Use of a Geographic Information System To Evaluate Regional Treatment Effects in a Gypsy Moth (Lepidoptera: Lymantriidae) Management Program

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J. Econ. Entomol. 89(5): 1192–1203 (1996)

ABSTRACT The effectiveness of aerial applications of *Bacillus thuringiensis* and diflubenzon (Dimilin) in a gypsy moth, *Lymantria dispar* (L.), management program was evaluated using a geographic information system. System data included counts of overwintering egg mass densities, defoliation maps, and treatment block boundaries collected by the Appalachian Integrated Pest Management Program in Virginia and West Virginia from 1989 to 1992. Diflubenzuron treatments resulted in greater foliage protection and population reduction than did applications of *B. thuringiensis* except when egg mass densities before treatment were <1,000 egg masses per hectare. Generally, neither treatment provided foliage protection in the year following treatment, especially when treatment blocks were small or near to defoliating populations, or both.

KEY WORDS *Lymantria dispar,* defoliation, suppression, gypsy moth, geographical information system, insecticide

THE GYPSY MOTH, *Lymantria dispar* (L.), is an important insect pest of forests in the northeastern United States. Defoliation by the gypsy moth can cause extensive tree mortality and many other ecological and socioeconomic effects (Twery 1991, Gottschalk 1993).

Many states in the northeastern United States conduct programs to reduce the impacts of potentially defoliating gypsy moth populations. These programs are typically part of the Federal and State Cooperative Suppression Program or they are funded independently by local governments or land owners. Although many of these programs place some effort on biological and silvicultural control of endemic populations, most programs focus on the use of aerial application of insecticides to control outbreak populations. Every year, >100,000 ha of forest land in the United States are sprayed under the Cooperative Suppression Program to minimize defoliation by the gypsy moth (USDA Forest Service 1992).

Management objectives and constraints vary among programs located in different states, but most programs restrict their attempts to minimize gypsy moth damage to areas of specific land use or areas where certain socioeconomic values are threatened, or both. Specific procedures vary among the various states and agencies that participate in these programs, but nearly all of the suppression programs rely on preseason counts of egg masses for treatment thresholds (Ravlin et al. 1987). Most programs currently use applications of *Bacillus thuringiensis* var. *kurstaki* and diflubenzuron (Dimilin) to suppress populations. Procedures for evaluating the effectiveness of aerial suppression vary among states, but they generally include aerial sketch mapping to monitor the location of defoliation annually (Talerico 1981).

Although there have been numerous reports of the effects of various formulations of *B. thuringiensis* and diflubenzuron on defoliation and population reduction in experimental trials (e.g., White et al. 1981; Dubois et al. 1988, 1993), there have been relatively few reports of the effects of operational gypsy moth aerial suppression activities. Here we differentiate experimental trials from operational programs as spray programs in which the primary purpose is to test the application, rather than protect a specific resource. Beginning in 1986 the U.S. Forest Service began a database of operational spray blocks for state programs participating in the Cooperative Suppression Program

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(Twardus and Machesky 1990). States report egg mass densities before and after treatment, defoliation levels, and numerous other observations for individual spray blocks. Summaries of these reports are useful for evaluating the effectiveness of suppression programs. However, this database has 4 shortcomings as follows: (1) most states report only a fraction of their total treatment areas; (2) methods for measuring population densities and defoliation are not standardized and are typically error-prone (Ravlin et al. 1987, Liebhold et al. 1991a); (3) data are collected only in treated areas, making it difficult to make comparisons with untreated areas; and (4) data are not georeferenced, resulting in an inability to determine effectiveness on a regional scale.

For the reasons given above, data are lacking that allow evaluation of the effects of regional aerial suppression on reducing gypsy moth populations and their defoliation. In this article, we explore the use of a geographic information system (GIS) for determining the effects of an operational aerial suppression program on gypsy moth populations. GIS software is designed to manage and manipulate spatially referenced data. With the increasing adoption of areawide management, these software systems appear to be useful tools in various aspects of pest management (Coulson et al. 1993, Liebhold et al. 1993a, Roberts and Ravlin 1993). To date, application of GIS technology to pest management has focused largely on either characterization of habitat susceptibility or for prediction of outbreaks (Reardon et al. 1987, Gage et al. 1990, Liebhold et al. 1993a). The use of GIS for analyzing the effectiveness of a management program thus is a potentially useful approach that has not been previously explored.

Materials and Methods

Software. All data were initially input using the ARC/INFO GIS software. To perform the analyses, coverages were imported to the GRASS GIS. GRASS is a raster-based, public domain GIS that was developed by the U.S. Army Corps of Engineers for the UNIX operating system (Liebhold et al. 1993a, U.S. Army Corps of Engineers 1993). The conversion of data from vector (ARC/INFO) to raster format was thus performed before any analyses. All GRASS coverages were formatted using 1-ha grid cells (100 by 100 m) and the Universal Transverse Mercator projection (Snyder 1987).

Data. Data used in this study were collected during the Appalachian Integrated Pest Management Gypsy Moth Program (AIPM). AIPM was a joint program of the U.S. Forest Service, other national, and various state agencies from 1988 to 1992 (USDA 1989, Reardon 1991). The objective of AIPM was to demonstrate the use of integrated pest management of the gypsy moth in the central Appalachian mountains. The AIPM project was located in a 6,400,000-ha area in Virginia and West Virginia that straddled the expanding front of the gypsy moth in North America (Fig. 1). The biological objectives of AIPM were to minimize the adverse effects of the gypsy moth and to slow its spread. Our objective was to evaluate activities aimed at minimizing the adverse impacts. These activities occurred in approximately the northern 1/3 of the project area where populations had been established for several years and were building to outbreak levels.

During the AIPM program, many forested areas were aerially sprayed to prevent defoliation by the gypsy moth. Most of these areas were sprayed with either *B. thuringiensis* or diflubenzuron. Treatment block locations were initially drawn on 1:24,000 standard U.S. Geologic Survey quadrangle maps and then digitized. These data were used to form 4 coverages of yearly treatment block locations for 1989–1992 (Fig. 2). Each raster cell in these coverages was coded as either no treatment, *B. thuringiensis*, diflubenzuron, other, or unknown.

Gypsy moth pheromone traps were deployed annually within the AIPM area on a grid (≈2 by 2 km) in Virginia and a grid (3 by 3 km) in West Virginia. These traps were standard disparlure-baited milk carton traps (Elkinton and Childs 1983). At the end of the trapping season, the number of males within each trap was recorded, as were the universal transverse mercator coordinates. Whenever the number of males per trap exceeded 200, egg mass densities were sampled using 3–10 fixed-radius plots of 0.01 ha (Kolodny-Hirsch 1986, Liebhold et al. 1994a) in each 1-km^2 cell coincident with the trap. Cells with a catch of >500 were sampled first, and cells with a capture of 200–500 male moths were sampled as time allowed (Rutherford and Fleischer 1989, Fleischer et al. 1991). Egg mass sample plots were located as widely dispersed as possible within each area, although plots were located preferentially in stands considered capable of supporting gypsy moth populations (i.e., host tree species were present) (Rutherford and Fleischer 1989). The universal transverse mercator coordinates of each egg mass plot were estimated from 1:24,000 topographic maps. In total, 141,737 egg mass density samples were taken from 1988 to 1991 (Fig. 3, Table 1). Although most egg mass plots were located within the AIPM area, a few additional plots collected as part of similar gypsy moth management programs in adjoining areas were included in the database and used in the interpolation described below.

Ordinary kriging was used to create a raster GIS coverage of interpolated (100 m between each node) egg mass densities (Fig. 4). Ordinary kriging is a geostatistical technique for estimating values at unsampled locations as weighted averages of values in nearby locations and has been applied previously in forming interpolated surfaces of gypsy moth and other insect counts (Isaaks and Srivistava 1989; Liebhold et al. 1991b, 1993b; Deutsch and Journel 1992; Roberts and Ravlin 1993). A normal-

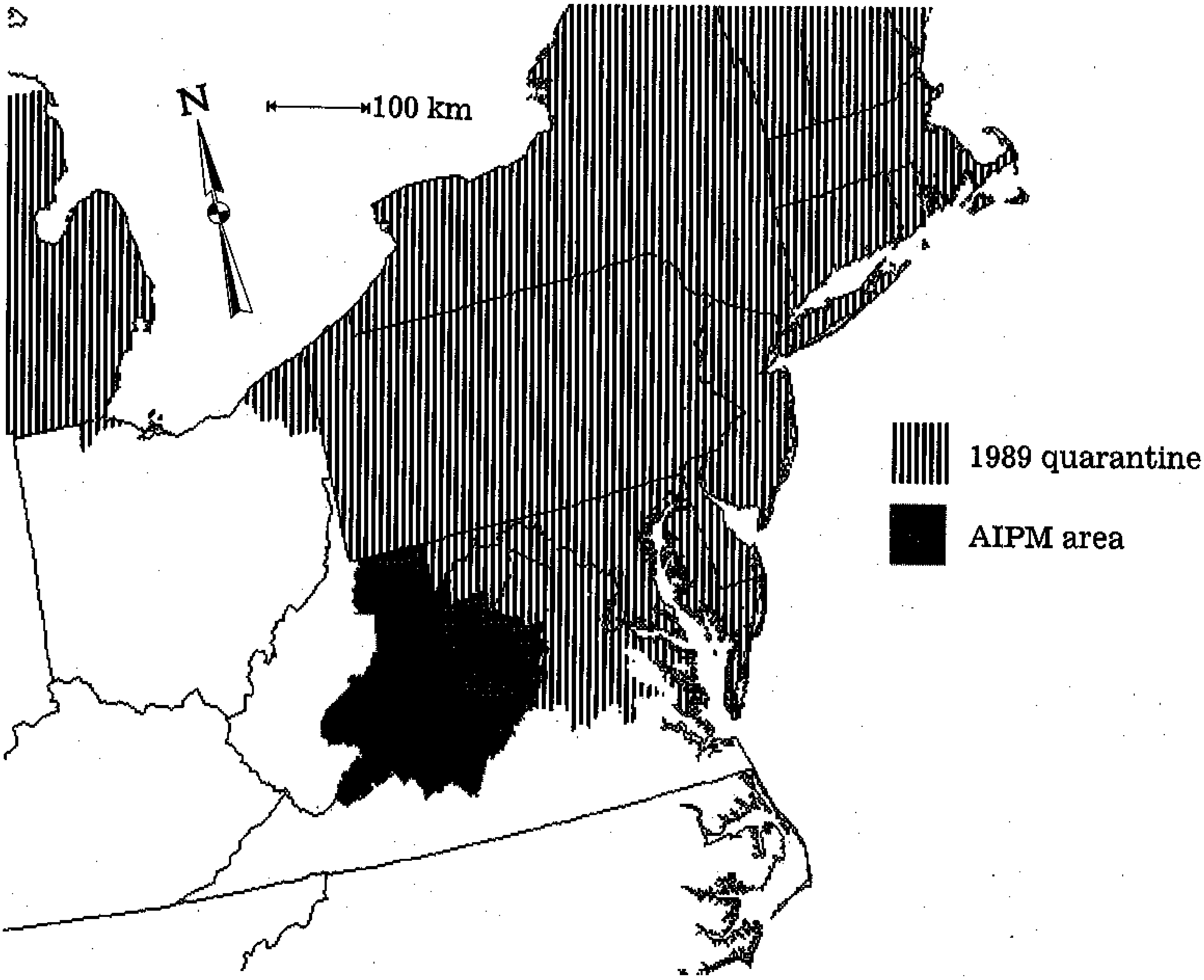

Fig. 1. Location of the AIPM project area (black shading) in northeastern United States.

Fig. 2. Location of aerial suppression treatment blocks in AIPM area in 1990.

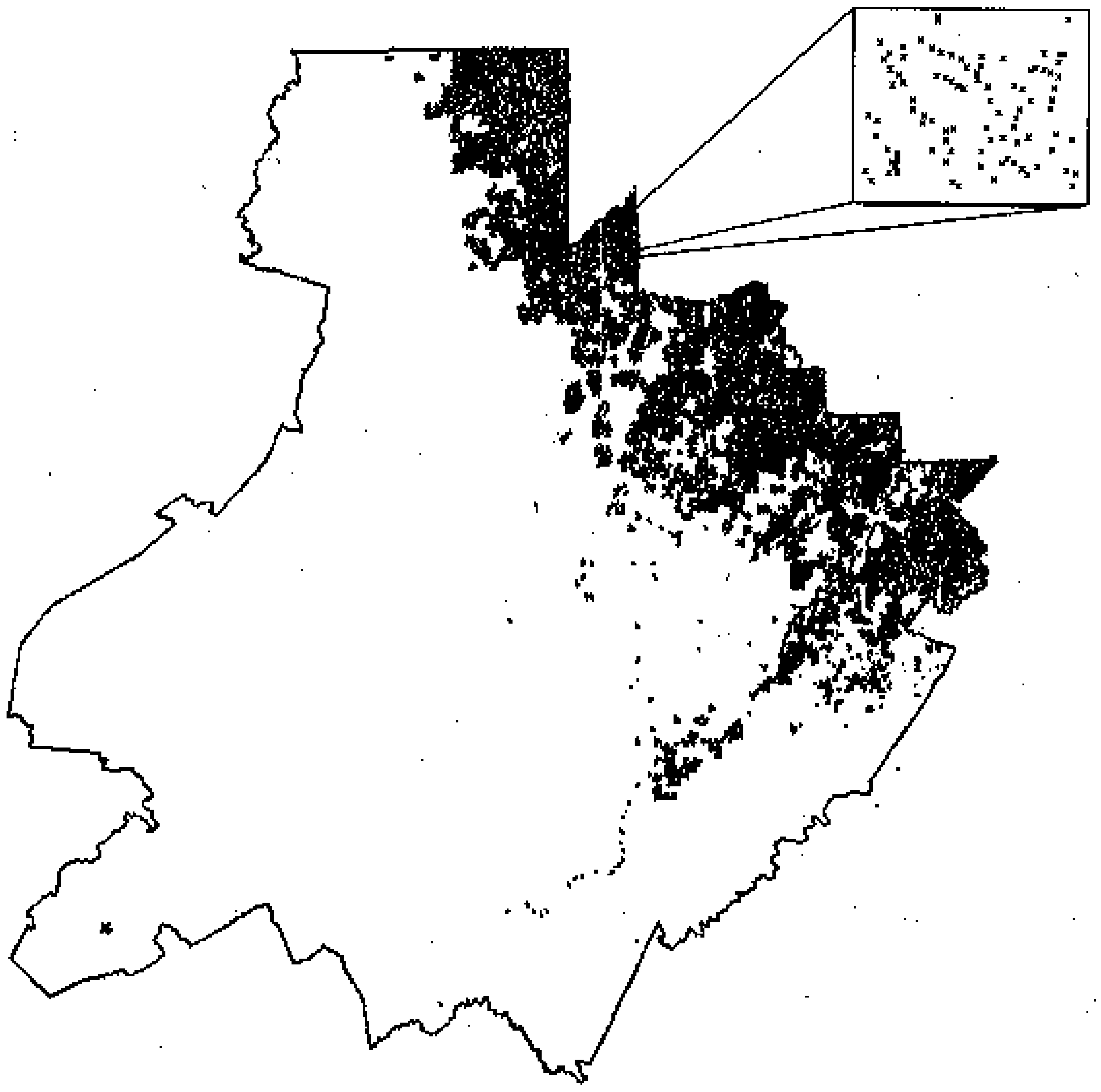

Fig. 3. Location of egg mass sample plots in AIPM area in 1990.

Table 1. Total numbers of egg mass plots each year of the AIPM project

Year	AIPM and adjoining areas, ha	AIPM only, ha
1988	4,927	4,822
1989	14,158	14,014
1990	18,637	18,525
1991	19,638	19,294

scores transformation was used before kriging to correct the skewed distribution of egg mass counts, and kriged estimates were then back-transformed to their original scale (Deutsch and Journel 1992).

In Virginia, defoliation was recorded with the use of high-altitude optical bar photography (Ciesla and Acciavatti 1982), which was collected during the week of peak defoliation. Optical bar photography was taken to the laboratory and the boundaries of areas with noticeable defoliation was recorded on standard 1:24,000 topographic maps. In West Virginia, defoliation was recorded using aerial sketch mapping (Talerico 1981). Maps were sketched directly on 1:24,000 maps during a series of low-level reconnaissance flights in late July when defoliation was at its peak. Defoliation polygons were then digitized as polygons in the GIS and imported to GRASS using 1-ha raster cells. In some areas, defoliation was coded as light, medium, or heavy, but for consistency, all defoliation was recorded as either absent or present (0, 1) (Fig. 5). The minimum level for detection of defoliation using this method is ≈30% (R. Acciavatti, U.S. Forest Service, personal communication).

Analysis. For each year, every cell that fell in a treatment block was categorized into groupings by state (Virginia or West Virginia), treatment type (*B. thuringiensis*, diflubenzuron, or no treatment), and pretreatment egg mass density class (0–500, 500–1000, 1,000–2,000, 2,000–4,000, 4,000–6,000, 6,000–8,000, 8,000–10,000, > 10,000 egg masses per hectare). Cells were excluded from the analysis if they were <100 m from a treatment block boundary (this was to reduce the effect of error in block location during treatment), if the estimated pre- or posttreatment egg mass density exceeded 200,000/ha (it was assumed that these densities were the result of a coding error), or if the cell was >500 m from either the nearest pretreatment egg mass plot or the nearest posttreatment egg mass plot (geostatistical analysis of these data indicated that spatial dependence in egg mass counts is very low beyond 500 m). Untreated cells were excluded from the analysis if they were within 100 m of a block boundary or >5 km from a block boundary. The total area in each egg mass density category is shown in Table 2. Data from 1989 was largely excluded from the analyses because there were too few hectares in most categories.

For each year–state–treatment type–egg mass density class category, we computed mean egg mass density in year t (pretreatment egg mass density; mean of interpolated egg mass counts), mean egg mass density in year $t + 1$ (posttreatment egg mass density, mean of interpolated egg mass counts), proportion of area defoliated in year t, proportion of area defoliated in year $t + 1$, proportion of area retreated in year $t + 1$,

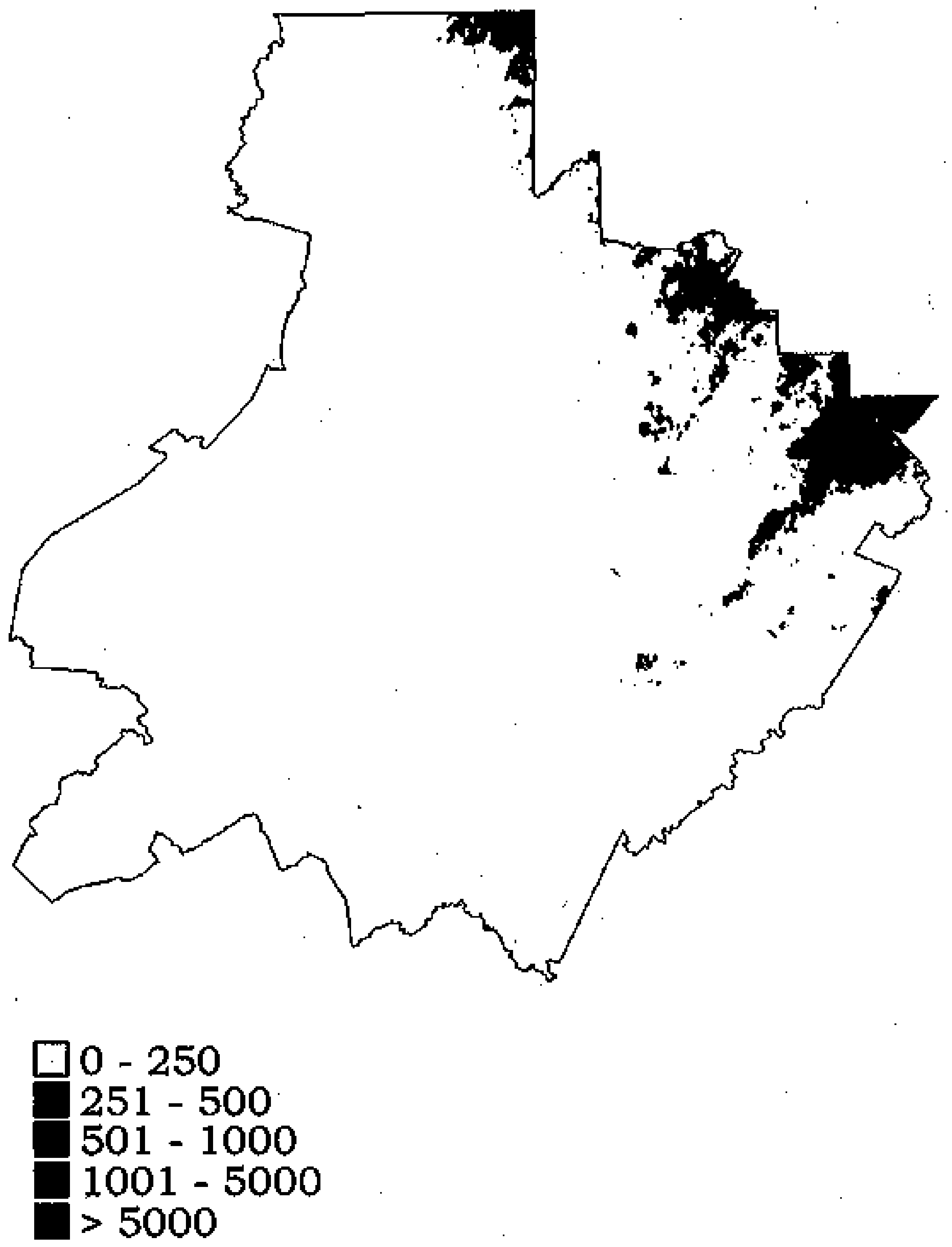

Fig. 4. Interpolated egg mass densities (egg masses per hectare) in the AIPM area in 1990.

Fig. 5. Defoliation in the AIPM project area in 1990.

Table 2. Total area in geographical subsets used in the analyses

Year	State	Density egg masses/ha	Total ha		
			Untreated	Diflubenzuron	*B. thuringiensis*
1989	Virginia	0–500	54,943	1,687	36
		500–1,000	1,452	242	9
		1,000–2,000	1,474	246	2
		2,000–4,000	726	214	0
		4,000–6,000	294	93	0
		6,000–8,000	146	77	0
		8,000–10,000	109	61	0
		>10,000	270	140	0
1990	Virginia	0–500	122,234	3,621	11,207
		500–1,000	6,199	869	3,766
		1,000–2,000	6,350	1,263	3,612
		2,000–4,000	6,852	1,706	4,665
		4,000–6,000	3,890	1,344	3,225
		6,000–8,000	2,344	1,220	1,455
		8,000–10,000	1,572	1,225	1,046
		>10,000	3,317	1,599	2,211
1991	Virginia	0–500	136,567	2,062	6,180
		500–1,000	6,725	447	1,467
		1,000–2,000	9,716	992	2,116
		2,000–4,000	10,990	1,465	1,902
		4,000–6,000	7,128	802	936
		6,000–8,000	5,776	658	627
		8,000–10,000	3,516	387	357
		>10,000	4,582	926	381
1992	Virginia	0–500	210,331	7,036	6,854
		500–1,000	12,683	1,667	1,339
		1,000–2,000	15,451	2,589	2,554
		2,000–4,000	17,131	3,820	4,505
		4,000–6,000	9,267	1,333	2,297
		6,000–8,000	5,334	562	1,303
		8,000–10,000	2,101	193	457
		>10,000	4,264	319	643
1989	West Virginia	0–500	22,579	4,107	928
		500–1,000	71	550	67
		1,000–2,000	25	558	83
		2,000–4,000	0	310	12
		4,000–6,000	2	17	0
		6,000–8,000	0	11	0
		8,000–10,000	0	6	0
		>10,000	0	8	0
1990	West Virginia	0–500	151,952	4,004	8,259
		500–1,000	1,536	2,649	3,117
		1,000–2,000	1,956	5,610	2,634
		2,000–4,000	1,775	5,349	986
		4,000–6,000	565	3,253	238
		6,000–8,000	405	1,860	182
		8,000–10,000	242	1,343	199
		>10,000	464	3,156	281
1991	West Virginia	0–500	157,308	8,786	4,403
		500–1,000	2,335	1,406	850
		1,000–2,000	2,119	2,110	1,005
		2,000–4,000	1,130	1,246	750
		4,000–6,000	441	677	247
		6,000–8,000	224	495	57
		8,000–10,000	31	172	16
		>10,000	16	132	13
1992	West Virginia	0–500	225,931	1,057	7,747
		500–1,000	2,329	304	1,559
		1,000–2,000	3,318	857	1,335
		2,000–4,000	2,940	1,264	911
		4,000–6,000	1,529	472	401
		6,000–8,000	1,215	374	63
		8,000–10,000	388	159	3
		>10,000	951	445	3

proportion of area retreated or defoliated in year $t + 1$, and total area used for analysis. Mapped estimates of gypsy moth egg mass density, pheromone trap capture, and defoliation are highly spatially autocorrelated (Liebhold et al. 1991b, 1995). Spatial autocorrelation among samples violates the assumption of independence inherent in traditional confidence interval estimates

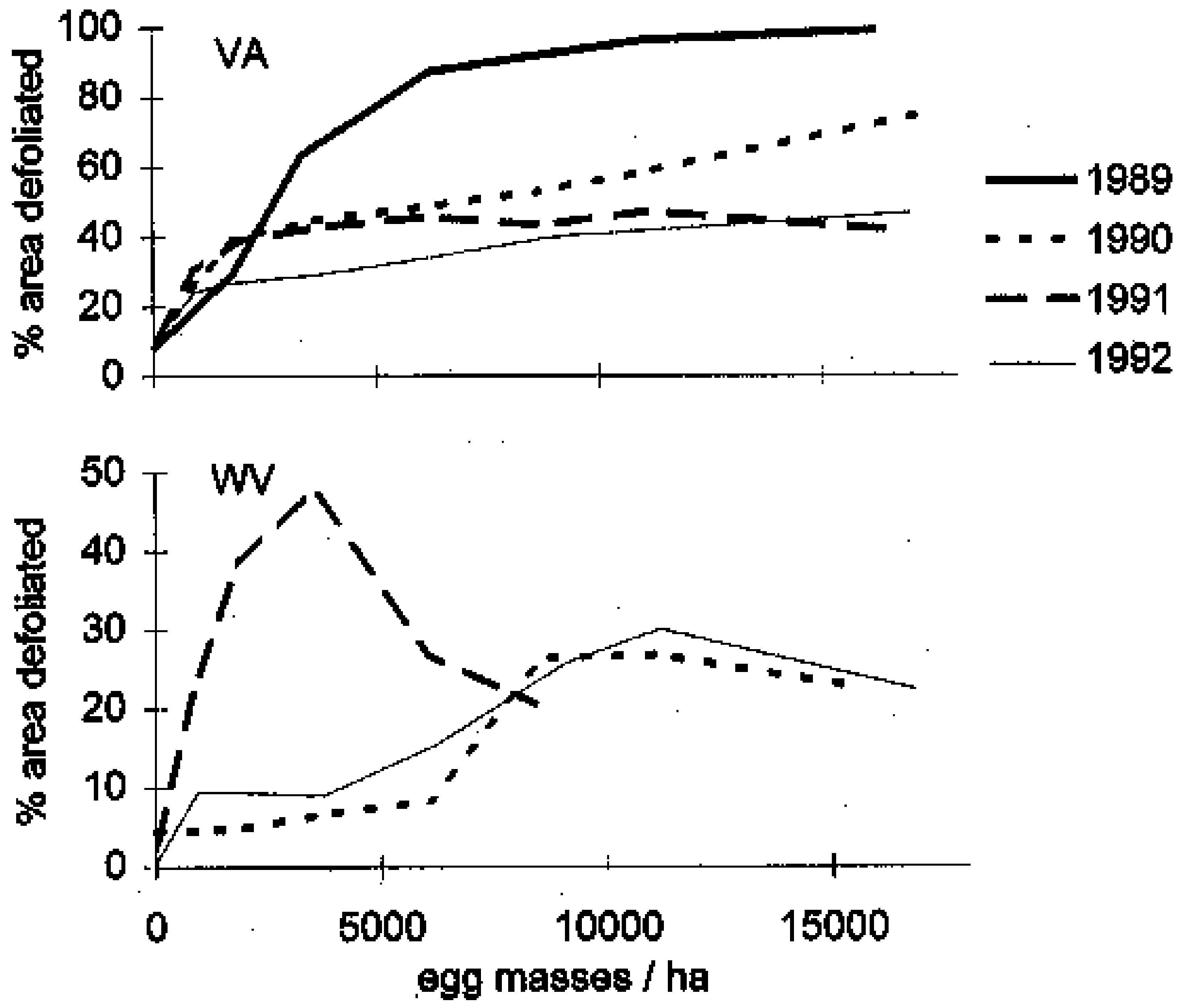

Fig. 6. Proportion of cells defoliated versus preseason egg mass density for different years in untreated areas in Virginia and West Virginia.

(Cressie 1991); therefore, we did not compute standard errors for the means of these values.

Results and Discussion

There was generally a strong relationship between preseason egg mass density and defoliation in untreated areas (Fig. 6). Numerous studies have documented the relationship between preseason egg mass density and defoliation at the individual stand level (Gansner et al. 1985, Montgomery 1990, Williams et al. 1991, Liebhold et al. 1993b). These studies generally have reported that 30% defoliation occurs when egg mass densities range from 1,000 to 2,000 egg masses per hectare. We found that most cells were below the threshold for detection of defoliation when egg mass densities ranged from 1,000 to 2,000 per hectare (Fig. 6). This discrepancy is most likely explained by the fact that in this study, defoliation was assessed in all cells but egg mass density plots were preferentially located in suitable host types. It is likely that many of the cells where defoliation did not occur were in cells where susceptible forests did not occur.

The relationship between egg mass density and defoliation varied among years and between states. For example, defoliation levels were greater in 1989 in Virginia than they were in other years, probably because of the effects of forest type (Liebhold et al. 1994b), weather (Miller et al. 1989), and other extrinsic factors on regional and yearly gypsy moth population trends. Conditions may have been favorable for gypsy moth survival in 1989, resulting in high levels of defoliation. Defoliation levels were low in 1992, most likely because poor conditions resulted in low survival. There were insufficient high-density populations to plot these defoliation relationships for 1989 in West Virginia.

The effects of treatment on defoliation are presented in graphical form in Fig. 7. There was usually less defoliation in treated than in untreated areas when pretreatment egg mass density was >1,000 egg masses per hectare. Defoliation was low in both treated and untreated areas when gypsy moth densities were low. Diflubenzuron-treated areas tended to have less defoliation than *B. thuringiensis*-treated areas when pretreatment densities were >2,000 egg masses per hectare. This coincides with previous reports that diflubenzuron tends to provide better foliage protection than *B. thuringiensis* at high population densities (Twardus and Machesky 1990).

For a given insecticide and pretreatment egg mass density, proximity to defoliation in the previous generation consistently caused an increase in the probability of defoliation (Fig. 8). This pattern was evident for areas treated with *B. thuringiensis* and with diflubenzuron. There are 2 likely reasons for this pattern as follows: (1) immigration by dispersing larvae increased with proximity to defoliation, and (2) proximity to defoliation was correlated with rising populations. Historical studies indicate that gypsy moth outbreaks tend to develop in spatially adjacent areas, even though there may be no dispersal among these areas (Liebhold and Elkinton 1989, Liebhold and McManus 1991, Hohn et al. 1993, Zhou and Liebhold 1995).

A comparison of population replacement rate, R ($R = \log N_{t+1}/N_t$), between egg masses in treated and untreated areas is presented in Fig. 9. Populations in untreated areas behaved as expected (Campbell 1967), when populations were low, replacement rate was generally high but then decreased as initial population density increased. This relationship reflects the inherent density-dependent population behavior that governs the dynamics of natural gypsy moth populations (Campbell 1973, Liebhold 1992). In both states in 1991, the equilibrium density (density at which $R = 0$, indicating a stable population) was near 4,000 egg masses per hectare in untreated areas. The equilibrium for Virginia in 1990 was ≈8,000 egg masses per hectare, indicating that conditions were more favorable for population growth in that year than in 1991. The equilibrium density in untreated areas in West Virginia in 1990 was <2,000 egg masses per hectare, suggesting that conditions were not as favorable for sustaining high populations as in Virginia. Selection of areas for aerial suppression was not performed at random and may have biased the selection of untreated sites to occur preferentially in sites less suitable for gypsy moth growth (i.e., forest composition of low susceptibility). This could explain the difference in population growth in untreated portions of Virginia versus West Virginia, especially because a larger proportion of West Virginia was treated in any given year than in Virginia (Table 2). It is also possible that differences in population growth among areas and years may have been caused by some unknown differences in population quality.

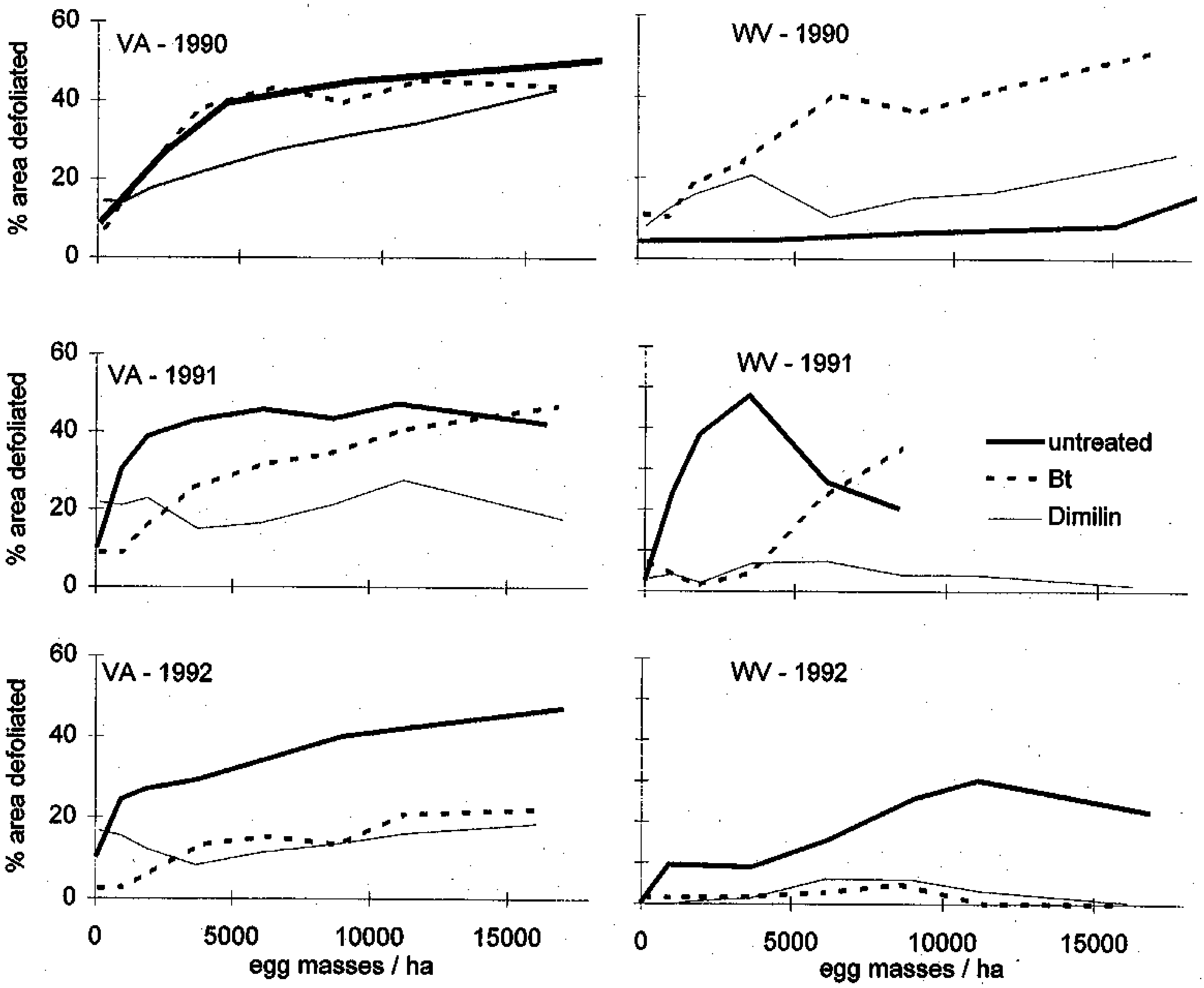

Fig. 7. Proportion of cells defoliated versus preseason egg mass density for different years in treated and untreated areas in Virginia and West Virginia.

Theoretically, aerial suppression should cause a reduction in the posttreatment egg mass density; this would be indicated by a reduction of *R* compared with values at untreated locations. In both West Virginia and Virginia in 1990 and 1991, *R* was lower for areas treated with diflubenzuron, indicating that there was an effect on population growth. However, the results were less consistent for areas treated with *B. thuringiensis*. In Virginia in 1991 and 1990 and in West Virginia in 1990, there was little difference in *R* between untreated and treated areas, indicating that *B. thuringiensis* caused little or no population reduction. However, in 1991 in West Virginia, *B. thuringiensis* caused substantial population reduction, apparently greater than that obtained using diflubenzuron. These results generally agree with those of Twardus and Machesky (1990, 1992), who stated that population reduction caused by diflubenzuron usually exceeds that of *B. thuringiensis*. Experimental trials of various *B. thuringiensis* formulations also indicated that although *B. thuringiensis* usually provided adequate foliage protection, it did not reduce the population reliably (Reardon et al. 1994).

For a given pretreatment egg mass density, values of *R* were generally lower in treated portions of West Virginia than in corresponding areas in Virginia (Fig. 9). This difference may be at least partially explained by the use of large treatment blocks in West Virginia in 1991 (Table 3). The use of large treatment blocks probably reduced the probability of immigration of dispersing larvae from adjoining untreated areas. For a given pesticide and pretreatment egg mass density, populations generally increased more in small blocks in both states and years (Fig. 10).

In summaries of defoliation (Fig. 7) and change in population density (Fig. 9), treatment had little effect in West Virginia in 1990. Both defoliation and *R* were not substantially lower in treated areas, especially for areas treated with *B. thuringiensis*. We do not know whether the lack of a difference between treated and untreated areas in West Virginia represented a failure in the aerial application, the result of an unexplained population decline in the untreated areas, or a combination of both. Records indicate that extensive rain occurred during the period that treatments were applied, and some

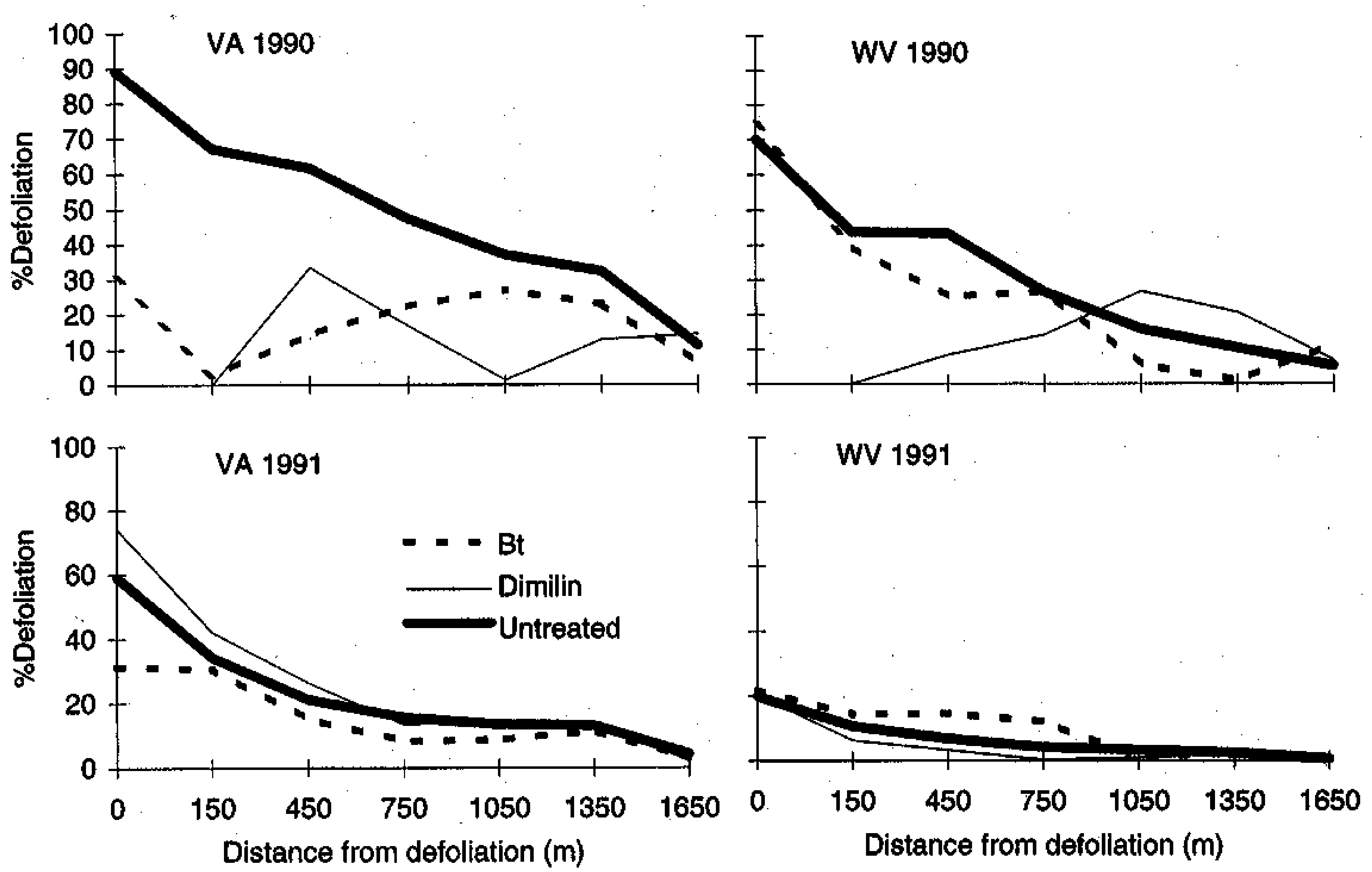

Fig. 8. Relationship between proximity to defoliation in previous year and defoliation in treated and untreated areas where egg mass densities ranged from 0 to 250 egg masses per hectare.

blocks were treated later than optimal for achieving maximal effect. These factors may have contributed to reduced insecticide effectiveness, especially for *B. thuringiensis* applications. Several logistical problems also occurred during this period, and there is evidence that areas outside of treatment block boundaries may have received insecticide applications because of drift or pilot error. Accidental treatment outside of block boundaries could help explain why so little defoliation occurred and why populations declined markedly in "untreated" areas in that year (Figs. 7 and 9). Similarly, logistical problems may also have caused some areas within treatment blocks to be left untreated; this would explain high levels of defoliation in those areas.

Although most evaluations of the effects of aerial suppression on gypsy moth dynamics focused only

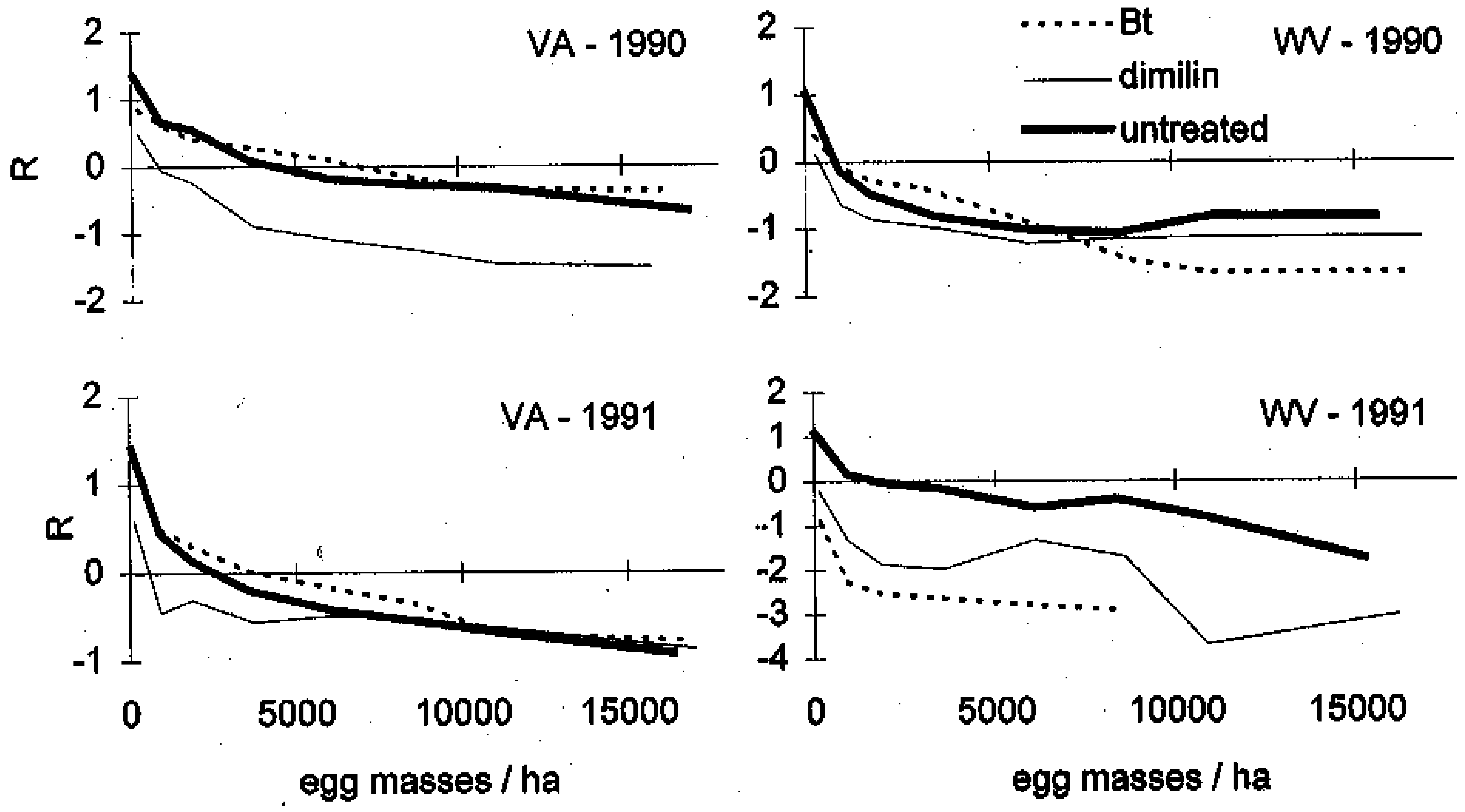

Fig. 9. Log change in egg mass density (R) versus preseason egg mass density for different years in treated and untreated areas in Virginia and West Virginia.

Table 3. Mean area (ha) of treatment blocks

State	Year	Mean size, ha	SE
Virginia	1989	111.3	51.0
Virginia	1990	297.1	62.6
Virginia	1991	133.7	12.1
Virginia	1992	139.4	14.1
West Virginia	1989	398.1	156.6
West Virginia	1990	247.3	45.4
West Virginia	1991	320.0	60.4
West Virginia	1992	183.5	25.5

on the posttreatment generation (Twardus and Machesky 1990, 1992), in this study it was possible to investigate the fate of treated areas for ≤2 yr following treatment. Table 4 lists the proportions of each treatment area that either was defoliated or retreated in the year following treatment, or defoliated in the same year as the treatment. In Virginia, ≥25% of the treated area was either retreated or defoliated. The proportion of area retreated or defoliated in West Virginia was generally <25%. This difference may be partially explained by the use of smaller blocks in Virginia in 1991 (Table 3). When small blocks are used, immigration may be so large that populations may require treatment the following year (Fig. 9). The area retreated or defoliated in the year following treatment was greater in 1990 in West Virginia than in 1991; this is likely related to the general failure of population reduction in West Virginia in 1990 discussed above (Fig. 9).

There are several possible sources of error in our analysis. In addition to standard sampling error associated with egg mass and male moth counts, there are errors associated with the spatial positioning of egg mass plots and pheromone traps as well as with the positioning of defoliation polygons. Unfortunately, there are little, if any, data that quantify these errors; thus, a classical analysis of error propagation (Chrisman 1987) is not possible. The general congruence of the results of our analysis with those of treatment block level analyses (Twardus and Machesky 1990, 1992) lends credence to the validity of our results. Also, it was not possible to estimate CIs for the mean values of percentage defoliation and *R*. Because a high degree of spatial dependence exists between values that are near each other, it would be inappropriate to apply ordinary univariate measures of uncertainty.

Geographic information systems have been recognized as valuable tools in forest pest management (Ravlin 1991, Coulson et al. 1993, Liebhold et al. 1993b). The potential applications of GIS in forest pest management have been limited largely to analyses of where (hazard rating) and when (outbreak models) outbreaks occur. Our analysis is a new application of GIS technology for posttreatment evaluation of the outcomes of pest management activities.

Although previous studies in individual experimental trials and operational spray blocks have documented the effectiveness of *B. thuringiensis*

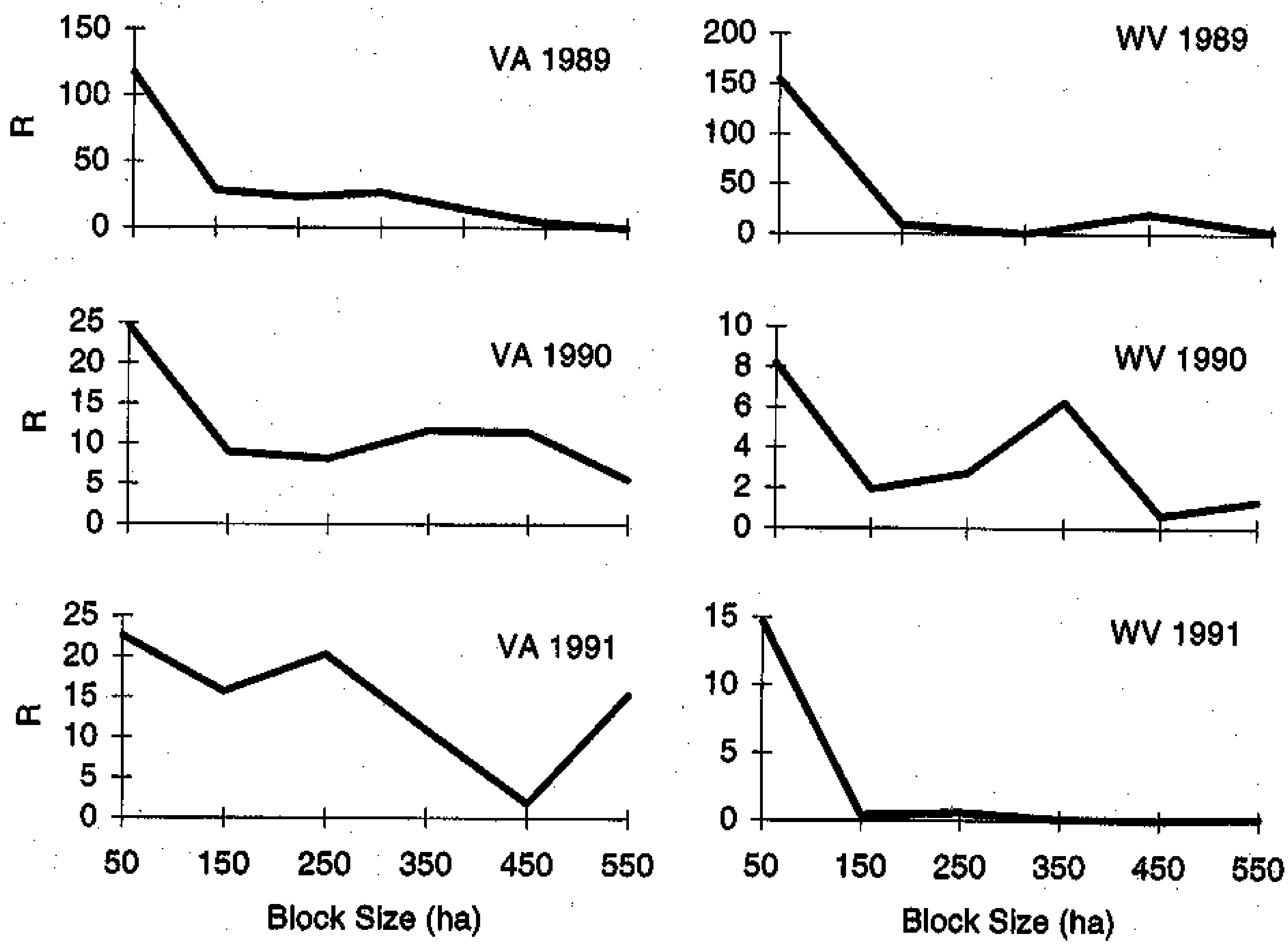

Fig. 10. Relationship between block size and change in egg mass density (*R*) in *B. thuringiensis*-treated areas with pretreatment egg mass densities of 0–250 egg masses per hectare. *R* is not expressed as a logarithim.

Table 4. Proportion of treatment areas defoliated in same year as treatment or defoliated or retreated in following year

State	Density egg masses/ha	% retreated or defoliated			
		1990		1991	
		diflubenzuron	*B. thuringiensis*	diflubenzuron	*B. thuringiensis*
Virginia	0– 500	25	45	43	55
	500– 1,000	29	52	52	55
	1,000– 2,000	30	50	53	58
	2,000– 4,000	32	45	38	64
	4,000– 6,000	33	40	45	66
	6,000– 8,000	32	42	39	66
	8,000–10,000	30	42	55	53
	>10,000	25	38	28	64
West Virginia	0– 500	18	29	4	10
	500– 1,000	8	27	5	0
	1,000– 2,000	5	28	4	1
	2,000– 4,000	6	22	2	2
	4,000– 6,000	13	11	6	0
	6,000– 8,000	13	7	3	0
	8,000–10,000	12	6	0	0
	>10,000	13	1	1	0

and diflubenzuron with respect to foliage protection and reduction of gypsy moth densities, the results of this study shed new light on the effectiveness of treatments in a regional management program. These results demonstrate that an operational gypsy moth program, such as AIPM, largely may be successful in protecting foliage in the same year as application (Fig. 7). However, this analysis shows that it may be more difficult to reduce egg mass densities, especially when populations are rising (Fig. 9).

In some cases, pesticide applications over a large region generally may not prevent defoliation for more than a single year (Table 4). This problem is most evident when small spray blocks are used or the treatment area is in close proximity to an untreated outbreak area, or both Most economic evaluations of the value of aerial suppression as a tool for preventing gypsy moth defoliation are based upon the assumption that a single application can prevent the damages associated with an entire outbreak (McCay and White 1973, Gansner and Herrick 1987, Hicks et al. 1989). Our results suggest that aerial suppression can achieve that level of success reliably only through the use of diflubenzuron in large treatment blocks. However, diflubenzuron is toxic to a wide spectrum of arthropods and has a long residual persistence in canopy and leaf litter and will adversely affect populations of nontarget invertebrates (Martinat et al. 1988, Sample 1991). Presumably, these undesirable effects on nontarget populations would be exacerbated when diflubenzuron is applied over large blocks. Thus, when designing regional gypsy moth management programs, it is important to weigh the relative environmental costs versus efficacy of specific approaches to suppressing populations.

Acknowledgments

We are grateful for the many workers who contributed their time and effort to the compilation of the data presented here. We also thank Frank Sapio, Kathy Sheehan, and Kevin Thorpe for reviewing an early draft of this manuscript. This research was funded in part by funds from the National Center of Forest Health Management and by the U.S. Forest Service Gypsy Moth Research and Development Program.

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Received for publication 3 October 1995; accepted 3 April 1996.