ABSTRACT Three different gypsy moth, *Lymantria dispar* (L.), sampling techniques were compared for their spatial correlation with regional defoliation maps. Counts of gypsy moth pupae and egg masses under burlap bands, and counts of male moths in pheromone-baited traps were taken in a network of 150 plots distributed irregularly throughout Massachusetts. These counts were compared with aerial sketch maps of gypsy moth defoliation collected during the same period and digitized into cells (2 by 2 km) in a geographic information system. The spatial correlation between counts of the three gypsy moth life stages and defoliation was examined using indicator cross-correlograms. A cross-correlogram quantifies the spatial covariation between two variables by plotting the cross-correlation for a series of interpoint distances. Cross-correlograms indicated that there was substantial correlation between egg mass counts and subsequent defoliation. These correlations extended to 10 cells (20 km) in some cases. Similar patterns were observed for counts of pupae. In contrast, there was little cross-correlation between defoliation and counts of male moths. These results indicate that counts of egg masses (or pupae) under burlap bands may be the most suitable variable to measure for predicting gypsy moth defoliation on a regional scale. The lack of correlation between male moth counts and regional defoliation is discussed.

KEY WORDS *Lymantria dispar*, sampling, geostatistics

Every year, >300,000 ha of forest land in the United States are sprayed to minimize the adverse effects of defoliation by the gypsy moth, *Lymantria dispar* (L.) (USDA Forest Service 1992). Specific procedures vary among the various states and agencies that participate in these programs, but nearly all of the programs within the generally infested area rely on preseason counts of egg masses to evaluate the necessity of treating stands to prevent defoliation (Ravlin et al. 1987).

A variety of sampling procedures exists for estimating the density of gypsy moth egg masses in a given stand, though none are universally adopted. Many states prefer to use a number of fixed-radius plots that vary in area from 0.05 to 0.01 ha (Kolodny-Hirsch 1986). Wilson & Fontaine (1978) developed a fixed-and-variable-radius plot method whereby gypsy moth egg masses are counted on trees that have been selected with a 20-factor prism and on ground objects within a series of prisms and objects within a series of

Because both of these methods are both time-consuming and labor-intensive, Eggen & Abrahamson (1983) developed a timed walk procedure to estimate egg mass densities referred to as the *five minute walk*. They presented an algorithm that converts counts acquired within a 5-min period into the more conventional expression of egg masses per unit area. Recently, Liebhold et al. (1991a) and Fleischer et al. (1991) reported that this technique is subject to bias and did not provide estimates that are within an acceptable level of precision.

Considerable evidence suggests that errors in decision-making are quite common in current gypsy moth management programs (Liebhold et al. 1991a, 1993a). Many stands where preseason counts indicate no defoliation will occur (and treatment is therefore unnecessary) become defoliated. Conversely, many stands where preseason counts indicate defoliation will occur do not become defoliated even if they are not treated. There are many possible reasons for these errors: measure-
ment error that occurs from taking relatively few egg mass samples from a heterogeneously distributed population; intrinsic variation about the relationship between the true preseason egg mass density and subsequent defoliation; other variables (e.g., host type, proximity to other outbreaks) affect the relationship between egg mass density and defoliation (Liebhold et al. 1993a).

Because of the financial constraints of most gypsy moth management programs, it is difficult to avoid considerable sampling error in egg mass density estimates. Under commonly used sampling intensities, the standard error of the estimate is often >50% of the mean (Liebhold et al. 1991a). Kolodny-Hirsch (1986) and Fleischer et al. (1991) developed sequential sampling schemes that allow managers to control error in egg mass density estimates relative to treatment threshold densities. However, these sequential sampling schemes place an upper limit on numbers of samples. Thus, sampling error is still considerable when estimates are near decision thresholds.

Most egg mass density thresholds that are used to make decisions about the need for control are based on the correlation between egg mass density in year t-1 and defoliation in year t. Several groups have taken field data from untreated plots and related density estimates to subsequent defoliation levels and then fit equations to these data (Campbell 1966, Cansner et al. 1985, Montgomery 1990, Williams et al. 1991, Liebhold et al. 1993a). Unfortunately, the correlation between preseason egg mass densities and subsequent defoliation levels is quite poor (Liebhold et al. 1993a). The problem is most acute for stands where preseason egg mass counts range from 250 to 2,500 egg masses per hectare; through this range in densities defoliation varies from 0 to 100%, and there appears to be little relationship between density and defoliation.

The spatial dynamics of gypsy moth outbreaks are highly complex and notoriously difficult to predict. Twenty-five years ago, Campbell (1967) recognized that the dynamics of gypsy moth populations are affected by population conditions in nearby areas. Others have recognized that there is often considerable synchrony in annual fluctuations in the development of gypsy moth outbreaks (Liebhold & McManus 1991). Typically, populations seem to rise and fall in synchrony over large regions, probably as a result of similar weather effects on population processes (Miller et al. 1989). Though astute gypsy moth managers take advantage of information on regional conditions and population trends, this procedure is rarely formalized in the decision-making process. In many management programs, regional population levels are monitored through the use of grids of pheromone-baited traps or egg mass counts (Reardon et al. 1987, Gage et al. 1990, Ravlin 1991, Reardon 1991). Presumably, data from these regional monitoring systems can be used, along with stand-level information, to generate improved stand-level defoliation predictions.

Gage et al. (1990) used a geographic information system (GIS) to develop models for predicting pheromone trap catch from trap catch in previous years, and they demonstrated how trap capture maps were related to defoliation maps. Presumably, a similar approach that uses egg mass counts instead of pheromone trap capture data would be possible. Hohn et al. (1993) developed a geostatistical model that forecasts probabilities of future gypsy moth defoliation from historical spatial patterns of defoliation in the same area; this model quantifies the temporal persistence and spread of defoliation in a predictive model. Ultimately, the approaches of Gage et al. (1990) and Hohn et al. (1993) could be combined in models that predict maps of regional probabilities of defoliation using both historical defoliation maps, forest type maps, and networks of permanent census plots.

In this study, we compared three different gypsy moth census methods for their ability to assess regional population conditions and to predict defoliation. We used geostatistical analyses to compare networks of counts of egg mass and pupae under burlap bands and counts of males in pheromone-baited traps for their spatial correlation with the presence of defoliation. These results should be useful in the design of regional population monitoring systems.

**Materials and Methods**

**Data.** In 1984, the Massachusetts Department of Environmental Management established a network of 150 plots irregularly distributed throughout the state (Fig. 1). Plots were located in forest stands that were considered susceptible to gypsy moth defoliation. A plot consisted of a standard milk carton pheromone trap surrounded by 20 oaks (*Quercus* sp.) >13 cm (diameter at breast height) on which burlap bands were placed. Traps were deployed in early summer and were revisited in late summer or early fall. Counts were made of...
all egg masses and pupal remains under the burlap bands, and pheromone-baited traps were taken to a laboratory where male moths were counted. In 1984, all traps were baited with (+) dislurpse, as is the usual practice in most gypsy moth trapping programs (Schwablke 1981). Results of the 1984 trapping indicated that most traps were becoming saturated (Elkinton 1987), and therefore, beginning in 1985, traps were baited with racemic (50:50 +−) dislurpse to reduce total trap capture and prevent saturation. Pheromone trapping was discontinued in 1987.

A GIS, IDRISI, was employed to assemble and collate gypsy moth data (Eastman 1989). IDRISI is a raster-based (grid cell) GIS designed to capture, store, analyze, and display geographical data. A basemap of Massachusetts county boundaries was used to define the study area. This map was generated from latitude and longitude coordinates projected using the Azimuthal Equal-Distant Projection (Snyder 1987). This projection conserves distance linearly from a designated point (Boston, MA). A grid cell size (2 by 2 km) was selected as standard for all map layers in the GIS. Each map layer comprised 198 by 93 cells. This grid size was selected because it represented the minimum dependable spatial resolution of the available defoliation maps.

The Massachusetts Department of Environmental Management monitors gypsy moth defoliation annually in all parts of the state using aerial sketch maps. Maps are sketched during a series of low-level reconnaissance flights in late July when defoliation is at its peak. Thirty percent defoliation is considered the lower threshold for detection from the air. In situations where there is doubt as to the cause of the defoliation, ground checks for the presence of gypsy moth life stages are made. Initially, the aerial sketch maps are overlaid on standard U.S. Geological Survey (1:24,000) topographical maps. Subsequently, a composite mosaic map is generated for the entire state at 1:760,000 scale. Mapping processes may vary from region to region and from year to year in these sketch maps, possibly resulting in systematic and nonsystematic data errors (Talerico 1981, Chrisman 1987). The likely presence of these errors dictated the coarse spatial resolution of the digital representation of these maps used in this study (rasters [2 by 2 km]).

To create a uniform set of geographically referenced defoliation data, the composite defoliation maps for the period 1985 to 1991 were first transferred to mylar stable-base sheets. At least four geographic points, on clearly recognizable intersections of county boundaries, were located accurately. The prepared maps were then scanned using a digital scanner set at 59 dots per centimeter resolution. Binary TIFF files from the scanner were converted to IDRISI map layers. The transformation of each map layer to a common base map resolution and projection was achieved through a rubber-sheeting procedure (Liebhold et al. 1993b). In transforming maps of various scales and projections, IDRISI resamples each scanned defoliation image to match the location of the four geo-reference points on the base map (Eastman 1989).

Because defoliation data were coded as either 0 or 1, depending on whether it exceeded the defoliation threshold (30%), the variable is an indicator or binary variable. A variety of geostatistical procedures is available for quantifying and modeling spatial dependence in indicator variables (Journel 1993, Isaaks & Srivastava 1989, Kemp et al. 1990, Liebhold et al. 1991b).

Analysis. Geostatistical techniques are designed to quantify and model spatial correlation. Underlying these procedures is the expectation that, on average, samples close together will have more similar values than those that are farther apart. Spatial correlation of a single variable is referred to as autocorrelation. For any distance and direction, a sample separates sample data locations the spatial autocorrelation statistic can be estimated:

$$\rho(h) = \rho(x) = \frac{\text{cov}(h)}{s_h s_{h+h}}$$

where $z(x)$ and $z(x + h)$ are two data points separated by the vector $h$, $z(x)$ is the tail and $z(x + h)$ is the head of the vector, $N(h)$ is the total number of data pairs separated by lag $h$, $s_h$ and $s_{h+h}$ are the mean of the points that correspond to the tail and head of the vector, respectively, and $s_h$ and $s_{h+h}$ are the standard deviations of the tail and head values of the vector (Isaaks & Srivastava 1989, Srivastava & Parker 1989, Rossi et al. 1992). The autocorrelation statistic is analogous to the Pearson correlation coefficient (Sokal & Rohlf 1981) between values at points separated by distance $h$. As such, $\rho(h)$ can theoretically vary between 1, indicating a perfect positive correlation, and −1, indicating a perfect negative correlation, though in practice (h) can either be >1 or <1 when ergodicity is present (Srivastava & Parker 1989). The autocorrelogram is a graph of autocorrelation, $\rho(h)$, versus lag distance, $h$. In a typical autocorrelogram $s(h)$ is close to 1 near $h = 0$, but as $h$ increases it declines, sometimes becoming negative.

Equations 1 and 2 can be extended to examine the spatial covariance between two variables, $u$ and $v$. The cross-correlation statistic is estimated:

$$\rho_{uv}(h) = \frac{\text{cov}(u(x), v(x + h))}{s_{u-h}s_{v+h}}$$

$$\rho_{uv}(h) = \frac{\text{cov}[u(x_i), v(x_i + h)]}{s_{u-h}s_{v+h}}$$

$$\rho_{uv}(h) = \frac{\text{cov}[u(x_i), v(x_i + h)]}{s_{u-h}s_{v+h}}$$
The cross-correlogram is a graph of cross-correlation, $p_{xy}^h(h)$, versus lag distance, $h$. If two variables are spatially correlated positively, the cross-correlogram will typically be positive near $h = 0$ and then decline toward 0 with increasing $h$. If the two variables are spatially related negatively, the cross-correlogram will be negative near $h = 0$ and approach zero with increasing $h$. The distance, $h$, at which $p_{xy}^h(h)$ approaches zero indicates the range of the spatial correlation between the two variables.

When computing cross-correlograms, we compared counts of pupae and egg masses with defoliation observed the following year (Cage et al. 1990).

Egg mass, pupal, and male moth counts are continuous variables, but defoliation is a binary (0, 1) indicator variable. Luster (1985) described the contact effect that may arise when calculating the cross-correlation between continuous and indicator variables. The coding of one variable as a continuous variable, while the other is represented by an indicator, may cause cross-correlation to become obscured or misinterpreted. To avoid a contact effect, we transformed the various gypsy moth census counts into indicator variables. Frequency distributions of each of the three variables for each year were calculated. Threshold values for the in-
Spatial autocorrelation was strongest in 1985, 1986, and 1987. Although 1985 and 1986 were years of high levels of defoliation, much less defoliation occurred in 1987 (Fig. 2). Liebhold & Elfinkton (1989) reported that from 1961 to 1987 in this same region, area defoliated and spatial autocorrelation of defoliation were correlated. Fig. 4 A-E shows that autocorrelations of yearly egg mass counts all exhibited considerable autocorrelation that extended for distances up to 30 km (15 cells). This finding is in agreement with similar analyses of these data by Liebhold et al. (1991b).

The irregular nature of the autocorrelations was probably caused in part by the relatively small sample size of these data (150 points). Autocorrelograms of the pupal counts were similar to those of the egg mass counts (Fig. 5 A-E); autocorrelation extended for distances up to 40 km.

The frequency distributions of counts of egg masses and pupae were generally skewed positively. Zero values composed ≈50% of the counts. For this reason we were only able to use the 50th percentile and above as thresholds for the indicator transform of these variables.

Cross-correlograms of the egg mass counts with defoliation are shown in Fig. 4 F-J. In all years except 1990, there was a substantial level of positive cross-correlation between egg mass counts and defoliation. The magnitude of this cross-correlation declined consistently with distance, but cross-correlation existed at distances as great as 20 km.
Cross-correlation was generally strongest for egg mass counts in which the 80th percentile (1.79 egg masses per tree) was used as the threshold for the indicator transform, though the 90th percentile (3.09 egg masses per tree) performed nearly as well.

Similar patterns were observed in the cross-correlations between pupal counts and defoliation (Fig. 5 F–G). Again the 80th (4.04 pupae per tree) or 90th (5.25 pupae per tree) percentile generally exhibited the greatest cross-correlation with defoliation.

The cross-correlograms of defoliation with male moth counts were quite different (Fig. 6 D–F). Cross-correlations calculated from 1986 and 1987 data exhibited little evidence of spatial covariation (cross-correlograms were generally flat), and cross-correlations were often negative. The largest cross-correlations were obtained using an indicator transform at the 90th percentile (757.0 males per trap), but this cross-correlation was essentially zero and showed no evidence of spatial structure. The autocorrelograms of male moth counts in 1986 and 1987 (Fig. 6 B and C) were erratic and showed no evidence of spatial dependence. These results indicate that in 1986 and 1987 trap catches were not spatially correlated with observed defoliation.

Results were somewhat different from the 1985 male moth data. Cross-correlation was generally low, but the declining trend in the cross-correlograms indicated a certain level of spatial correlation (Fig. 6D). Furthermore, the autocorrelograms also exhibited a declining trend indicative of a spatial structure (Fig. 6A). Again, the highest level of cross-correlation was observed using the 80th and 90th percentile indicator transform. Although these results indicated a level of spatial covariation between the 1985 trap catch data and defoliation, the magnitude of cross-correlation was much lower than that observed with egg mass and pupal counts.

The male moth count histograms (Fig. 7) did not exhibit the skewed distributions that predominated in the pupal and egg mass counts. The 1985 counts were distributed symmetrically or perhaps skewed negatively; this distribution probably was caused by a trap saturation effect (Elkinton 1987). In 1986 and 1987, traps were baited with racemic disparlure, which reduced the trap counts and caused a positive skew in the distributions.

Counts of egg masses under burlap bands may be more useful than counts of pupae in gypsy moth-management programs because egg masses usually remain intact throughout the winter and thus can be censused over a period of several months. For operational usage, permanent plots should be distributed throughout the susceptible forest type either within a grid or in an irregular network of sites such that no adjacent points are farther apart than 10 km. Liebold et al. (1991b) reported that the range of spatial dependence in gypsy moth egg mass counts is quite variable among regions and among seasons but if egg mass sample points are located on a 10 km grid, it is likely that every location will be within the range of spatial correlation of at least one sample point. Egg mass counts can be interpolated using a weighted distance technique such as kriging (Liebold et al. 1991b, 1993b). A technique such as indicator kriging (Liebold et al. 1991b) would be useful to express the probabilities of exceeding the threshold value of 1.79 egg masses per tree.

It is surprising that counts of adult males were poorly correlated spatially with defoliation. In 1984, (+) disparlure was used as the attractant, and most traps were probably approaching saturation. Elkinton (1987) showed that trap efficiency (fraction of males approaching the trap that are captured) declined when there were as few as 500 males per trap even though the trap capacity was 2,000 males. This saturation could explain the lack of correlation with defoliation. However, the spatial correlation of trap captures with defoliation was greater in 1985 than it was in 1986 and 1987. In those years, racemic disparlure was used as the attractant, trap capture was diminished, and traps did not become saturated. Therefore, it is unlikely that the lack of correlation with defoliation was caused by trap saturation.

Grids of pheromone-baited traps have been widely used, with some success, to characterize regional population conditions for areas along the leading edge of the gypsy moth infestation (Ravlin et al. 1987, Reardon et al. 1987, Gage et al. 1990, Reardon 1991). Gage et al. (1990) reported that pheromone trap catch was positively correlated with gypsy moth defoliation in a network of plots across Michigan. In those studies, a large fraction of the traps were located in areas not yet invaded by gypsy moths and at those sites most traps captured <10 males. In our study, most traps captured >100 males, even at sites many kilometers from the nearest detectable defoliation. Carter et al. (1992) found no correlation in defoliation level and pheromone trap capture in a series of plots in Virgina where gypsy moth populations had been established for several years. They concluded that pheromone-baited traps draw moths from over too large an area and for too long a period to reflect the densities of gypsy moth populations in the immediate vicinity of the trap. Ravlin et al. (1991) developed a similar theory, that when the gypsy...
Fig. 6. (A–C) Spatial autocorrelograms of male moth counts (1985, 1986, 1987, respectively) after indicator transform; separate autocorrelograms are given for indicator variables generated using 10–90 percentiles as thresholds. (D–F) Cross-correlograms between adult male counts and defoliation (1985, 1986, 1987, respectively); separate cross-correlograms are given in which the 10–90 percentiles were used as thresholds in the indicator transform of adult male counts.
The gypsy moth has become extensively established, males from throughout the region mix into a cloud of moths, thus obscuring any local concentrations of larval populations.

Though we did not predict any spatial correlation between male moths and defoliation in this study, it is possible that some correlation may exist at a larger spatial scale and that pheromone trap counts could be used to monitor population conditions over large regions (e.g., among states). In 1986, for example, it is clear that more moths were captured in the eastern portion of Massachusetts, compared with the west (Fig. 2), and this matches the general occurrence of defoliation in that region. Our analysis did not detect this correlation because it examined spatial correlation at a smaller spatial scale (<40 km). We intentionally restricted our analysis to this scale because autocorrelation and cross-correlation statistics are only reliable at distances less than one-half the smallest dimension of the area encompassing observations (Liebhold et al. 1993b). Although spatial correlations between male moth captures and defoliation may exist at larger spatial scales, this may be of limited use to gypsy moth management, because decisions are rarely made at those scales. However, it is possible that grids of pheromone-baited traps over large areas could provide managers with an early warning system that indicates whether populations are increasing in the region and that egg mass or other types of samples are needed to delineate the location of high-density populations.

As stated above, it is also possible that male trap counts may be more highly correlated with defoliation for populations near the leading edge of infestation. Furthermore, these results do not preclude the use of pheromone-baited traps as tools for detecting new gypsy moth populations at and beyond the fringes of the gypsy moth range (Schwalbe 1981).

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