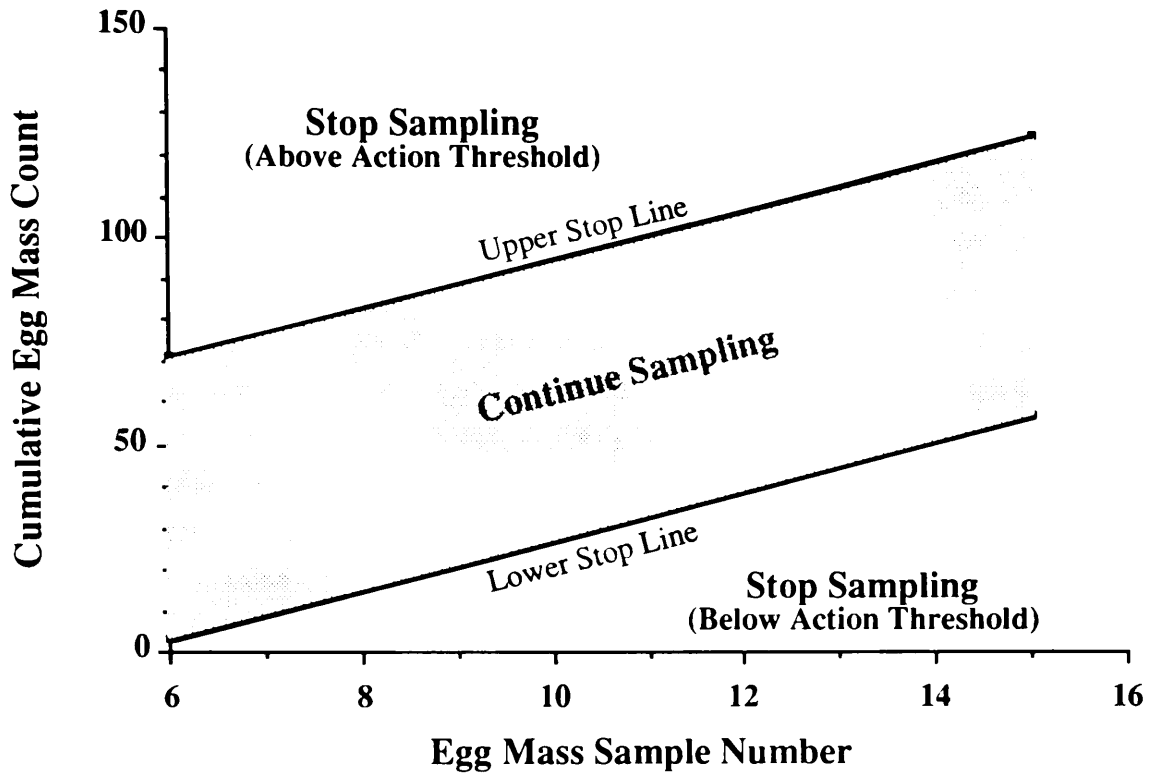


Fig. 5. Stop lines for classifying a gypsy moth population as being above or below the action threshold of 618 egg masses/ha (250 egg masses/ac.)

Chapter 3

Binomial Egg Mass Sampling Plans for Low Density Gypsy Moth Populations in Continuously Forested Habitats

The gypsy moth is an important pest of trees in the northeastern United States and has recently expanded its range west to Wisconsin and south to North Carolina (Twardus 1991). Monitoring the gypsy moth is required to determine if treatment is necessary to prevent population outbreaks which result in defoliation and possible tree mortality. Egg mass sampling is the most commonly used method to estimate population densities for making treatment decisions (Ravlin et al. 1987). Egg masses are used to monitor gypsy moth populations because they are present for a longer time period than other life stages.

Egg mass sampling methods include fixed- and variable-radius plots (FVR plots) (Wilson and Fontaine 1978), fixed-radius plots (Kolodny-Hirsch 1989), and timed walks (Eggen and Abrahamson 1983). Sequential egg mass sampling plans based on a negative binomial distribution using 0.01 ha fixed-radius plots have been developed for continuously forested habitats (Fleischer et al. 1991) and urban and suburban habitats (Carter et al., unpublished manuscript). Although these sampling methods provide accurate estimates of population densities, they are very time consuming. The time required to sample egg masses has been estimated to range from 11.25 man-minutes for 0.01 ha fixed-radius plots to 27.60 man-minutes for fixed-and variable-radius plots (20 basal area factor). Fixed-radius plots have been determined to be the most cost efficient and precise sampling method (Kolodny-Hirsch 1986).

Sequential sampling is an approach that can usually reduce the total time spent taking samples (Sterling 1975). However, because of the preponderance of zero egg mass counts they are not recommended for forested habitats with low egg mass densities or areas within a previous year's spray block (Kolodny-Hirsch 1986, Fleischer et al. 1991, respectively). In low density areas (< 250 egg masses/ha) sequential sampling was determined to be too labor intensive since an estimated five hours would be required to sample a population using fixed-radius or FVR plot samples with a fixed level of precision of 25% (Kolodny-Hirsch 1986). Wilson and Fontaine (1978) also reported that FVR plot samples were too labor intensive for low density populations. Sequential sampling plans developed by Fleischer et al. (1991) were not recommended for areas within a previous year's spray block because the variance was much less than the mean

suggesting that the negative binomial distribution used in these plans is not appropriate (Fleischer et al. 1991).

Binomial sampling is a labor-saving technique in which the presence or absence of an insect is used to estimate population density. Binomial sampling has been shown to provide accurate population estimates with a substantial saving in cost. Binomial sampling is based on defining the relationship between the population mean (m) and the proportion of samples with T organisms (P_T), where $T=0,1,2,..$ is referred to as a tally threshold. The relationship between m and P_T is based on theoretical or empirical models. Binomial sampling using theoretical models include the use of the negative binomial distribution (Pielou 1960, Binns and Bostanian 1988, 1990a, Nyrop et al. 1989, Jones 1991). The empirical model has been used by Kono and Sugino (1958), Gerrard & Chiang (1970), Nachman (1984), Kuno (1986), and Binns and Bostanian (1990b). The empirical model has two parameters which can be estimated from the linear regression of $\ln(m)$ on $\ln(-\ln P_T)$. The independent variable, P_T , is defined as the proportion of samples with individuals at or below the tally threshold.

Although binomial sampling is generally faster, sampling plans often require a greater number of samples to estimate the population density than when using an absolute counting method to get the same desired degree of precision. The increased sample size occurs because less information is collected at each sample site and because the variance associated with the estimated mean is greater due to variability associated with the dispersion of the population and uncertainty associated with P_T and the m . The increased number of samples required and the increased variance associated with sampling often makes binomial sampling impractical (Nyrop et al. 1989).

Current sampling methods and plans have been shown to be inefficient for low density gypsy moth populations yet a sampling method is still needed. Lysyk & Sanders (1987) showed that binomial sampling was feasible for sampling endemic populations of spruce budworm. Binomial sampling could also prove to be a useful gypsy moth egg mass sampling method for estimating low density populations. The objective of this study was to develop binomial sampling plans for low density populations (<618 egg masses/ha) to provide accurate population estimates in continuously forested habitats.

MATERIALS AND METHODS

Study Areas and Sampling Procedure. Fixed- and variable-radius plot samples were taken in 9 ha study areas. Egg mass samples were taken from 1984 through 1990 in

areas located in Virginia, Maryland, and Massachusetts. FVR plot samples were taken from 50 to 100m apart in each study area. The number of plots sampled ranged from 16 to 49 samples in a study area per year. Study areas (n=32) in which at least 21 egg mass samples were taken and the mean egg mass density was less than 618 egg masses/ha were used for the data analysis.

Each tree sampled within a plot was stratified into five areas which included: ground - .304 m of the bole, .304 m - .914 m bole, .914 m - 1.82 m bole, 1.82 m- to the crown, and the crown. The crown of the tree was defined as the area in which the first significant branching occurred. The number of egg masses within each strata was recorded separately.

Relationship between Study Area Mean and Variance. The number of egg masses/ha (\bar{x}) and the variance (s^2) was calculated for each study area as suggested by Wilson and Fontaine (1978). The parameter estimates from this relationship are necessary to calculate the variance of the predicted mean for the binomial sampling plan. The relationship between the \bar{x} and s^2 was determined by linear regression and fitted to Taylor's (1961) mean-variance model:

$$\ln s^2 = a + b \ln \bar{x} \quad [1]$$

(PROC REG, SAS Institute 1989).

Relationship between \bar{x} and P_T . The binomial sampling plan is based on defining the relationship between the proportion of trees with zero egg masses and the mean. Once this relationship has been determined a predicted population mean can then be estimated for any observed value of P_T (Pielou 1960, Gerrard & Chiang 1970).

The proportion of trees with zero egg masses (P_T) per plot was determined for the entire tree, the bole of the tree (ground to the crown), and the first 1.82 m of the bole from all the trees for each study area. These strata were chosen to examine the relationship between the \bar{x} and P_T to determine if time could be improved by only having to survey a small proportion of the tree. Tally thresholds other than zero were not examined because the egg mass densities were very low and the majority of trees did not have egg masses present. Linear regression (PROC REG, SAS Institute 1989) was used to determine the relationship between the study area mean (\bar{x}) and P_T :

$$\ln \bar{x} = c + d \ln(-\ln P_T) \quad (\text{Binns \& Bostanian 1990}) \quad [2]$$

for each tree strata.

The predicted natural logarithm of the egg masses density ($\ln \hat{m}$) can be calculated using the estimated parameters c and d and an observed value of P_T , where $\ln \hat{m} = \ln \bar{x}$ (Eq. 2). An estimate of \hat{m} can then be calculated as

$$\hat{m} = \exp(\ln \hat{m}). \quad [3]$$

Variance of Predictions. The prediction variance for $\ln(\hat{m})$ comes from three separate sources: error in the estimates of c and d , biological error (i.e., the deviation of an individual population from the regression line), and sample error of $\ln(-\ln P_T)$. Schaalje et al. (1991) suggested the following equation to account for these sources of variation:

$$V_{\ln \hat{m}} = \frac{d^2(1 - P_T)}{nP_T(\ln P_T)^2} + MSE \left\{ 1 + \frac{1}{N} + \frac{[\ln(-\ln P_T) - pbar]^2}{SSP} \right\} \quad [4]$$

$$+ (MSE - (\exp(a + (b - 2)(\ln \hat{m})) / n))$$

where a and b are regression parameters from Eq. 1, d is from Eq. 2, N is the number of observations used in the regression (Eq. 2), n is the desired number samples to be taken from a population, MSE is the residual mean square error of the regression, SSP is the sum of squares of $\ln(-\ln P_T)$ of the regression, $pbar$ is the mean of $\ln(-\ln P_T)$ used in regression. The variance of \hat{m} can be calculated as

$$V_{\hat{m}} = \hat{m}^2 V_{\ln \hat{m}} \quad (\text{Nachman 1984}). \quad [5]$$

The relative variability of \hat{m} , $C_{\hat{m}}$, can then be calculated as:

$$C_{\hat{m}} = \frac{V_{(\hat{m})}^{\frac{1}{2}}}{\hat{m}} = V_{\ln \hat{m}}^{\frac{1}{2}}. \quad (\text{Lysyk \& Sanders 1987}) \quad [6]$$

Comparison of Sampling Methods. Relative variability the standard error expressed as a proportion of the mean. The relative variability of the binomial sampling method and the FVR plot sampling method was used to compare the reliability of the estimates of the two methods. The relative variability for the FVR plot method was determined by using Eq. 1 to calculate the variance ($V_{\bar{x}}$) over a range of means (\bar{x}). The means were calculated from Eq. 2 for observed P_T values ranging from .001 to .99. The relative variability for the means could then be calculated as follows:

$$C_{\bar{x}} = \frac{\left(\frac{V_{\bar{x}}}{n} \right)^{\frac{1}{2}}}{\bar{x}} \quad [7]$$

where n is the desired sample size (Nachman 1984, Lysyk & Sanders 1987).

Comparisons between methods should also consider the cost of sampling (Nachman 1984). The total cost of sampling was determined by the time required to complete one sample and included the time necessary to travel from one sample plot to another plus the time required to set up and complete the sample. The time required to sample an individual tree (for binomial sampling) was determined from field surveys of the man-minutes required to walk 50 m and to survey the first 1.82 m of the bole, the bole of the tree, and the entire tree. Four groups of two people conducted the surveys by having one person record the time another person took to conduct a survey. The average time required to walk 50 m was .505 minutes, the first 1.82 m required .149 minutes, the bole of the tree required 1.11 minutes, and the entire tree required 2.31 minutes. The time required to sample the tree assumes that an egg mass is not observed until the last portion of the tree is surveyed. The time required to sample a fixed- and variable-radius plots was obtained from a previous study by Kolodny-Hirsch (1986). The relative efficiency of a sample method is defined as:

$$RE = \frac{1}{C_{\bar{x}}} \frac{1}{(C_s * n)} \quad [8]$$

where $C_{\bar{x}}$ is the relative variability of the sampling method, C_s is the total cost of obtaining a sample, and n is the desired sample size (Lysyk & Sanders 1987).

Sample size was examined by comparing the relative variability and relative efficiency of 9, 16, 49, and 98 samples for both the FVR plot sampling method and binomial sampling method. These sample sizes were chosen since they could be evenly distributed over a nine hectare study area on either a 50 meter grid (49 or 98 samples) or a 100 meter grid (9 or 16 samples). The sample size of 98 was chosen to use as an extreme sample size for comparing relative variability and relative efficiency. A sample size of 98 is not possible since it requires two fixed- and variable-radius plot samples to be taken at the same location.

Validation of Binomial Sampling Method. Four 9 ha study areas were randomly selected to use as validation data sets to determine the accuracy of the binomial sampling plans and were not used for developing the sampling plans. An expected mean was obtained from the FVR plot samples taken from each study area. Ten different validation sets from each study area for each sample size were constructed. The number of FVR plots chosen was determined by the desired sample number and were evenly distributed over the study area. In each study area, a tree was randomly selected from each FVR plot. The proportion of zeros on the bole of the tree was determined and used

to calculate a predicted mean (Eq. 2) for each validation set. The predicted mean was then compared to the expected mean as determined for the maximum number of FVR plot samples taken in each study area.

RESULTS

A total of 28 study areas were used in the analysis with an average of 125 ± 15 egg masses/ha in a study area. Four study areas were located in Virginia, six were located in Maryland, and eighteen study areas were located in Massachusetts. The number of trees per study area ranged from 77 to 306. The proportion of trees with zero egg masses (P_T) was determined for the entire tree, the bole of the tree, and the first 1.82 m of the bole. P_T ranged from 0.625 to 1.0 for the entire tree, 0.65 to 1.0 for the bole of the tree, and 0.797 to 1.0 for the first 1.82 m of the bole. An empirical model was used to determine the relationship between P_T and the mean.

Regression relationships. The relationship between the study area mean and variance was

$$\ln s^2 = 0.967 + 1.42 \ln \bar{x}$$

and is shown in Fig. 1. The relationship was significant ($F = 519.552$; $df = 28$; $P = .0001$) and the mean explained most of the variation in the variance ($r^2 = .952$).

The relationship between the \bar{x} and P_T for the entire tree, bole of the tree, and first 1.82 m of the bole is shown in Fig. 2 a-c. Parameter estimates for the linear regressions are listed in Table 1. The comparison of methods was completed using the parameter estimates of the P_T for only the bole of the tree. This strata was chosen because of the high r^2 ($r^2 = .854$) and the time required to take a sample is minimized since only the bole of the tree is surveyed. P_T for the entire tree provided a better fit to the regression ($r^2 = .917$) but sampling the entire tree (2.31 minutes) requires twice the time than only sampling the bole of the tree (1.11 minutes). P_T for the first 1.82 m of the bole did not explain as much of the variability as the other strata ($r^2 = .686$).

Comparisons of Methods. The relative variability of the FVR plot samples and the binomial samples was calculated for the sample sizes of 9, 16, 49, and 98. Since the regression relationships were constructed on population densities that were less than 618 egg masses/ha, comparisons between relative variability and relative efficiency were only made with predicted means less than 700 egg masses/ha.

The relative variability of the fixed- and variable-radius plot samples and the binomial samples is shown in Figure 3. The relative variability of the FVR plot method

ranged from .035-.454. The relative variability of the binomial method was considerably higher and ranged from 1.941 to 5.834.

The relative efficiency of the fixed- and variable-radius plot samples and the binomial samples is shown in Figure 4. The costs of obtaining a sample for each sample size and sampling method are listed in Table 2. The relative efficiency of 9 and 16 FVR plot samples was higher than the binomial method. The binomial sampling method was more efficient for 9 samples than 49 or 98 FVR plot samples for population densities less than 800 egg masses/ha. A sample size of 16 for the binomial method was more efficient than 49 or 98 FVR plot samples if the population density was less than 90 egg masses/ha.

Validation of the Binomial Sampling Plans. Validation sets were constructed for the sample sizes of 9 and 16 binomial samples. Binomial samples of 49 and 98 were not compared to the FVR plot samples because these sample sizes were not efficient (Fig. 4). Using a sample size of 9 binomial samples resulted in the overestimation of the actual population density 27% of the time. The remaining 73% of the validation sets had a P_T of 0.0. With a sample size was 16, 55% of the validation sets resulted in a P_T of 0, 10% underestimated the actual population density, and the remaining 35% provided estimates which overestimated the actual density by approximately 5 egg masses.

DISCUSSION

Binomial sampling for surveying low density gypsy moth populations is not a effective sampling method. The relative efficiency of the binomial method was much lower than the fixed- and variable-radius plot method for the sample sizes of 49 and 98. The binomial method was efficient for 9 samples and 16 samples (when $m < 90$ egg masses/ha) but these sample sizes provided incorrect population estimates or a large number of the samples had a P_T of zero.

Although binomial sampling significantly reduces the time required to take an sample (2.56 minutes compared to 29.01 man-minutes for a sample size of 9) the variability associated with binomial sampling outweighs any savings in time. There is considerable variability associated with the binomial method. A plot of the mean versus standard error shows the increased variation associated with the binomial method compared to the FVR plot method (Fig. 5). The large variance associated with binomial sampling causes a large relative variability and low relative efficiency for the binomial method and makes this technique impractical. An increase in sample size to 200 trees did not reduce the relative variability enough to improve the relative efficiency. Also an

average of 164 trees per study area were sampled using the FVR plot method so a very large sample size for the binomial method may not be worthwhile.

Since the use of binomial sampling for low density populations is not feasible, a previously developed sampling method will have to continue to be used. Kolodny-Hirsch (1986) determined that 0.01 ha fixed-radius samples were the most efficient egg mass sampling method and we would suggest that fixed-radius samples be conducted for low density populations. To reduce the time and cost of sampling, sequential sampling plans may also be used for continuously forested areas which are not within a previous year's spray block (Fleischer et al. 1991) and urban/suburban areas (Carter et al., unpublished manuscript). Areas within a previous year's spray block will continue to be time consuming to sample until a sampling method can be developed which accounts for the egg mass spatial distribution at low densities. An improved understanding of the spatial distribution of egg masses in low density populations may provide useful for developing better sampling methods.

Although binomial sampling was not shown to be feasible for low density populations, it may be practical in medium to high density populations. In these populations an estimate of the population density would not be needed but the population could be classified as either above or below an action threshold. Sequential binomial sampling plans could also be implemented which would make sampling more cost effective and simpler (Nyrop & Binns 1991).

REFERENCES CITED

- Binns, M. R. & N. J. Bostanian. 1988. Binomial and censored sampling in estimation and decision making for the negative binomial distribution. *Biometrics* 4: 473-483.
- 1990a. Robust binomial decision rules for integrated pest management based on the negative binomial distribution. *Am. Entomologist*. Spring: 50-54.
- 1990b. Robustness in empirically based binomial decision rules for integrated pest management. *J. Econ. Entomol.* 83: 420-427.
- Eggen, D. A. & L. P. Abrahamson. 1983. Estimating gypsy moth egg mass densities. School of Forestry ESF 83-002, State University of New York, College of Environmental Science and Forestry, Syracuse, N.Y.
- Fleischer, S. J., F. W. Ravlin, & R. C. Reardon. 1991. Implementation of sequential sampling plans for gypsy moth (Lepidoptera: Lymantriidae) egg masses in eastern hardwood forests. *J. Econ. Entomol.* 84: 1100-1107.
- Gerrard, D. J. & H. C. Chiang. 1970. Density estimation of corn rootworm egg populations based upon frequency of occurrence. *Ecology* 51: 237-245.
- Jones, V. P. 1991. Binomial sampling plans for tentiform leafminer (Lepidoptera: Gracillariidae) on apple in Utah. *J. Econ. Entomol.* 84: 484-488.
- Kolodny-Hirsch, D. M. 1986. Evaluation of methods for sampling gypsy moth (Lepidoptera: Lymantriidae) egg mass populations and development of sequential sampling plans. *Environ. Entomol.* 15: 122-127.
- Kono, T. & T. Sugino. 1958. On the estimation of the density of rice stems infested by the rice stem borer. *Jpn. J. Appl. Entomol. Zool.* 2: 184-188.
- Kuno, E. 1986. Evaluation of statistical precision and design of efficient sampling for the population estimation based on frequency of occurrence. *Res. Popul. Ecol. (Kyoto)* 28: 305-319.
- Lysyk, T. J. & C. J. Sanders. 1987. A method for sampling endemic populations of the spruce budworm (Lepidoptera: Tortricidae) based on proportion of empty sampling units. Information Report OX-382. Great Lakes Forestry Centre, Sault Ste. Marie, Ont.
- Nachman, G. 1984. Estimates of mean population density and spatial distribution of *Tetranychus urticae* (Acarina: Tetranychidae) and *Phytoseiulus persimilis* (Acarina: Phytoseiidae) based upon the proportion of empty sampling units. *J. Appl. Ecol.* 21: 903-913.

- Nyrop, J. P., A. M. Agnello, J. Kovach, & W. H. Reissig. 1989. Binomial sequential classification sampling plans for European red mite (Acari: Tetranychidae) with special reference to performance criteria. *J. Econ. Entomol.* 82: 483-490.
- Nyrop, J. P. & M. Binns. 1991. Quantitative methods for designing and analyzing sampling programs for use in pest management, pp. 67-132. *In* D. Pimentel [ed.], *Handbook of pest management*. CRC. Boca Raton, Fl.
- Pielou, D. P. 1960. Contagious distribution in the European red mite *Panonychus ulmi* and a method of grading population densities from a count of mite-free infested leaves. *Canadian Journal of Zoology*. 38: 645-653.
- Ravlin, F. W., R. G. Bellinger, & E. A. Roberts. 1987. Gypsy moth management programs in the United States: status, evaluation, and recommendations. *Bull. Entomol. Soc. Am.* 33: 90-98.
- SAS Institute. 1989. *SAS user's guide: statistics*. SAS Institute, Cary, NC.
- Schaalje, G. B., R. A. Butts & T. J. Lysyk. 1991. Simulation studies of binomial sampling: a new variance estimator and density predictor with special reference to the Russian wheat aphid (Homoptera: Apidae). *J. Econ. Entomol.* 84: 104-147.
- Sterling, W. L. 1975. Sequential sampling of cotton insect populations, pp. 133-135. *In* *Proceedings, Beltwide Cotton Production Research Conference, New Orleans*.
- Taylor, L. R. 1961. Aggregation, variance, and the mean. *Nature* 189: 732-735.
- Twardus, D. B. 1991. Gypsy Moth News. *USDA*. 26(June): 4-5.
- Wilson, R. W., Jr., & G. A. Fontaine. 1978. Gypsy moth handbook: gypsy moth egg-mass sampling with fixed- and variable-radius plots. *USDA Agriculture Handbook* 523.

Table 1. Regression parameters for the relationship between the $\ln(\bar{x})$ and $\ln(-\ln P_T)$ for the three tree strata used to determine the proportion of trees with zero egg masses per 9 ha study area.

Parameters	Tree Strata		
	Entire Tree	Bole of Tree	0-6' of Bole
Model: $\ln \bar{x} = c + d \ln(-\ln P_T)$			
<i>c</i>	8.37 ± 0.40	8.24 ± 0.53	9.28 ± 0.98
<i>d</i>	1.84 ± 0.10	1.66 ± 0.13	1.46 ± 0.19
MSE ^a	0.98	1.74	3.76
SSP ^b	94.05	96.31	116.50
pbar	-3.257	-3.54	-4.71
N	28	28	28
r ²	0.917	0.854	0.686

^a Sum of squares of $\ln(-\ln P_T)$ used to estimate the variance of predicted $\ln(\bar{x})$, see text.

^b Mean of $\ln(-\ln P_T)$ used to estimate the variance of the predicted $\ln(\bar{x})$, see text.

Table 2. Average sample times (minutes) required to survey a fixed- and variable-radius plot sample and an individual tree (binomial sample) for $n = 9, 16, 49,$ and 98 .

Sample Method	n	Sample Time ^a (minutes)	Travel Time ^b (minutes)	Total Time (minutes)
Fixed- and variable-radius plot	9	27.60	1.41	29.01
	16	27.60	1.41	29.01
	49	27.60	0.51	28.11
	98	55.20	0.51	55.71
Binomial	9	1.15	1.41	2.56
	16	1.15	1.41	2.56
	49	1.15	.51	1.66
	98	2.31	.51	2.82

^a Time required to set up sample site and survey site for egg masses on the entire tree for the fixed- and variable-radius plots and the bole of the tree for the binomial method

^b Time required to travel from one sample site to another

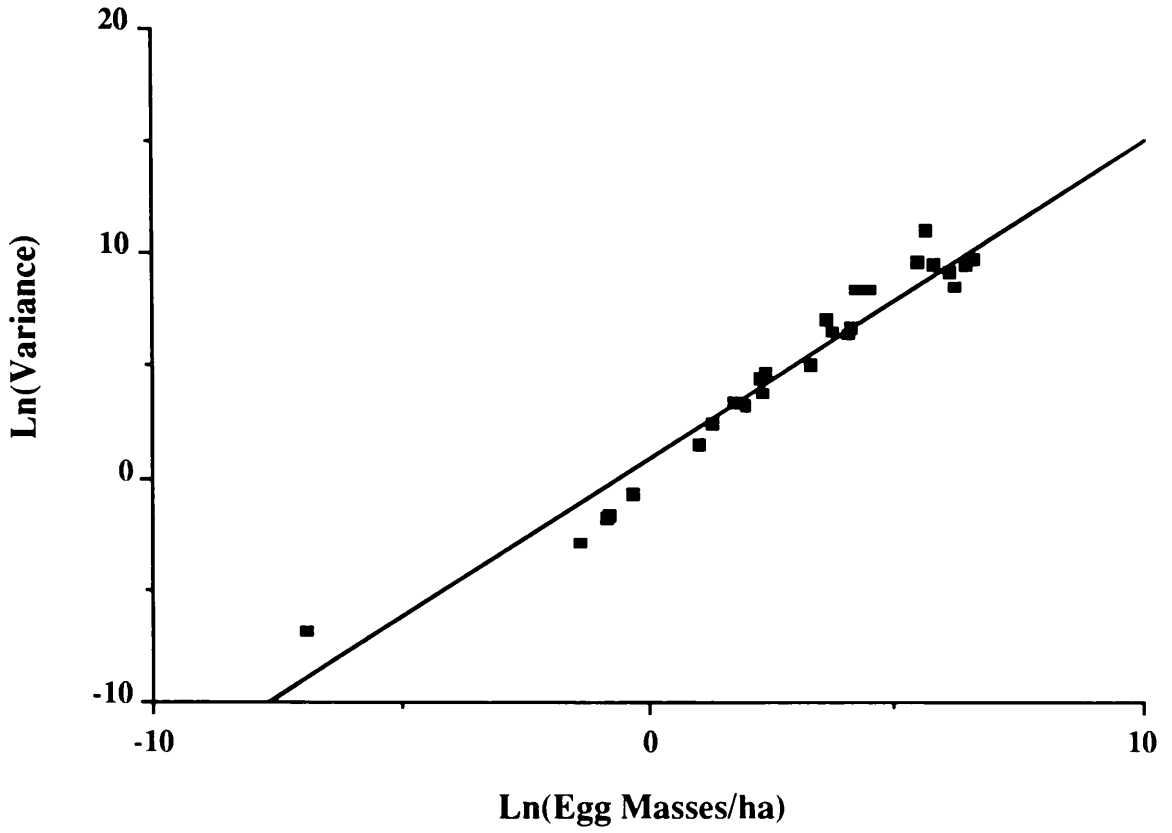


Fig. 1. Relationship between the mean egg masses/ha and variance for 28 study areas in Virginia, Maryland, and Massachusetts.

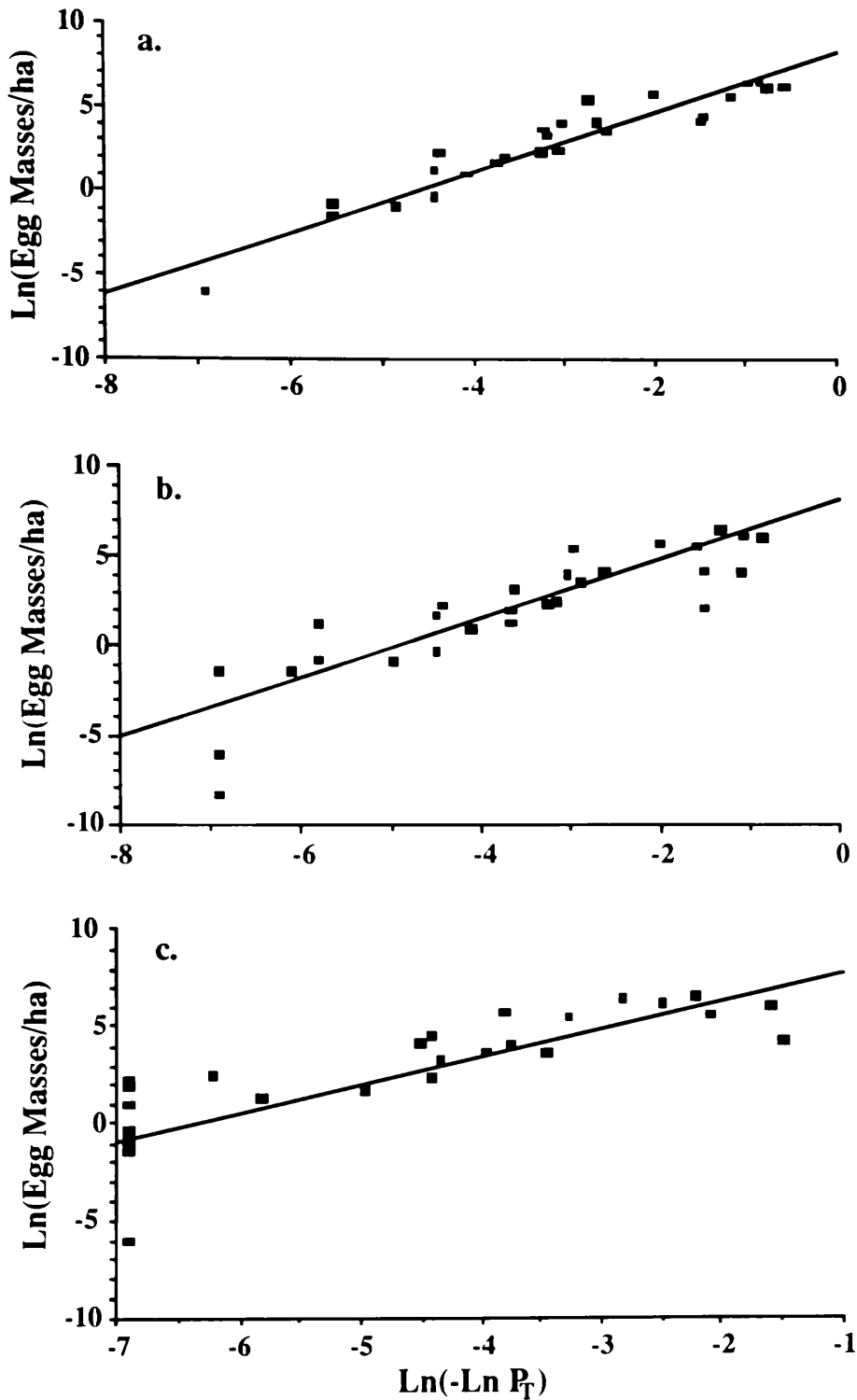


Fig. 2. Relationship between the proportion of trees with no egg masses (P_T) and the mean egg masses/ha for 28 study areas in Virginia, Maryland, and Massachusetts. (a) P_T calculated from the entire tree, (b) P_T calculated from the bole of the tree, and (c) P_T calculated from the first 1.82 m of the bole of the tree.

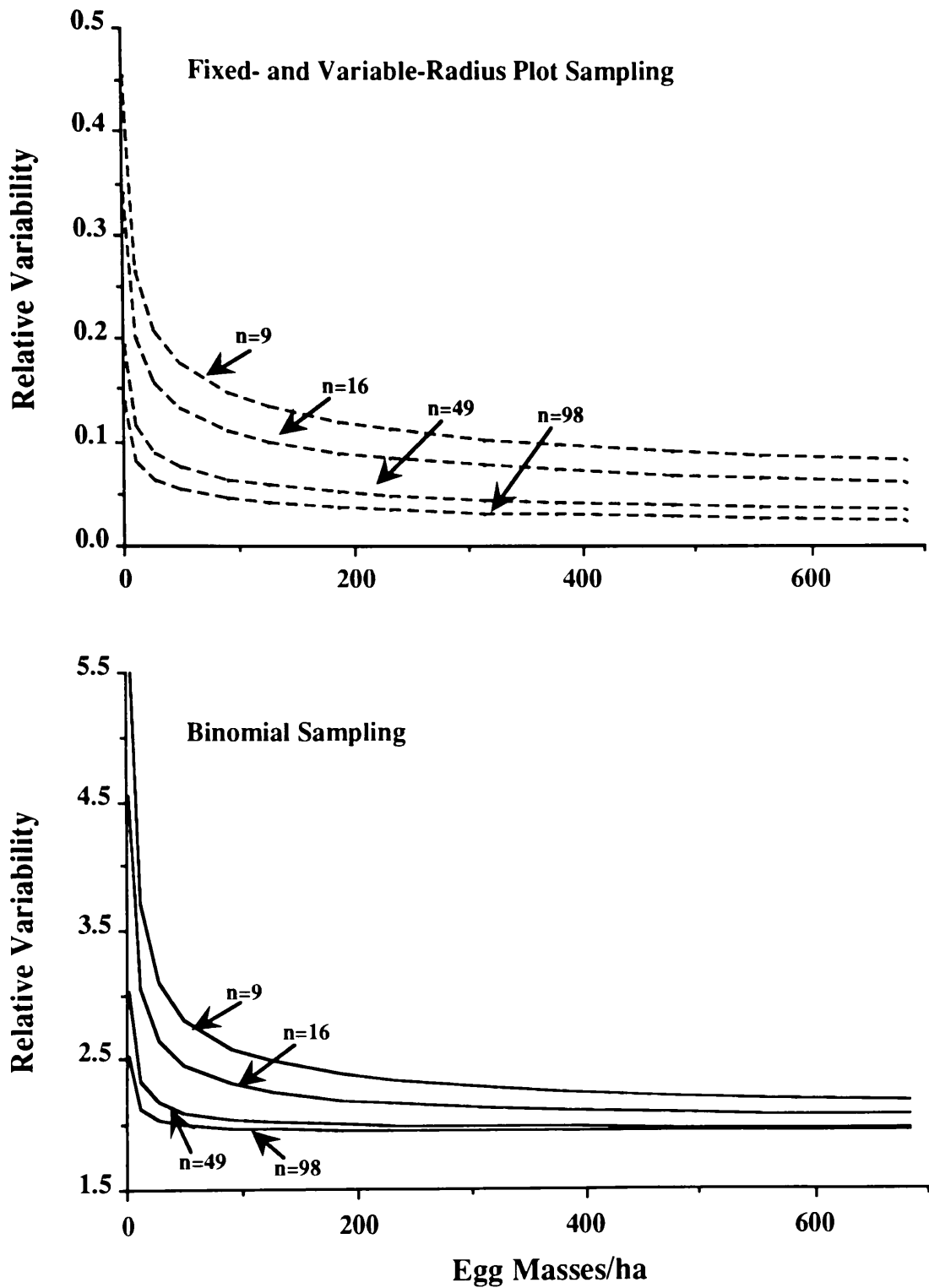


Fig. 3. Relative variability of the fixed- and variable-radius plot sampling method and binomial sampling method at various densities for $n = 9, 16, 49,$ and 98 .

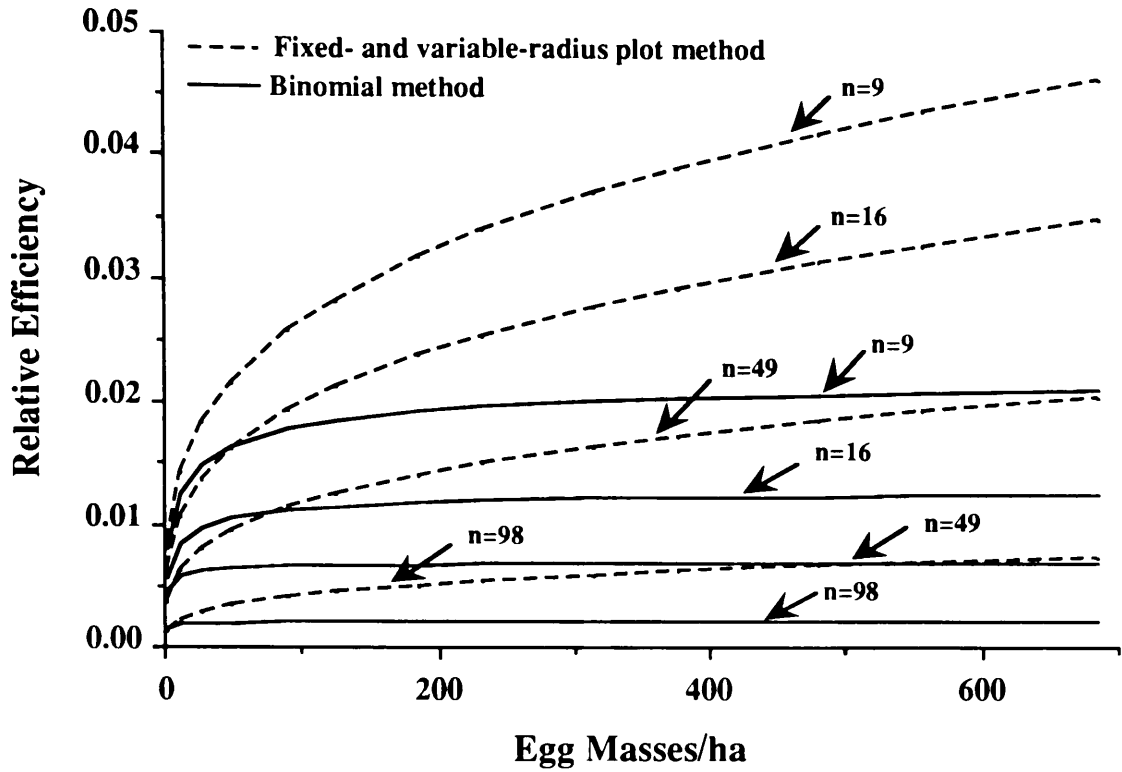


Fig. 4. Relative efficiency of the fixed- and variable-radius plot sampling method and binomial sampling method at various densities for $n = 9, 16, 49,$ and 98 .

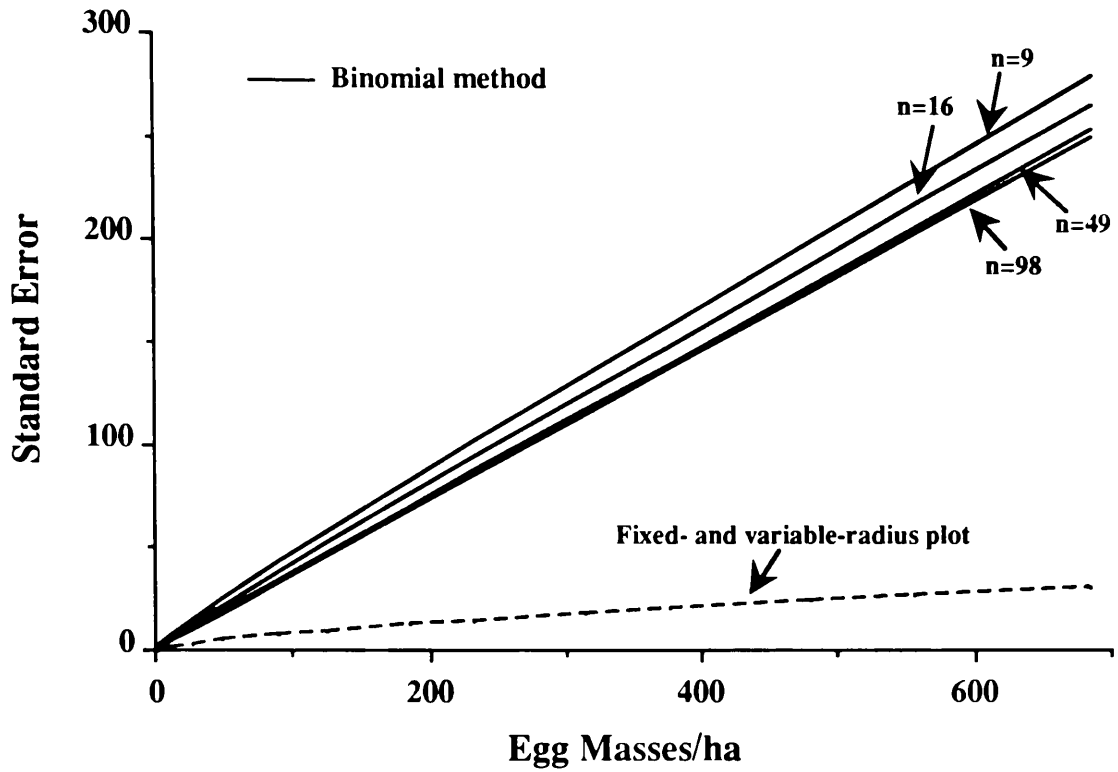


Fig. 5. Relationship between the mean and standard error for the fixed- and variable-radius plot sampling method and binomial sampling method for $n = 9, 16, 49,$ and 98 .

Chapter 4

The Relationship between Gypsy Moth Egg Mass Sample Counts when Foliage is Present and Absent and the Probabilities of Exceeding Action Thresholds when Sampling with Foliage Present

The gypsy moth, primarily a pest in northeastern United States, has recently expanded its range south to North Carolina and west to Wisconsin (Twardus 1991). Management programs initiated to lessen the impact of the gypsy moth require accurate population density estimates for treatment decisions to be cost effective. Gypsy moth populations are monitored by larval, pupal, and/or egg mass sampling, pheromone-baited traps, and defoliation surveys. Egg mass sampling is the primary method used for making control decisions (Ravlin et al. 1987). The most common egg mass sampling methods include fixed-and variable-radius plots (Wilson & Fontaine 1978), fixed-radius plots (Kolodny-Hirsch 1986) and timed walks (Eggen & Abrahamson 1983). Fleischer et al. (1991) developed sequential sampling plans using fixed-radius plots in eastern hardwood forests for the action thresholds of 618, 1,236, or 2,471 egg masses/ha (250, 500, and 1,000 egg masses/acre respectively, Etter 1979). In the United States, the most common action threshold is 618 egg masses/ha (Ravlin et al. 1987).

Egg mass sample counts are affected by several factors including weather conditions, tree species, stand density, leaf area, egg mass density, the surveyor (Wilson et al. 1981), and location within a study area (Bellinger et al. 1989). Wilson and Fontaine (1978) reported that egg mass counts taken with foliage present (summer) were generally consistent with those taken with foliage absent (winter) but that surveys with foliage present are more time consuming. Despite this increase in time, gypsy moth managers are often required to complete egg mass surveys before leaf abscission due to federal and state cooperative suppression regulations which require treatment decisions to be completed by November (D. Twardus, personal communication). To meet this deadline, managers most often begin egg mass sampling in August and assume that their egg mass samples are not influenced by the presence of foliage.

However, foliage clearly restricts visibility of egg masses. Thus, the accuracy of egg mass samples taken when foliage is present is questionable. An understanding of the relationship of egg mass counts taken prior to and after leaf abscission is required to

provide managers with egg mass density estimates which more closely represent the true population densities and yet allows managers to sample as early as possible.

An alternative to making management decisions by estimating population densities is to determine probabilities of exceeding action thresholds. Managers do not necessarily need to know absolute population densities but instead the risk of exceeding an action threshold. This logic is used in sequential sample plans (Nyrop and Binns 1991, Fleischer et al. 1991) and is also appropriate for determining the probability of egg mass counts exceeding action thresholds after leaf abscission when samples are taken prior to leaf abscission.

The objectives of this study were to: 1) determine if there is a significant difference between summer and winter egg mass counts, 2) quantify the relationship between summer and winter counts, and 3) determine the probability of exceeding an action threshold when samples are taken in the summer.

MATERIALS AND METHODS

Egg mass samples were taken in the summers and winters of 1986 and 1989 throughout the northern region of Virginia. Most plots were located in the leading edge of the gypsy moth infestation. Leading edge areas are newly invaded by the gypsy moth yet contiguous with generally infested areas and are experiencing gypsy moth-related defoliation for the first time (Carter et al. 1991). Ninety-seven fixed- and variable-radius plots (20 BAF) were established on a fifty meter grid in two 9 ha study areas in the northern district of the Shenandoah National Park (Warren and Rappahannock Counties) in 1986. In 1989, thirty-nine fixed- and variable-radius plots (20 BAF) were established in Warren, Clarke, Shenandoah, Page, Rappahannock, Madison, Greene, and Rockingham Counties in preferred host habitat (Fig. 1).

Summer egg mass sampling began after male moth flight had ceased and continued through September. Winter egg mass samples were taken after leaf abscission through February. Within each plot, tree species and diameter at breast height were recorded for all trees and each tree was examined for egg masses. The trees were tagged during the summer to ensure that the same trees were resurveyed during the winter.

Statistical Analyses. Statistical analyses were conducted on the combined 1986 and 1989 individual tree egg mass counts and total plot egg mass counts. The data were analyzed using the actual counts taken and not on the number of egg masses per hectare. The data were tested for normality using the Shapiro-Wilk test (PROC UNIVARIATE,

SAS Institute 1989). Neither data set met the assumption of normality ($P < 0.0001$) and transformations did little to improve the fit so nonparametric statistics were applied to complete the analysis. Differences between summer and winter counts were compared using the Wilcoxon rank-sum test (PROC NPAR1WAY, SAS Institute 1989). The relationship between summer and winter counts was examined by linear regression of winter counts on summer counts using the nonparametric Theil-Sen method of slope estimation and the Hodges-Lehmann method of a y intercept estimation (Hollander and Wolfe 1973). Kendall's K tested for non-unity slope of the regression equation (Hollander and Wolfe 1973).

The plot data was analyzed using the Virginia Tech Nonparametric Statistical Package (Pirie 1989) to obtain a slope and intercept but this package did not have the capacity to perform calculations on data sets with >300 observations. A computer program was written to calculate the linear regression for the tree data which was capable of handling a large number of observations and is described below. The Theil-Sen estimator of the slope is determined by the median of the pairwise slopes, given by

$$\text{Slope} = \text{median} \left\{ \frac{Y_j - Y_i}{X_j - X_i} : i \text{ and } j \text{ such that } X_i \neq X_j \right\}$$

The tree data set consisted of 726 observations which results in the computation of 219,056 pairwise slopes (263,175 pairwise slopes minus 44,119 slopes which can be discarded because they failed to satisfy the restrictions that $X_i \neq X_j$) which exceeded the computer's memory capacity. To overcome this limitation, an idea about what the slope estimate should be was obtained from the plot data and then categories of values (to the nearest two decimal places) which bracketed the slope estimate were set up in an array. Each pairwise slope was then computed to the nearest two decimal places and put into the proper category. When the program terminated we had a list of values and counts indicating how many pairwise slopes were equal to each category value. This was used to determine the slope and Y-intercept estimates and confidence interval.

Probability of Exceeding Action Threshold. The number of egg masses per hectare was calculated for summer and winter counts for each plot. The summer egg mass counts were grouped into classes at intervals of two hundred (excluding zero) and the frequency distribution of winter counts for each summer interval was determined (PROC FREQ, SAS Institute 1989). For each summer interval, the cumulative frequency in which winter counts were above each of the action thresholds of 618 and 1,236 egg masses/ha was used to construct a probability curve. The probability curve was

constructed by fitting a logistic curve to the cumulative probability data using the equation :

$$Y = \{ 1 + \exp [-K *(X-C)] \}^{-1/Q}$$

where Y is probability of exceeding a threshold and X is the midpoint of the summer egg mass class. The parameter K determines the steepness of the logistic curve, parameter Q determines the skewness, and parameter C the position of the midpoint of Y (Régnière 1984). Due to insufficient data, the probability of exceeding an action threshold of 2,471 em/ha was not calculated on a plot basis.

RESULTS AND DISCUSSION

Gypsy moth populations ranged from 0 to 52,520 egg masses/ha. A total of 726 trees in 136 plots were examined. Winter egg mass counts were higher than the summer counts in 63.2% of the plots, less in 17.6% of the plots, and equal in 19.2% of the plots. These results differed from Wilson and Fontaine (1978) who reported that winter counts were higher than summer counts in approximately 50% of their surveyed plots and less in 50% of the plots.

Summer egg mass counts per tree averaged 35.75 ± 3.91 and winter counts per tree averaged 43.84 ± 4.29 . Summer egg mass counts per plot averaged 191.70 ± 39.0 and winter counts per plot averaged 234.05 ± 41.65 .

Winter counts were found to be significantly different from summer counts on a per tree basis ($\chi^2 = 129.03$, $df = 79$, $P = 0.0003$) and on a plot basis ($\chi^2 = 635.48$, $df = 136$, $P = 0.0001$). When examined by tree, the relationship between summer and winter counts (egg masses per tree) is described by the equation:

$$W = 1.18 * S;$$

with a 95% confidence intervals around the slope of 1.14 to 1.22 (Kendell's K = 8.834, $n=726$). This relationship implies that winter counts are 14 to 22 percent higher than summer egg mass counts. When examined by plot, the relationship between summer (S) and winter (W) counts (egg masses per plot) is described by the equation:

$$W = 2.28 + 1.23 * S;$$

with a 95% confidence intervals around the slope of 1.16 to 1.34 (Kendell's K = 3354.00, $n= 136$). Since mean egg mass densities have not been found to be different between fixed- and variable-radius plots and fixed-radius plots (Kolodny-Hirsch 1986), this relationship can be used to increase summer counts to winter counts for either plot size.

Probability of Exceeding an Action Threshold. The risk of exceeding two common action thresholds when using summer egg mass counts per hectare on a plot basis was determined and plotted (Fig. 2). If a summer count is known then the probability curves can be used to determine the probability that the count will exceed an action threshold that is based on winter counts. When a summer egg mass count is either much lower or higher than the action threshold then there is little risk involved in making an incorrect treatment decisions. When a summer egg mass count approaches the action threshold there is an increased chance that it will exceed the threshold yet some risk that it will not exceed the threshold. For example, given an action threshold of 618 egg mass/ha and a summer count of 200 egg masses/ha on a plot basis, there is only a 31.0% chance that a winter count would exceed the action threshold. If 600 egg mass/ha on a plot basis were counted, there is a 93.0% chance that a winter count would exceed the action threshold. If the manager feels that the 7% risk of not exceeding the action threshold is small enough then the decision to treat should be made.

Mathematically if a summer count is at the action threshold, than the probability of exceeding the action threshold should be 100%. However, there is error in sampling and predation of egg masses which results in lower winter counts. Sampling errors include missing egg masses when counting, especially on higher branches, or not being unable to distinguish old egg mass from new egg masses. Thus when sampling errors occur in the winter, the summer counts may be higher. In addition, predation may reduce the number of egg masses from summer to winter. The result is that the probability at the action threshold is not 100%. This is evident for the 1,236 egg masses/ha action threshold. The probability curve shows that when the summer egg mass count is at the threshold, there is only a 80% chance it would have exceeded the threshold using a winter count.

CONCLUSION

The most likely reason that winter counts are higher than summer counts is due to the greater visibility of egg masses when foliage is absent. To accurately determine egg mass density, samples should not be taken until after leaf abscission. However, for management use of summer egg mass counts is critical to meet federal and state cooperative suppression program deadlines. To accomplish these deadlines managers can continue to sample in the summer, but need to compensate for the difference between summer and winter egg mass counts to assure accurate estimates of egg mass densities.

We also suggest the use of probabilities to determine if summer egg mass counts will exceed action thresholds. This method allows managers to continue sampling in the summer but the treatment decisions will more closely resemble decisions made using winter egg mass sample counts and does not require the manager to compensate for differences between summer and winter counts. However, the level of risk of making an incorrect treatment decision is subjective and is determined by the needs of the individual managers. Although the probabilities curves were developed with empirical data and may not extend to all populations and habitats, the concept of using probabilities to make treatment decisions has been shown to be a viable alternative to using actual population estimates.

Although this paper relies heavily on the commonly used action thresholds, we feel that additional research on action thresholds is required. This includes determining how closely egg mass densities correspond to defoliation (Montgomery 1990) and the probabilities of exceeding different levels of defoliation given an egg mass density, site characteristic and management objectives. Since the managers main reason for treating is to reduce gypsy moth defoliation, determining the probability of a summer egg mass count exceeding a certain level of defoliation could provide managers with a versatile and useful decision making tool.

REFERENCES CITED

- Bellinger, R. G., F. W. Ravlin, & M. L. McManus. 1989. Forest edge effects and their influence on gypsy moth (Lepidoptera: Lymantriidae) egg mass distribution. *Environ. Entomol.* 18: 840-843.
- Carter, M. R., F. W. Ravlin, & M. L. McManus. 1991. Changes in gypsy moth (Lepidoptera: Lymantriidae) fecundity and male wing length resulting from defoliation. *Environ. Entomol.* 20: 1042-1047.
- Eggen, D. A. & L. P. Abrahamson. 1983. Estimating gypsy moth egg mass densities. School of Forestry ESF 83-002, State University of New York, College of Environmental Science and Forestry, Syracuse, N.Y.
- Etter, D. O., Jr. 1979. Thresholds-Appendix K. Comprehensive gypsy moth pest management system. National Gypsy Moth Management Board.
- Fleischer, S. J., F. W. Ravlin, & R. C. Reardon. 1991. Implementation of sequential sampling plans for gypsy moth (Lepidoptera: Lymantriidae) egg masses in eastern hardwood forests. *J. Econ. Entomol.* 84: 1100-1107.
- Hollander, M. and D. A. Wolfe. 1973. *Nonparametric Statistical Methods*. Wiley, New York.
- Kolodny-Hirsch, D. M. 1986. Evaluation of methods for sampling gypsy moth (Lepidoptera: Lymantriidae) egg mass populations and development of sequential sampling plans. *Environ. Entomol.* 15: 122-127.
- Montgomery, M. E. 1990. Role of site and insect variables in forecasting defoliation by gypsy moth. In: Watt, A.D., S.R. Leather, M.D. Hunter, and N.E.C. Kidd (eds.) *Population dynamics of forest insects*, Natural Environment Research Council - Institute of Terrestrial Ecology Conference, Proceedings. Intercept, Edinburgh.
- Nyrop, J. P. and M. Binns. 1991. Quantitative methods for designing and analyzing sampling programs for use in pest management, pp. 67-132. In D. Pimentel [ed.], *Handbook of pest management*. CRC. Boca Raton, FL.
- Pirie, W. R. 1989. *Virginia Tech Nonparametric Statistical Package*. Department of Statistics and Statistical Consulting Laboratory, VPI & SU, Blacksburg, VA.
- Ravlin, F. W., R. G. Bellinger & E. A. Roberts. 1987. Gypsy moth management programs in the United States: status, evaluation, and recommendations. *Bull. Entomol. Soc. Am.* 33: 90-98.
- Régnière, J. 1984. A method of describing and using variability in development rates for the simulation of insect phenology. *Can. Ent.* 116: 1367-1376.

- SAS Institute. 1989. SAS user's guide: statistics. SAS Institute, Cary, N.C.
- Twardus, D. B. 1991. Gypsy Moth News. USDA. 26 (June): 4-5.
- Wilson, R. W., Jr., & G. A. Fontaine. 1978. Gypsy moth handbook: gypsy moth egg-mass sampling with fixed- and variable-radius plots. USDA Agriculture Handbook 523.
- Wilson, R. W., Jr., S. W. Ivanowsky, & R.L. Talerico. 1981. Detection and Evaluation. pp 34-38. In C. C. Doane & M. L. McManus [eds.], The gypsy moth: research toward pest management. USDA Technical Bulletin No. 1584.

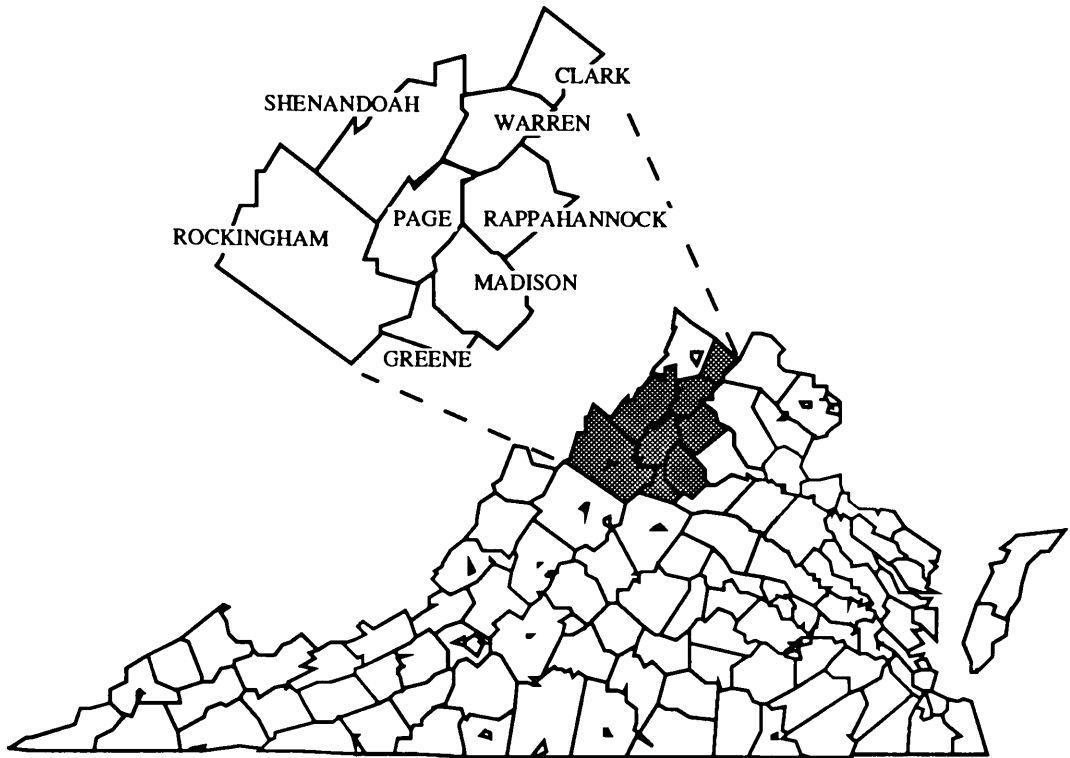


Fig. 1. Virginia counties where egg mass sample sites were located during 1986 ($n = 97$) and 1989 ($n = 39$).

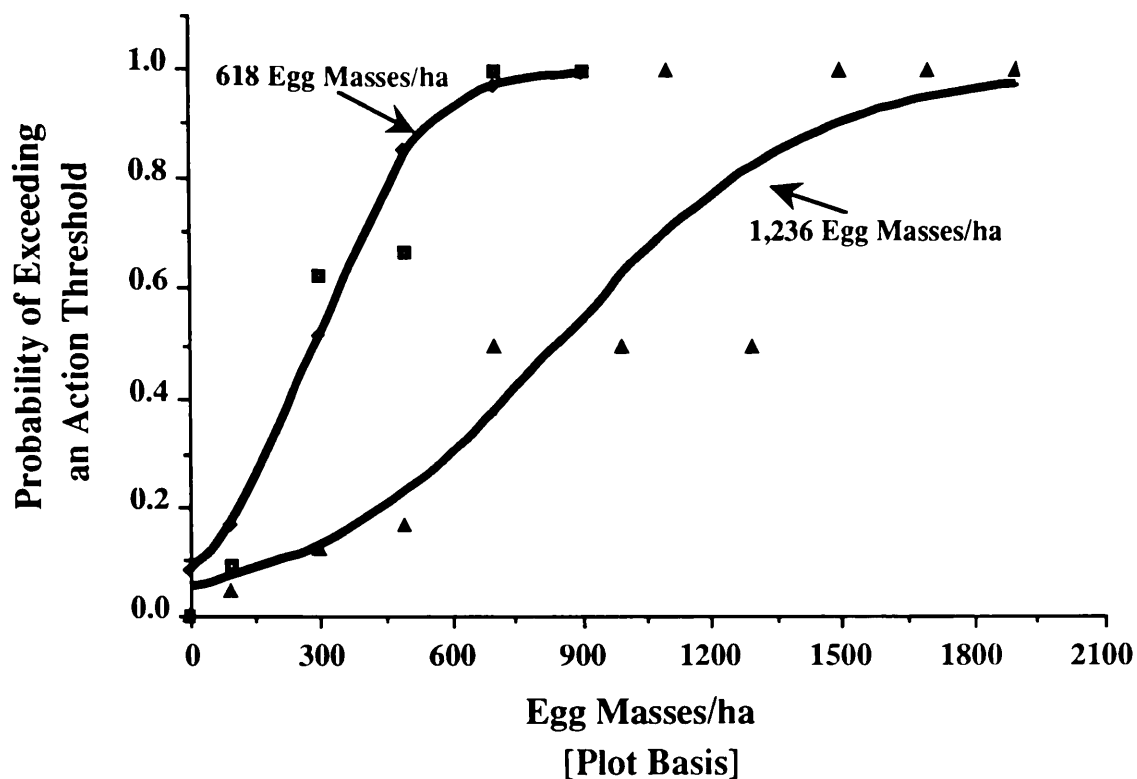


Fig. 2. Probability of a summer egg masses per hectare count for a plot exceeding the action thresholds of 618 egg masses/ha (■) or 1,236 egg mass/ha (▲). Observed probabilities of a summer egg mass count exceeding an action threshold are included for both action thresholds. Logistic curve equation for action threshold of 618 egg masses/ha is $\{1+\exp[-0.00846 * (X-296.21)]\}^{-1/1.02}$ and 1,236 egg masses/ha is $\{1+\exp[-0.00344 * (X-843.55)]\}^{-1/0.992}$ where X is a summer egg mass count.

Chapter 5

Summary

The gypsy moth is an important pest of trees in the northeastern United States and has recently expanded its range south to North Carolina and west to Wisconsin (Twardus 1991). Monitoring and control of gypsy moth populations is necessary to try to prevent outbreaks which result in defoliation and possible tree mortality. Millions of dollars are expended for monitoring and control of the gypsy moth yearly.

Gypsy moth populations are monitored by larval, pupal, and/or egg mass sampling, pheromone-baited traps, and defoliation surveys. Egg mass sampling is the primary method used for making control decisions (Ravlin et al. 1987). Egg mass sampling methods include fixed- and variable-radius plot samples (Wilson and Fontaine 1978), fixed-radius plots (Kolodny-Hirsch 1986), and timed walks (Eggen & Fontaine 1983, Fleischer et al. 1991).

Fleischer et al. (1991) developed sequential sample plans using 0.01 ha fixed-radius plots in eastern hardwood forests for the action thresholds of 618, 1,236, and 2,471 egg masses/ha (250, 500, and 1,000 egg masses/ac. respectively, Etter 1979). Use of these sequential sampling plans resulted in a significant saving of time in forested habitats but were not recommended for areas influenced by man or man-made objects (urban and suburban habitats). Since gypsy moths are an urban pest as well as a forest pest, the need for sampling plans that would reflect the changes in egg mass distribution due to man-made objects was apparent. The sampling plans developed by Fleischer et al. (1991) were also not recommended in areas which had been within a spray block the previous year because of differences in the egg mass distribution. Kolodny-Hirsch (1986) recommended that sequential sampling not be implemented in low density populations due to intensive labor cost. The goal of the research presented here was to develop and validate gypsy moth egg mass sampling plans that optimize the allocation of limited resources of labor, time, and money while producing accurate measures of population density. Specifically, the objective of this research was to develop egg mass sampling plans that reflected the influence of habitat, changes in egg mass distribution, and provided population densities or density categories for control decisions.

Sequential sampling plans were developed for urban and suburban habitats for the action thresholds of 618, 1,236, and 2,471 egg masses/ha. An urban/suburban habitat was defined as areas where the housing density ranges from 0.247 houses/ha to 12.35

houses/ha. Sampling plans were developed from 0.01 ha fixed-radius plot samples collected in 111 2.6 km² grids cells in northern Virginia. The sequential sampling plans were based on a negative binomial distribution with a k equal to 0.527. The sampling plans produced a minimum of 6 to 7 samples and a maximum of 15 to 24 samples for a 2.6 km² grid cell. Use of the sequential sampling plans resulted in a 31-49% savings in time compared to a fixed sample size plan.

Binomial sampling is a method in which the only information retained from a sample unit is the presence or absence of the pest in the sample unit. Binomial sampling has been shown to provide an effective sampling method for low densities pest populations (Lysyk & Sanders 1987). Since present egg mass sampling methods were not recommended for low density gypsy moth populations, binomial sampling was examined as a method to provide accurate population estimates in continuously forested habitats.

Binomial sampling plans were shown not to be feasible for low density (<618 egg masses/ha) populations. Fixed- and variable-radius (FVR) plot samples were taken in 28 study areas in Virginia, Maryland, and Massachusetts. The relationship between the mean number of egg masses and proportion of trees with zero egg masses was determined for three tree strata. Tree strata included the entire tree, the bole of the tree, and the first 1.82 m of the bole. Relative variability and relative efficiency for sample sizes of 9, 16, 49, and 98 were used to compare the FVR plot sampling method and the binomial sampling method. Relative variability for the FVR plot sampling method ranged from 0.035-0.454 compared to 1.94 to 5.83 for binomial sampling. The relative efficiency of 9 and 16 FVR plot samples was higher than the binomial samples. Binomial sampling was more efficient than 49 FVR plot samples for 9 samples if the population density was below 800 egg masses/ha and 16 samples if the population density was below 90 egg masses/ha. Validation of binomial sampling using 9 and 16 samples resulted in a large proportion's of zero or overestimation and underestimation of the actual population densities. It was determined that binomial sampling is not an effective method for low density populations in forested habitats.

With the development of sequential sampling plans for urban/suburban habitats, managers can conduct egg mass surveys from forested to highly developed habitats with a minimum of time and cost. Although binomial sampling was not feasible for low density populations in forested areas, the use of binomial sampling should not be discarded for gypsy moth populations. Binomial sampling may be feasible for urban

/suburban habitats or forested habitats with higher population densities. Thorpe et al. (1992) also recommended that binomial sampling be investigated for residential areas. Binomial sampling for these habitats would provide managers with a quicker and simpler method for determining population density or density categories for control decisions.

For effective control decisions to be made it is necessary to have accurate estimations of the population density. To meet state and federal suppression regulations, gypsy moth managers are often required to complete egg mass surveys before leaf abscission. Sampling egg masses with leaves present assumes that the counts are not being obstructed by the foliage but it is likely that foliage would interfere with counting egg masses. An improved understanding of the relationship between egg mass counts taken when leaves are present and absent was examined.

Fixed- and variable-radius plot samples were conducted before and after leaf abscission on the same trees in 136 plots. Winter counts were found to be significantly different than summer counts. When examined on an individual tree basis, winter counts were approximately 14-22% higher than summer counts. On a plot basis, winter counts were approximately 16-34% higher than summer counts. Since gypsy moth managers need to sample as early as possible, the probability of a summer egg mass count exceeding an action threshold was determined.

The object of egg mass sampling is to make control decisions to prevent defoliation. The probability of exceeding a level of defoliation instead of an action threshold may provide managers with a more useful decision tool. This would allow managers to decide what level of defoliation is acceptable for a given area. The probability of exceeding a level of defoliation could be used in sequential or binomial sampling. The sampling plans would determine if treatment was necessary based on a certain level of defoliation instead of an action threshold. The probability of a summer egg mass count exceeding a certain level of defoliation instead of an action threshold may also be a useful decision tool.

Although this research relied heavily on the action thresholds presently being used additional research in this area is warranted. Action thresholds need to be developed for individual habitats which reflect the spatial differences and levels of defoliation which can be tolerated.

REFERENCES CITED

- Eggen, D. A. & L.P. Abrahamson. 1983. Estimating gypsy moth egg mass densities. School of Forestry ESF 83-002, State University of New York, College of Environmental Science and Forestry, Syracuse, N.Y.
- Etter, D. O, Jr. 1979. Thresholds - Appendix K. Comprehensive gypsy moth pest management system. National Gypsy Moth Management Board.
- Fleischer, S.J., F.W. Ravlin, & R.C. Reardon. 1991. Implementation of sequential sampling plans for gypsy moth (Lepidoptera: Lymantriidae) egg masses in eastern hardwood forests. *J. Econ. Entomol.* 84: 1100-1107.
- Lysyk, T. J. & C. J. Sanders. 1987. A method for sampling endemic populations of the spruce budworm (Lepidoptera: Tortricidae) based on proportion of empty sample units. Information Report OX-382. Great Lakes Forestry Centre, Sault Ste. Marie, Ont.
- Kolodny-Hirsch, D. M. 1986. Evaluation of methods for sampling gypsy moth (Lepidoptera: Lymantriidae) egg mass populations and development of sequential sampling plans. *Environ. Entomol.* 15: 122-127.
- Ravlin, F.W., R. G. Bellinger, & E.A. Roberts. 1987. Gypsy moth management programs in the United States: status, evaluation, and recommendations. *Bull. Entomol. Soc. Am.* 33: 90-98.
- Thorpe, K. W. & R. L. Ridgeway. 1992. Gypsy moth (Lepidoptera Lymantriidae) egg mass distribution and sampling in a residential setting. *Environ. Entomol.* 21: 722-730.
- Twardus, D. B. 1991. Gypsy Moth News. USDA. 26(June): 4-5.
- Wilson, R. W., Jr., & G. A. Fontaine. 1978. Gypsy moth handbook: gypsy moth egg-mass sampling with fixed- and variable-radius plots. USDA Agriculture Handbook 523.

APPENDIX

Appendix 1. FORTRAN program to determine maximum likelihood estimate of the index of aggregation , K. The program inputs include the input file name, output file name, and chi-square class size interval. The chi-square class size interval should chosen so that the fewest amount of classes with zero observations is obtained. An example of an input data set is provided after the FORTRAN program.

C This program fits a negative binomial frequency distribution to an array of
 C ungrouped observations using the maximum likelihood method of Bliss and
 C Fisher (1953) Biometrics, Vol. 9, pp. 176-200. Goodness of fit is tested by a
 C chi-squared test.
 C Parameters of the data set are as follows:
 C NPROB = Problem reference number (zero after last data set) (
 C M = Number of observation in data set
 C XR = Vector of observations (Length K)
 C

```
REAL K0, K1, K
DIMENSION XR(100), X(2000), F(2000), FA(2000), FN(2000),
+NUM(2000), FNUM(2000)
```

```
CHARACTER*40 FNAME
CHARACTER*40 FOUT
WRITE (*,'(A)') ' ENTER INPUT FILE NAME--'
READ (*,'(A)') FNAME
OPEN(5,FILE=FNAME)
```

```
WRITE (*,'(A)') ' ENTER OUTPUT FILE NAME--'
READ (*,'(A)') FOUT
OPEN(6,FILE = FOUT,STATUS = 'NEW')
```

```
WRITE (*,*) 'ENTER CLASS SIZE INTERVAL--'
```

```

READ (*,*) ISIZE

1  READ (5,100) NPROB
100 FORMAT (I5)
    IF (NPROB.EQ.0) STOP
    N=0
    READ (5,*) M,(XR(I),I=1,M)
    DO 2 I = 1,M
        NUM(I) = XR(I)/ISIZE
2  CONTINUE
    DO 3 I=1,M
        N= N + 1
        X(N) = XR(I)
3  CONTINUE

C
C  Tabulate observed frequency distribution for new number (num) determined
C  from class interval size
    XMAX=NUM(1)
    DO 5 I = 2,N
        IF (XMAX.GE.NUM(I)) GO TO 5
        XMAX = NUM(I)
5  CONTINUE
    NCL = XMAX + 2.0
    DO 6 I = 1,NCL
6  F(I) = 0.0
    DO 7 I=1,N
        IP = NUM(I) + 1.0
7  FNUM(IP) = F(IP) + 1.0

C
C  Tabulate observed frequency distribution
    YMAX = X(1)
    DO 500 I = 2,N

```



```

      IF (YMAX.GE.X(I)) GO TO 500
      YMAX = X(I)
500  CONTINUE
      KNCL = YMAX + 2.0
      DO 600 I = 1, KNCL
600  F(I) = 0.0
      DO 700 I = 1, N
      IP = X(I) + 1.0
700  F(IP) = F(IP) + 1.0

```

C

C Tabulate accumulated frequencies

```

      AN = N
      S = 0.0
      DO 8 I = 1, KNCL
      S = S + F(I)
8    FA(I) = AN - S

```

C

C Compute mean and variance and test for over-dispersion

```

      SX=0.0
      SX2= 0.0
      DO 9 I = 1, N
      SX = SX + X(I)
9    SX2 = SX2 + X(I) * X(I)
      XBAR = SX/AN
      VAR = (SX2-SX*SX/AN) / (AN-1.0)
      CHI2 = (AN-1.0) * VAR / XBAR
      NDF = N-1
      WRITE(6,103) NPROB, CHI2,NDF
103  FORMAT (1x,'NEGATIVE BINOMIAL DISTRIBUTION'//,1X,'PROBLEM',
      +I4//,1X,'TEST OF OVER-DISPERSION'//,1X,'CHI-SQUARED = ',
      +1PE12.4,' WITH ',I4,' DEGREES OF FREEDOM')

```

C

C Compute first two trial values of K.

DEN = VAR - XBAR

IF (ABS(DEN).LT.0.0001 * ABS(VAR)) GO TO 14

K0 = XBAR * XBAR / DEN

IF (XBAR/K0.LE.(-1.0)) GO TO 14

Z0 = ZF(K0, KNCL, FA, XBAR, AN)

K1=K0

AK0 = ABS(K0)

NCYC = 0

IF(Z0) 10,19,11

10 DIFF = -0.2 * AK0

GO TO 12

11 DIFF = 0.2 * AK0

12 K1 = K1 + DIFF

IF (XBAR/K1.LE.(-1.0)) GO TO 14

Z1 = ZF(K1,KNCL,FA,XBAR,AN)

NCYC = NCYC + 1

IF (Z0 * Z1) 15,20,13

13 IF (NCYC.LT.100) GO TO 12

14 WRITE (6,104)

104 FORMAT (//,1X,'NO SUITABLE ESTIMATES OF K. EXECUTION
TERMINATED')

GO TO 1

C

C ESTIMATE K BY INTERPOLATION (METHOD OF FALSE POSITION).

15 NCYC = 0

16 DEN = Z1-Z0

IF (ABS(DEN).LT.0.0001 * ABS(Z1)) GO TO 14

K=(K0 * Z1 - K1*Z0)/DEN

IF (XBAR/K.LE.(-1.0)) GO TO 14

Z = ZF(K,KNCL,FA,XBAR,AN)

NCYC = NCYC + 1

```

IF (ABS(Z).LT.0.0001) GO TO 21
IF (NCYC.GE.100) GO TO 14
IF ( Z*Z0) 17,21,18
17 K1=K
   Z1=Z
   GO TO 16
18 K0=K
   Z0 = Z
   GO TO 16

C
C  CONSTRUCT THEORETICAL FREQUENCY DISTRIBUTION AND TEST
C  GOODNESS OF FIT
19 K=K0
   GO TO 21
20 K=K1
21 CALL NEGBIN (NCL, N, XBAR, K, FN)
   CALL CHISQ (FNUM,FN, NCL, CHI2, NDF, N1, N5)
   NDF=NDF-2

C
C  OUTPUT RESULTS.
   WRITE (6,105)
105 FORMAT (///,1X,'CLASS',11X,'CLASS', 9X,'OBSERVED',8X,
+ 'THEORETICAL',/, 1X,'NUMBER',10X,'SIZE',10X,'FREQUENCY',7X,
+ 'FREQUENCY'//)
   DO 22 I = 1,NCL
   NX = I-1
22 WRITE (6,106) I,NX,FNUM(I),FN(I)
106 FORMAT (I5,I6,F18.1,F18.3)
   WRITE (6,107) XBAR,VAR,K,CHI2,NDF,N1,N5
107 FORMAT (//,1X,'MEAN = ',F10.4, 10X, 'VAR = ', F13.5//,
+1X,'K = ',F11.5//,
+1X,'CHI-SQUARED = ',1PE12.4,' WITH',I6,' DEGREES OF

```

```

FREEDOM',//,
+1X,'NUMBER OF CELLS WITH EXPECTED FREQUENCY LESS THAN
1=',I4,//,
+1X,'NUMBER OF CELLS WITH EXPECTED FREQUENCY LESS THAN
5=',I4,//)

```

C Initialize arrays to zero

```
DO 150 I = 1,M
```

```
XR(I) = 0.0
```

```
X(I) = 0.0
```

```
150 CONTINUE
```

```
DO 151 I = 1,N
```

```
NUM(I) = 0.0
```

```
FNUM(I) = 0.0
```

```
X(I) = 0.0
```

```
F(I) = 0.0
```

```
FA(I) = 0.0
```

```
151 CONTINUE
```

```
GO TO 1
```

```
END
```

```
SUBROUTINE NEGBIN (NCL, N, XBAR, K, FN)
```

C

C.....

C This subroutine constructs a negative binomial frequency distribution FN

C containing N observations in ncl classes and having given values of mean

C (XBAR) and K.

C.....

C

```
REAL K
```

```
DIMENSION FN(NCL)
```

```
AN=N
```

```

NCLM = NCL-1
FN(1) = AN / ((1.0 + XBAR/K)**K)
SFN = FN(1)
DO 1 I=2,NCLM
  AIM = I-1
  FN(I) = FN(I-1) * (K+AIM-1.0) * XBAR / (K+XBAR) / AIM
1 SFN = SFN + FN(I)
  FN(NCL) = AN-SFN
  RETURN
  END

```

```

FUNCTION ZF(K,KNCL,FA,XBAR,AN)

```

C

C.....

C This function subprogram computes Z for Fisher's maximum likelihood
C solution of a negative binomial distribution with parameter K, containing
C AN observations, mean XBAR, and accumulated frequencies FA,
C arranged in NCL classes

C.....

C

```

  REAL K
  DIMENSION FA(KNCL)
  ZF = 0.0
  DO 1 I=1,KNCL
    XN=I-1
1 ZF=ZF + FA(I) / (K+XN)
  ZF = ZF - AN * ALOG(1.0 + XBAR/K)
  RETURN
  END

```

```

SUBROUTINE CHISQ (FNUM, FN, NCL, CHI2, NDF, N1, N5)

```

C

C.....

C This subroutine computes chi-squared for vectors of observed and expected
 C frequencies, FNUM and FN, both of length NCL. Also returned are degrees
 C of freedom (NDF) and number of cells with expected frequencies less than 1
 C (N1) and 5 (N5).

C.....
 C

```

    DIMENSION FNUM(NCL), FN(NCL)
    CHI2=0.0
    DO 1 I = 1,NCL
1  CHI2 = CHI2 + (FNUM(I)-FN(I)) * (FNUM(I)-FN(I))/FN(I)
    NDF =NCL-1
    N1 =0
    N5 = 0
    DO 2 I = 1,NCL
    IF (FN(I).GE.5.0) GO TO 2
    N5 = N5 +1
    IF (FN(I).GE.1.0) GO TO 2
    N1 = N1+1
2  CONTINUE
    RETURN
    END
  
```

.....
 Example Input Data Set:

Problem reference number (NPROB)
 Number of observations (M), Observations (XR)

.
 .
 .

0 (After last data set)

i.e.: 1 (NPROB)
 10 (M) 10 17 18 16 12 14 13 11 9 18 (XR)

2

13 0025 1097 12 14 13 7 3 0

3

7 0030 60 10

0

Appendix 2. Grid Cells from Loudoun, Fairfax, and Arlington Counties used to develop sequential sampling plans for urban/suburban habitats. For each grid cell, the number of samples taken in the cell, the mean number of egg masses/gird, the variance, and the maximum likelihood value of k is recorded.

County	Grid Number	Number of			
		Samples in a gird	Mean	Variance	k
Loudoun	176	14	8.92	104.68	0.850
Loudoun	207	15	30.93	5805.06	0.334
Loudoun	204	14	4.71	31.60	0.299
Loudoun	269	10	3.50	7.83	1.809
Loudoun	271	12	0.75	1.65	0.428
Loudoun	351	10	1.70	2.90	2.290
Loudoun	359	10	15.50	951.83	0.298
Loudoun	420	19	7.94	121.05	0.585
Loudoun	447	10	7.30	192.23	0.285
Loudoun	451	13	9.07	51.07	1.217
Loudoun	479	16	2.06	32.86	0.172
Loudoun	481	10	1.30	6.45	0.301
Loudoun	483	11	6.09	46.09	1.497
Loudoun	512	22	1.63	15.86	0.092
Loudoun	540	14	11.50	313.34	0.222
Loudoun	546	11	27.27	1537.81	0.244
Loudoun	548	16	20.37	1161.18	0.337
Loudoun	567	10	0.80	6.40	0.033
Loudoun	568	11	45.00	5534.40	0.588
Loudoun	473	18	35.72	2678.33	0.327
Loudoun	575	12	155.16	24051.42	1.460
Loudoun	576	10	14.80	492.40	0.123
Loudoun	577	10	0.700	4.900	0.036
Loudoun	580	19	34.15	6490.14	0.422
Loudoun	586	18	6.72	141.50	0.304

Loudoun	588	19	55.63	6060.46	0.429
Loudoun	605	11	74.27	4832.01	0.495
Loudoun	617	12	8.91	536.99	0.090
Loudoun	618	29	6.96	218.89	0.237
Loudoun	626	14	.6429	3.01	0.068
Loudoun	630	12	14.25	304.20	0.551
Loudoun	632	10	81.10	9645.21	0.255
Loudoun	636	11	114.45	7727.47	1.802
Loudoun	639	10	5.40	88.26	0.098
Loudoun	642	11	29.00	1153.80	0.420
Loudoun	662	10	36.8	1424.17	0.441
Loudoun	677	21	55.52	3888.56	0.362
Loudoun	691	15	0.13	0.26	0.061
Loudoun	693	11	9.72	193.81	0.317
Loudoun	702	13	96.00	6380.50	1.476
Loudoun	703	11	69.00	5151.60	0.613
Loudoun	709	18	23.77	1387.00	0.226
Loudoun	726	10	21.00	1121.11	0.161
Loudoun	729	15	14.86	133.98	1.227
Loudoun	731	12	65.58	2185.35	0.921
Loudoun	732	10	92.20	2957.06	2.369
Loudoun	760	10	3.40	15.15	0.793
Loudoun	762	13	27.38	1250.92	0.190
Loudoun	763	16	17.43	2469.46	0.187
Loudoun	765	12	23.08	1671.90	0.081
Loudoun	793	13	6.84	320.30	0.120
Loudoun	796	18	30.55	3123.55	0.186
Loudoun	827	19	39.73	2958.20	0.221
Loudoun	829	15	1.80	12.45	0.119
Loudoun	859	15	56.86	1851.83	0.784
Loudoun	889	12	12.50	808.63	0.169
Loudoun	890	13	43.23	1913.85	0.411
Loudoun	920	11	28.63	1749.85	0.402
Loudoun	632	10	43.60	3701.37	0.293

Loudoun	554	10	41.70	1930.45	0.233
Loudoun	582	10	48.7	4214.90	0.553
Fairfax	6-2	10	209.40	15582.60	0.456
Fairfax	7-1	10	39.40	3616.71	0.388
Fairfax	10-2	10	95.40	17722.70	0.500
Fairfax	13-3	10	114.00	16222.67	0.607
Fairfax	17-2	15	15.53	899.26	0.414
Fairfax	20-3	12	38.75	1738.56	0.575
Fairfax	21-3	12	85.5	11512.64	0.518
Fairfax	21-4	11	15.81	825.56	0.186
Fairfax	26-2	13	19.23	1677.19	0.389
Fairfax	26-4	16	43.68	5446.2	0.484
Fairfax	29-2	10	36.5	2304.27	0.629
Fairfax	30-1	17	219.52	34867.27	0.686
Fairfax	36-2	12	132.08	16379.72	1.080
Fairfax	37-2	14	52.64	4432.86	0.602
Fairfax	37-4	10	39.70	9424.9	0.242
Fairfax	39-3	13	18.53	1872.93	0.194
Fairfax	40-2	12	14.75	462.93	0.311
Fairfax	41-1	11	32.72	1832.40	0.471
Fairfax	58-1	11	13.63	428.65	0.151
Fairfax	58-2	12	2.66	18.42	0.238
Fairfax	58-4	10	27.5	6967.38	0.083
Fairfax	61-3	15	3.26	20.92	0.502
Fairfax	61-4	10	21.00	288.22	1.025
Fairfax	68-4	11	114.63	18569.65	0.431
Fairfax	69-1	13	55.61	21009.59	0.176
Fairfax	69-2	10	23.00	176.11	0.247
Fairfax	70-3	12	24.0	1332.6	0.313
Fairfax	78-2	10	8.10	218.54	0.246
Fairfax	79-1	12	42.83	10941.20	0.276
Fairfax	79-4	11	3.90	55.89	0.215
Fairfax	80-1	14	91.92	10848.84	0.568
Fairfax	80-3	12	69.58	6331.72	0.749

Fairfax	89-1	11	17.36	899.65	0.524
Fairfax	90-1	13	33.38	1283.09	0.616
Fairfax	51-1	12	254.91	338004.50	0.247
Arlington	1	26	21.00	1392.24	0.365
Arlington	2	36	14.61	1731.38	0.361
Arlington	3	49	7.46	177.71	0.384
Arlington	4	41	3.63	25.18	0.763
Arlington	5	36	13.88	690.15	0.426
Arlington	6	32	23.65	1615.30	0.617
Arlington	7	34	8.23	247.82	0.343
Arlington	8	27	2.29	12.13	0.469
Arlington	9	39	6.38	103.40	0.515
Arlington	10	22	6.00	446.47	0.194
Arlington	11	21	9.28	12.1	0.494
Arlington	12	31	10.96	229.96	0.626
Arlington	13	34	9.61	175.69	0.519
Arlington	14	45	6.44	215.38	0.306
Arlington	15	22	4.50	79.11	0.312

Appendix 3. Study areas from Virginia, Maryland, and Massachusetts used to develop the binomial sampling plans. For each 9 ha study area, the number of fixed- and variable-radius plot samples taken, the egg masses/ha, and the proportion of trees with zero egg masses for three tree strata is recorded.

Site	State	Year	<i>n</i>	Egg masses/ha	Probability of Zero Egg Masses on a Tree Strata (P_T)		
					Entire tree	Bole of the tree	First 1.82 m of the bole
Beaverdam	MD	1986	49	0.443	0.996	0.996	1.00
Fairhill	MD	1986	49	88.37	0.793	0.800	0.987
Fairhill	MD	1987	49	10.86	0.954	0.958	0.997
Sprfld	MD	1986	49	0.247	0.996	1.00	1.00
Brewster	MA	1984	37	27.29	0.959	0.973	0.986
Brewster	MA	1985	37	497.65	0.568	0.709	0.919
Brimfield	MA	1985	21	0.728	0.974	0.974	1.00
Northfield	MA	1985	21	0.0	1.00	1.00	1.00
Northfield	MA	1984	37	0.0	1.00	1.00	1.00
Plot 1	MA	1985	37	699.40	0.652	0.765	0.896
Plot 16	MA	1985	35	621.18	0.686	0.716	0.941
Plot 16	MA	1984	31	57.60	0.952	0.952	0.976
Plot 5	MA	1986	21	231.78	0.936	0.949	0.962
Quabbin	MA	1985	21	0.716	0.988	0.988	1.00
Quabbin	MA	1986	31	0.442	0.992	0.992	1.00
Quabbin	MA	1989	21	10.49	0.961	0.961	0.987
Quabbin	MA	1990	21	9.75	0.987	0.987	1.00
Springfield	MA	1984	37	40.77	0.960	0.974	0.980
Springfield	MA	1989	21	315.12	0.874	0.874	0.977
Springfield	MA	1990	21	61.72	0.93	0.930	0.988
Upton	MA	1985	21	449.71	0.625	0.650	0.813
Wendell	MA	1984	37	2.84	0.983	0.983	1.00
Plot 1	VA	1985	49	36.21	0.923	0.944	0.968
Plot 3	VA	1985	49	3.63	0.988	0.996	0.996
Plot 4	VA	1985	49	275.40	0.731	0.883	0.814

Plot 2	VA	1986	49	5.53	0.976	0.988	0.992
Fairhill	MD	1985	49	69.35	0.797	0.797	0.797
Springfield	MD	1985	49	0.247	0.996	1.00	1.00

Appendix 4. Fixed- and variable-radius plot samples used to determine the differences between egg mass counts taken when leaves are present or absent. For each sample site, the number of trees, number of summer egg mass counted in the site, number of winter egg masses in the site, and the mean egg masses/ha for summer and winter counts was recorded.

Site	Year	Number of trees/Site	Summer	Winter	Summer Egg Masses/ha	Winter Egg Masses/ha
			Egg Mass Count	Egg Mass Count		
Bal1	1989	4	65	136	4237.49	8510.37
Bal2	1989	10	68	173	4873.66	12480.15
Bootgap1	1989	7	372	318	13484.03	10745.10
CG-13	1989	7	574	765	17712.40	25977.21
CG-2	1989	8	947	1357	44106.28	59957.19
DH1	1989	7	234	426	10901.24	19957.56
DH2	1989	6	197	568	8061.22	23702.71
Ehov1	1989	7	219	482	3120.77	6454.54
Ehov2	1989	4	113	159	4766.03	6550.94
Lowgap	1989	5	140	418	3816.85	12800.02
LR88	1989	7	47	54	2506.78	3267.06
Mass1	1989	4	12	9	420.76	321.16
Mass2	1989	4	2	1	65.76	32.88
Mass3	1989	5	289	394	15096.95	19273.83
Mass4	1989	4	87	90	6968.54	7101.61
Mdsch1	1989	6	822	1061	33876.80	43794.00
Mdsch2	1989	6	458	423	18364.06	17897.68
MD1	1989	5	58	255	4709.00	11223.42
MD2	1989	6	65	207	1800.38	6032.79
Pocotrfr	1989	8	477	756	32409.45	53385.38
PR1	1989	6	221	259	11240.16	11944.31
PR2	1989	7	337	370	12739.39	17123.95
PR3	1989	6	211	309	10175.98	15700.69
Rt611#1	1989	4	0	0	0.0	0.0
Rt611#2	1989	6	0	0	0.0	0.0

Rt636#1	1989	4	106	169	12269.38	19425.33
Rt636#3	1989	5	80	143	5477.01	10947.39
Rt636#4	1989	5	31	48	6708.69	112116.38
Sgrt613	1989	7	0	0	0.0	0.0
Sgs1	1989	10	0	1	0.0	21.14
Sgs10	1989	4	11	17	637.98	863.49
Sgs12	1989	4	3	9	150.92	481.93
Sgs4#1	1989	6	66	105	3639.52	5750.72
Sgs4#2	1989	6	167	148	8173.23	8503.82
Sgs8	1989	6	0	7	0.0	459.54
Sgs9	1989	7	21	18	582.46	548.19
Sriver	1989	7	399	710	15690.93	22973.20
Will1	1989	6	12	11	1225.03	1276.35
Will2	1989	6	11	7	1158.78	864.30
1B01	1986	8	391	517	8542.03	11054.09
1B02	1986	9	121	148	1722.99	1921.80
1B03	1986	6	0	0	0.0	0.0
1B04	1986	4	0	0	0.0	0.0
1B05	1986	7	112	138	2056.79	2180.38
1B06	1986	5	0	0	0.0	0.0
1B07	1986	6	0	0	0.0	0.0
1B08	1986	7	73	162	4038.11	5872.15
1B09	1986	5	18	31	435.31	733.92
1B10	1986	4	0	2	0.0	54.70
1B11	1986	5	0	0	0.0	0.0
1B12	1986	5	75	0	2181.86	0.0
1M01	1986	6	169	234	5413.54	6185.71
1M02	1986	4	54	118	678.60	1257.08
1M03	1986	4	0	0	0.0	0.0
1M04	1986	3	0	0	0.0	0.0
1M05	1986	3	47	58	489.33	621.11
1M06	1986	7	44	33	2165.01	1463.56
1M07	1986	4	0	1	0.0	16.54
1M08	1986	4	0	4	0.0	195.95

1M09	1986	7	9	40	271.59	1101.15
1M10	1986	5	0	0	0.0	0.0
1M11	1986	5	2	13	51.79	422.39
1M12	1986	4	5	17	51.01	234.67
1M13	1986	12	14	30	702.49	1049.66
1M14	1986	3	0	6	0.0	163.31
1M15	1986	4	0	2	0.0	12.52
1M16	1986	5	1	5	107.05	589.30
1P01	1986	3	32	43	550.59	804.77
1P02	1986	5	18	42	338.08	1289.74
1P03	1986	2	1	0	28.92	0.0
1P05	1986	4	6	3	150.59	75.29
1P06	1986	2	0	0	0.0	0.0
1P07	1986	5	24	48	354.65	747.69
1P08	1986	6	13	66	182.13	949.65
1P09	1986	4	1	2	61.88	108.11
1P10	1986	6	2	4	27.01	54.03
1P11	1986	6	1	0	62.92	0.0
1P12	1986	3	1	1	174.78	174.78
1P13	1986	5	15	27	371.30	685.78
1P14	1986	7	0	0	0.0	0.0
1P15	1986	4	8	14	236.43	330.03
1P16	1986	5	8	12	51.12	115.65
1P17	1986	4	0	0	0.0	0.0
1P18	1986	3	2	0	115.98	0.0
1P19	1986	3	0	2	0.0	83.46
1P20	1986	3	0	0	0.0	0.0
1P21	1986	1	1	1	60.87	60.87
4B01	1986	4	27	33	1050.35	1284.05
4B02	1986	6	1268	1488	19137.91	22659.37
4B03	1986	6	138	168	6783.18	10230.76
4B04	1986	9	596	580	20632.51	18200.45
4B05	1986	3	112	223	1755.81	4032.72
4B06	1986	5	570	660	23891.67	27566.35

4B07	1986	5	1778	1511	38801.80	32997.41
4B08	1986	2	147	137	7405.09	7555.84
4B09	1986	5	0	1	0.0	335.09
4B10	1986	7	1	0	24.83	0.0
4B11	1986	3	0	7	0.0	350.05
4B12	1986	3	0	0	0.0	0.0
4M01	1986	7	217	312	4674.08	6244.45
4M02	1986	2	1	1	61.88	61.88
4M03	1986	4	24	37	872.18	1400.24
4M04	1986	9	369	381	20970.53	23850.73
4M05	1986	5	170	350	7676.29	7469.09
4M06	1986	6	3122	3250	86948.70	90658.63
4M07	1986	4	1877	2159	21229.25	21771.49
4M08	1986	5	254	238	7593.30	7514.55
4M09	1986	6	1	21	37.71	1293.78
4M10	1986	6	0	0	0.0	0.0
4M11	1986	5	110	205	3102.63	4462.30
4M12	1986	2	1	1	44.31	44.31
4M13	1986	5	4	7	289.22	479.27
4M14	1986	9	1	1	17.89	17.89
4M15	1986	5	64	143	618.60	1349.26
4M16	1986	4	0	0	0.0	0.0
4P01	1986	4	0	0	0.0	0.0
4P02	1986	5	5	9	207.31	402.17
4P03	1986	2	39	22	1582.31	875.78
4P04	1986	3	123	232	1687.06	3168.44
4P05	1986	7	152	167	3265.39	3481.20
4P06	1986	8	4	13	247.48	715.87
4P07	1986	5	294	605	12646.23	23640.58
4P08	1986	7	2069	1919	61495.17	51659.43
4P09	1986	4	291	210	22647.13	17195.12
4P10	1986	5	635	715	7884.85	9350/83
4P11	1986	6	811	1014	33632.75	44316.18
4P12	1986	4	2196	2336	36300.28	39174.45

4P13	1986	10	0	2	0.0	41.32
4P14	1986	9	136	152	7313.95	7650.25
4P15	1986	7	223	223	9147.98	8881.51
4P16	1986	8	1	2	30.62	61.25
4P17	1986	4	41	33	2000.37	1806.44
4P18	1986	3	2	5	181.22	366.88
4P19	1986	7	0	0	0.0	0.0
4P20	1986	8	0	0	0.0	0.0
4P21	1986	4	20	52	470.18	1297.72

VITA

Jane Louise Carter was born June 4, 1967 in Charlottesville, Virginia. She spent the first eighteen years in Charlottesville and Winchester, VA. She attended John Handley High School in Winchester and graduated in 1985. She attended Randolph-Macon College in Ashland, Virginia where she earned a Bachelor of Science Degree majoring in Biology in 1984. She began a master of science program in Entomology at Virginia Polytechnic Institute and State University in August, 1990. Her major advisor was F. William Ravlin and the topic of her research was egg mass sampling plans for gypsy moth management decisions.

Jane Louise Carter