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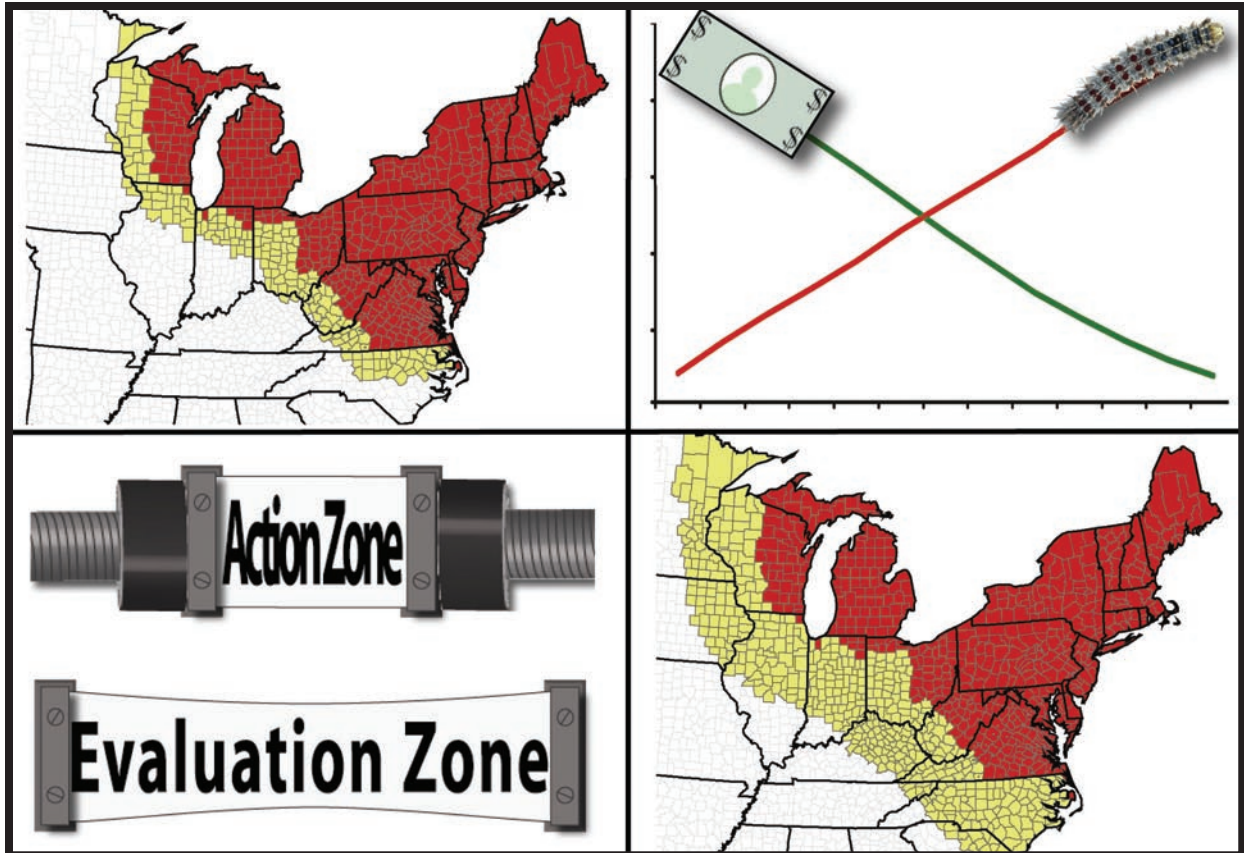
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Northern
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General Technical
Report NRS-37

Cost Analysis and Biological Ramifications for Implementing the Gypsy Moth Slow the Spread Program

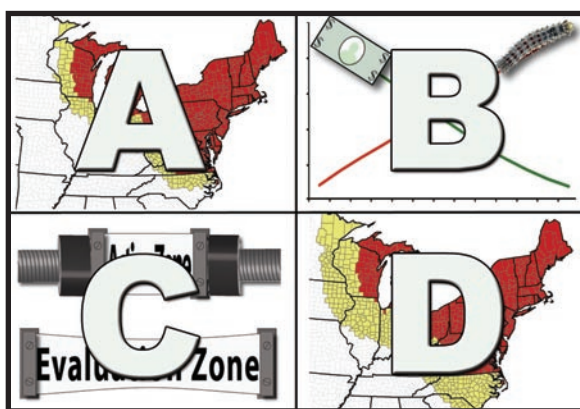
Patrick C. Tobin



Abstract

The gypsy moth Slow the Spread Program is a joint U.S. Forest Service and state effort aimed at reducing the rate of gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae), spread into new areas in the United States. Between 2000 and 2007, federal funding for this program has ranged from \$8 million to \$10 million, with an additional 25 percent of funds contributed by participating states. Changes in funding levels can have important ramifications on the implementation of this Program, consequently affecting the rate of gypsy moth spread. This report presents a cost analysis for implementing the Slow the Spread Program across a range of funding levels, and predicts the consequent changes in gypsy moth spread rates. This work should be useful to program managers in implementing the Slow the Spread Program given yearly financial constraints and fluctuations, and also potentially serve as a template in the design of barrier zone management programs against other nonindigenous species.

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A and D: Future predictions of gypsy moth range expansion (yellow) under two funding levels (see Fig. 11).

B: Relationship between future gypsy moth spread rates and annual funding levels for STS (see Table 5).

C: Conceptual strategy for implementing STS with increased funding constraints by reducing the active management area (Action Zone) and increasing the area used in STS evaluation (Monitoring Area).

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INTRODUCTION

The gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae), was introduced outside of Boston, Massachusetts, in 1869 (Riley and Vasey 1870, Forbush and Fernald 1896). It has since slowly but relentlessly spread to the north, south, east, and west at variable rates, from 2.6 to 21.1 km/year (Tobin et al. 2007a), and is now established from Ontario to Virginia, and Nova Scotia to Wisconsin (Fig. 1). Gypsy moth larvae are highly polyphagous folivores that can exploit more than 300 host trees including species within the preferred host genera of *Quercus*, *Larix*, *Populus*, *Salix*, and *Malus* (Liebhold et al. 1995). Since 1890, a variety of management programs have been implemented to reduce its movement from generally infested areas (i.e., areas regulated under the gypsy moth quarantine; U.S. Code of Federal Regulations, Title 7, Chapter III, Section 301.45) to uninfested areas (e.g., Forbush and Fernald 1896, Burgess 1930, Perry 1955, Ravlin et al. 1987, Reardon et al. 1993, Sharov et al. 2002b, Tobin and Blackburn 2007). The Slow the Spread Program (STS) is a management strategy that uses a barrier zone located along the expanding gypsy moth population front, and is currently implemented across the states of

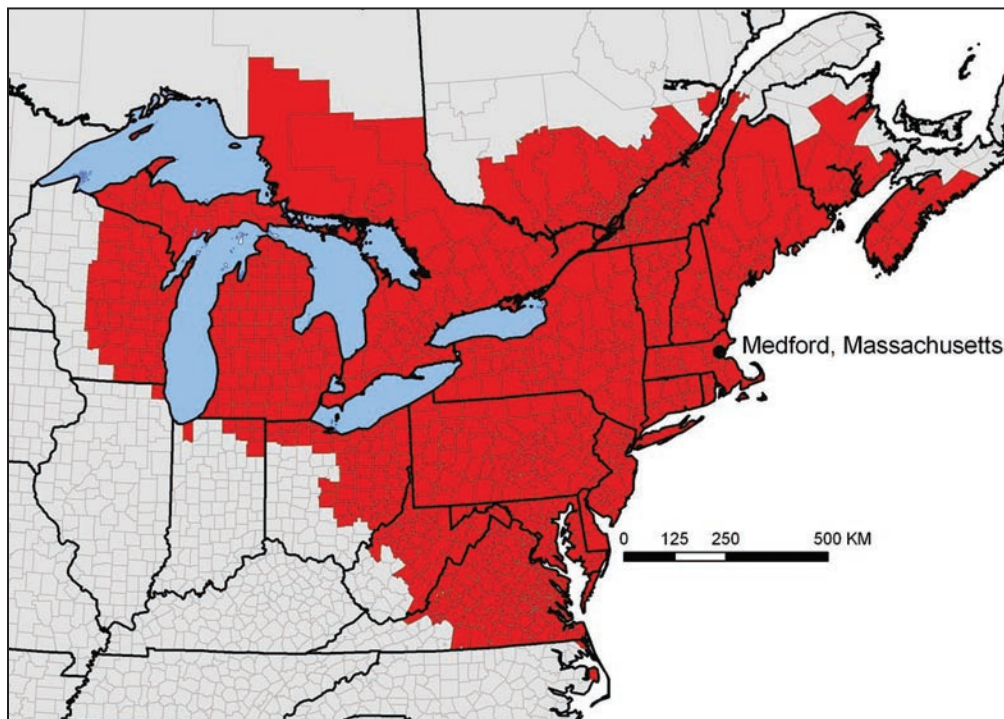


Figure 1.—Portions of the United States and Canada considered generally infested by the gypsy moth (red area) and consequently regulated under a quarantine, 2008 (U.S. Code of Federal Regulations, Title 7, Chapter III, Section 301.45 and Canadian Food Inspection Agency, Plant Health Division, Policy Directive D-98-09). The initial site of the gypsy moth introduction into North America (Medford, Massachusetts) is also shown.

North Carolina, Virginia, West Virginia, Kentucky, Ohio, Indiana, Illinois, Wisconsin, and Minnesota, encompassing nearly 40 million ha. Its primary goal is to reduce the rate at which the gypsy moth invades new areas. The delay in the future socio-economic and environment impacts due to gypsy moth provides an approximate 4:1 benefit-to-cost ratio (Leuschner et al. 1996).

The Slow the Spread Program

Under STS, extensive grids of pheromone-baited traps (>80,000 traps/year) are deployed to identify newly established gypsy moth populations ahead of the population front and estimate its yearly rate of spread. Management tactics target newly established populations, as colonies left unmanaged could persist, grow, and eventually coalesce with the moving population front. This increases the rate of spread through a process known as stratified dispersal, which results from both local growth and dispersal coupled with stochastic, long-distance jumps through anthropogenic or atmospheric transport mechanisms (Fig. 2; Hengeveld 1989, Andow et al. 1990, Shigesada and Kawasaki 1997). Higher management priorities are placed upon those colonies that are thought to most affect gypsy moth spread rates, such as higher density colonies located farthest from the generally infested area (Sharov et al. 2002b, Tobin et al. 2004, Tobin and Blackburn 2007).

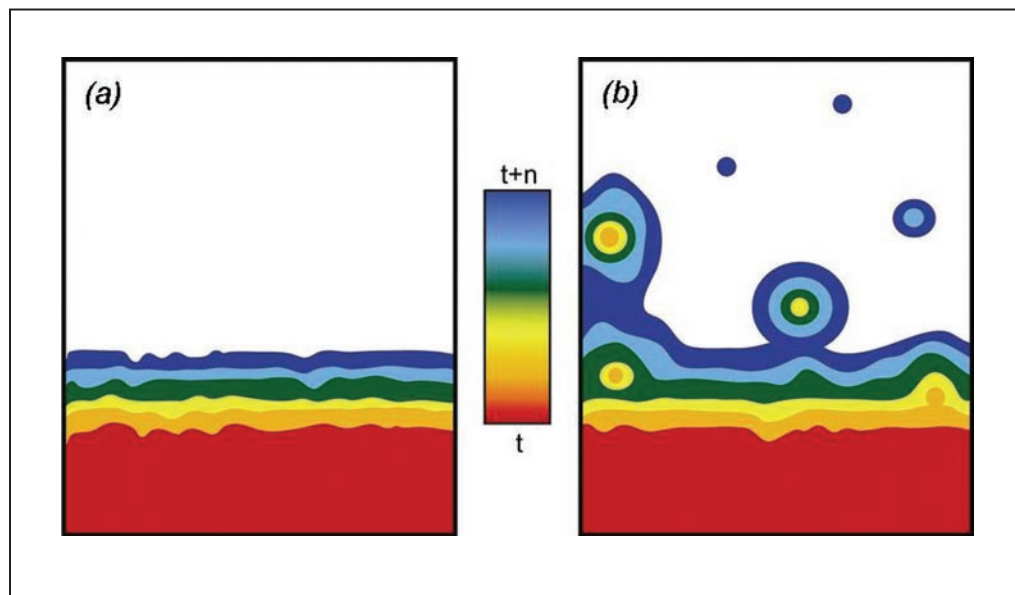


Figure 2.—Hypothetical range expansion of an invading species from initial time t to $t+n$ when spread proceeds by local growth and dispersal (a) or stratified dispersal (b). Long distance jumps can have profound ramifications in the rate at which an invader spreads into new areas.

The Slow the Spread Program area is divided into two zones: (1) an Evaluation Zone that is located proximal to the gypsy moth generally infested area, and (2) an Action Zone that is located distally (Fig. 3; Tobin et al. 2004). From 2000-2006, the extent of the Evaluation and Action zones were approximately 70 and 100 km wide, respectively (Fig. 3). The width of both zones were based upon prior research demonstrating that most new gypsy moth colonies arise within these distances from the generally infested area (Sharov and Liebhold 1998).

Pheromone-baited traps are deployed in both the Evaluation and Action Zones, but at different trap grid intensities (Fig. 3; Tobin et al. 2004). In the Evaluation Zone, traps are set 3 to 8 km apart, while in the Action Zone, traps are approximately 2 km apart. Higher gypsy moth densities, such as those within the Evaluation Zone, require less spatial resolution in trap deployment because gypsy moth populations tend to be highly spatially autocorrelated (Sharov et al. 1996). Therefore, gypsy moth densities at unsampled locations can be estimated through geostatistical methods (Isaaks and Srivastava 1989). In contrast, in the Action Zone, gypsy moth populations are rarer, lower in abundance, and consequently less spatially autocorrelated; thus, to detect newly established populations in this area, a greater trap resolution is needed

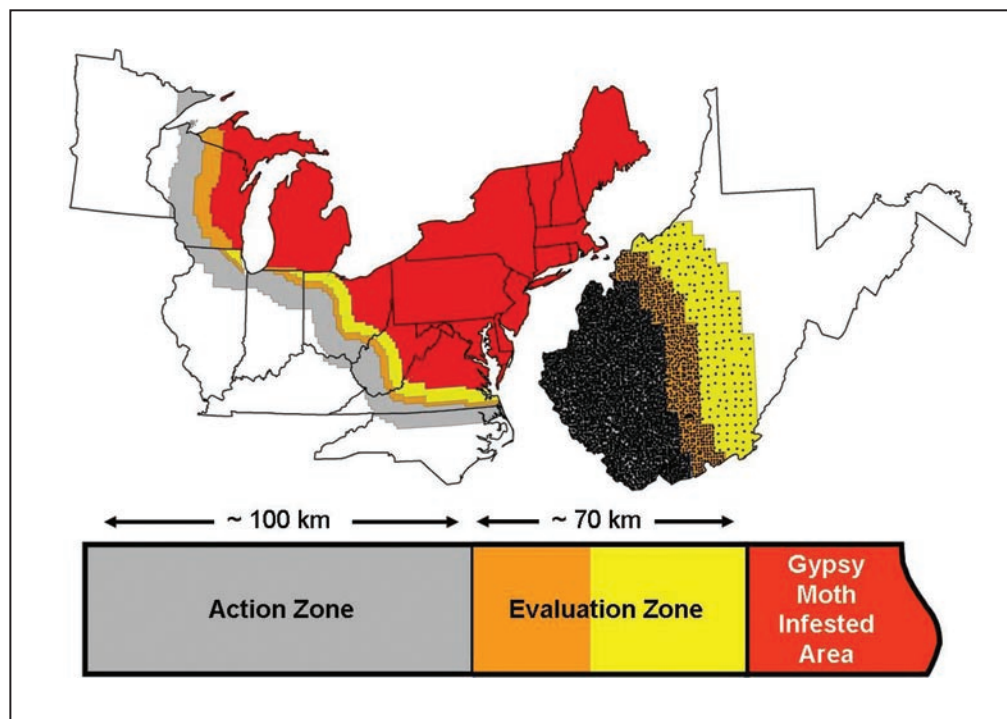


Figure 3.—The STS Program Area in 2007, showing the locations of the Action Zone (grey area) and Evaluation Zone (orange and yellow areas). The map of West Virginia presents an example of the different trap grid densities (pheromone-baited traps represented as small black dots) used in STS.

(Sharov et al. 1998). The Action Zone is also where active management is implemented (i.e., the elimination of low-density gypsy moth populations). In response to the initial detection of a newly established population in the Action Zone, the area is generally delimited through more extensive trapping, using traps set 500 to 1000 m apart, to better define the density and spatial extent of the newly established population (Sharov et al. 2002b, Tobin et al. 2004). Also, following a treatment against the population, delimiting trapping will be used to evaluate the effectiveness of the treatment (Sharov et al. 2002a, Tobin and Blackburn 2007). Different trap grid densities in the Evaluation and Action Zones were previously optimized for use in detection (Sharov et al. 1996), treatment evaluation (Sharov et al. 2002a), and in the estimation of gypsy moth spread (Sharov et al. 1995). An example of the management process of the Slow the Spread Program is presented in Figure 4.

Georeferenced trap catch data from the Evaluation Zone are used to estimate gypsy moth abundance and to delineate various gypsy moth population boundaries. The spatial location at which 1, 3, 10, 30, 100, or 300 male moths are expected to be trapped per trapping area is estimated (Sharov et al. 1995), and the mean spatial displacement between these gypsy moth population boundaries in successive years is calculated to estimate gypsy moth spread (Sharov et al. 1997, Tobin et al. 2007a). Annual rates of spread are then used to evaluate STS, and to adjust the boundaries of the Evaluation and Action Zones in response to gypsy moth range expansion.

The primary costs associated with STS are from treatment applications, traps and trap deployments, and fixed costs (i.e., personnel and database management). Several treatment options are used against different population densities and at different doses and/or number of applications, all of which affect the cost. There are also several technical considerations when implementing any management program such as STS across such broad geographical scales. Since the variable costs in STS are treatment and trap costs, altering the scale of STS (i.e., increasing or decreasing the width of the Action and/or Evaluation Zones) would affect its overall cost. In this analysis, I used 2000-2006 budget data for STS to decompose the costs associated with various trap grid densities and treatments. I then combined these costs with fixed costs to determine the extent over which STS can be implemented across a range of funding levels. This report should provide a template for federal and state program managers to make informed decisions as to how to coordinate STS given financial constraints. Finally, I estimated the biological ramifications, in terms of gypsy moth spread rates, based upon various implementation scenarios.

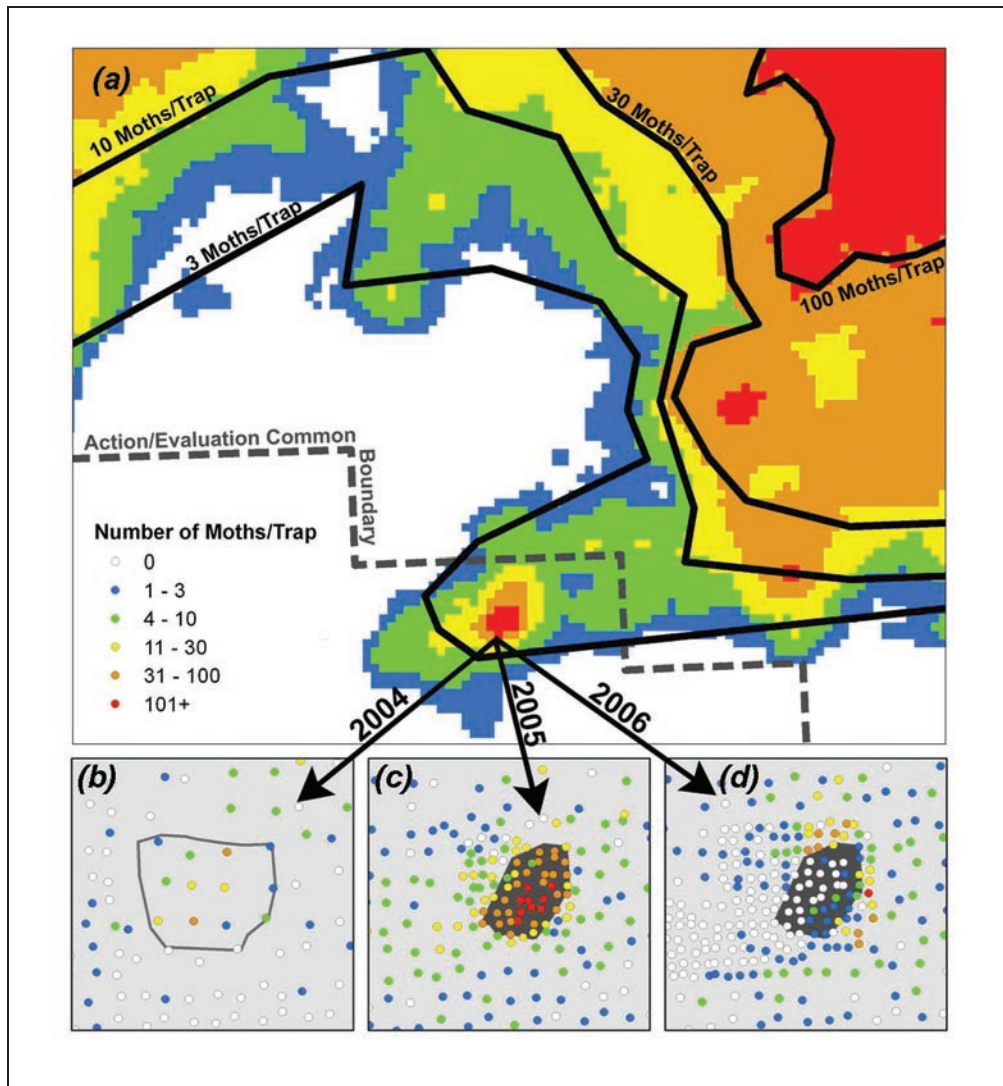


Figure 4.—Gypsy moth monitoring under STS in 2005 for a selected area, showing the spatial interpolation of trap catch data, estimated locations of gypsy moth population boundaries (3, 10, 30, and 100 moths per trap), and the boundary between the Action and Evaluation Zones (a). The trap catch data (represented as dots) from the ‘hot spot’ is shown in the prior year (b). The dark grey area represents an implemented treatment targeting the population in 2005 (c), and the trap catch data from 2006 reveal a substantially reduced population (d).

METHODS

Treatment Costs in the Slow the Spread Program

Treatment data from 2000 to 2006 were used to estimate costs for each treatment tactic used in STS. The primary treatment option is mating disruption. Plastic flakes impregnated with synthetic pheromone (Disrupt® II, Hercon® Environmental, Emigsville, PA) are applied aerially to foliage, flooding the air with pheromone and consequently interfering with the male moth's ability to locate females for mating (Thorpe et al. 2006). Other options are the biopesticide *Bacillus thuringiensis* variety *kurstaki* (Reardon et al. 1994), the insect growth regulator diflubenzuron (registered as Dimilin®) (U.S. Dep. Agric. 1995), and the gypsy moth nucleopolyhedrosis virus (registered as Gypchek®) (Reardon et al. 1996). Only those treatment tactics that were analyzed and were part of the record of decisions under the gypsy moth Final Environmental Impact Statement (U.S. Dep. Agric. 1995) can be used in STS.

Treatment tactics vary according to the density of the targeted population. Mating disruption is more effective in low-density populations that tend to be farther from the generally infested area, while *B. thuringiensis kurstaki* is more effective against high-density populations that tend to be closer to the generally infested area (Tobin and Blackburn 2007). Mean pretreatment moth density in areas treated using mating disruption (2000-2006) was 4.7 moths per trap (SE=0.3). Mating disruption is rarely used in areas where moth densities exceed 10 moths per trap (90 percent of the treatment blocks had pretreatment moth densities < 10), or when alternate life stages are found (i.e., egg masses). In contrast, mean pretreatment moth densities in areas treated with *B. thuringiensis kurstaki* was 17.5 moths per trap (SE=2.0). To account for the differences in the location of various treatment tactics, the proportion of acreage treated with each tactic and dose, across all years, was calculated based upon the location of the tactic relative to the beginning of the Action Zone (i.e., the boundary separating the Action and Evaluation Zones, cf. Fig. 3). Nonlinear regression (PROC NLIN, SAS Institute 1999) was used to fit an exponential model to each tactic and dose according to

$$P = \frac{1}{\left(1 + e^{(-rD+B)}\right)}, \quad (1)$$

where P is the proportion of treated acreage, D is the distance (km) from the beginning of the Action Zone, and r and B are parameters representing the rate of decrease and lag, respectively (Brown and Mayer 1988). This function was then used to estimate the mean acreage treated, per tactic and dose, at a given distance from the beginning of the Action Zone. Mean treated acreage was then combined with treatment costs to determine the average annual treatment costs given the overall width of the Action Zone implemented under STS.

Trapping Costs in the Slow the Spread Program

I measured the trap grid density within the implemented Action and Evaluation Zones, and then related the trapping costs as a function of the distance from the Action and Evaluation Zone common boundary. A uniform cost per trap of \$48 was used, which reflects the average cost per trap (excluding fixed costs associated with trapping, i.e., personnel salaries and fringe benefits) across all participating states from 2000 to 2006. Linear regression (PROG GLM, SAS Institute 1999) was used to estimate the total costs for trapping as a function of the distance from the Action and Evaluation Zone common boundary. Trap costs were then used to estimate Program-wide costs given the combined widths of the Action and Evaluation Zones.

Fixed Costs in the Slow the Spread Program

The fixed costs associated with STS are listed in Table 1. They include state and federal personnel costs, travel, database management including web support (e.g., www.gmsts.org), financial management services in support of the STS Foundation, Program-wide aerial applicator contracts, and work in support of National Environmental Policy Act (NEPA) compliance for gypsy moth management on federally owned lands. I used data from 2005 and 2006 to ensure that fixed costs were expressed in the most current dollars. Future increases in fixed costs due to inflation were not considered. Increases in the efficiency of STS due to advances in research and development, which could reduce costs, also were not considered.

Table 1.—Summary of recent fixed costs for STS, in thousands \$USD (percentages in parentheses)

Budget Category	Year	
	2005	2006
State costs (personnel salaries, fringe, and travel)	1,171 (46.9%)	1,400 (53.1%)
Financial management services	30 (1.2%)	30 (1.1%)
Forest service costs (personnel salaries, fringe, and travel)	140 (5.6%)	140 (5.3%)
Mating disruption application contract	15 (0.6%)	15 (0.6%)
NEPA	25 (1.0%)	25 (0.9%)
Database management	846 (33.9%)	759 (28.8%)
APHIS-Regulatory	270 (10.8%)	270 (10.2%)
TOTAL	2,497 (100%)	2,639 (100%)

Program Implementation and Gypsy Moth Spread

The annual rate of gypsy moth spread is based upon the mean year-to-year spatial displacement across all gypsy moth population boundaries (i.e., the 1, 3, 10, 30, 100, and 300 moths per trap boundaries; Sharov et al. 1995, Tobin and Blackburn 2007, Tobin et al. 2007a). I used annual gypsy moth spread rate data from 2000 to 2006 to estimate 3-year moving averages of spread (i.e., 2000-2002, 2001-2003, ..., 2004-2006) (Table 2). These spread rates do not reflect regional or state differences in spread previously reported (Sharov et al. 1999, Tobin and Whitmire 2005, Tobin et al. 2007a and b), but instead reflect overall spread rates under the current implementation of STS.

Previously, Liebhold et al. (1992) estimated gypsy moth spread at 21.7 km/year (in the absence of STS or any other management program). Sharov et al. (1998) derived a theoretical estimate of gypsy moth spread (17 km/year) using a model parameterized from gypsy moth demographic data, also in the absence of a management program. These values, coupled with 3-year moving averages of spread observed during the implementation of STS, were used to predict the relationship between levels of management activity (as denoted by the width of the Action Zone over which treatments are deployed) and projected rates of gypsy moth spread. These projected rates were then extrapolated to demonstrate the impact of long-term management activity on the expected gypsy moth range 20 years into the future.

Table 2.—Gypsy moth spread rates under STS, based upon the yearly displacement of male moth population boundaries

Year	Spread rate (km/year)	3-Year moving average of spread rate (km/year)
2000	-4.0	6.0
2001	13.8	9.7
2002	-0.4	3.1
2003	12.6	8.6
2004	-9.8	0.8
2005	4.8	2.5
2006	6.7	0.6

RESULTS

Treatment Costs

A summary of the use of treatment options available in STS and their respective costs is listed in Table 3. The relationship between the proportion of acres treated by each treatment tactic as a function of the distance from the beginning of the Action Zone is shown in Figure 5. Depending on the extent of STS, especially the width of the Action Zone over which the majority of treatments are deployed, treatment costs will vary nonlinearly (Fig. 5). Nonlinear parameter estimates for each treatment tactic function are listed in Table 4.

Trapping Costs

The mean overall cost for trapping within the Evaluation Zone is \$28,138 for each 5 km of width. Costs in the Evaluation Zone are fairly stable within 50 km of the boundary between the Action and Evaluation Zones, and then the costs begin to decline as the intertrap distance changes from 3 to 5 to 8 km (Fig. 6b and d). A piecewise linear regression model was fit to this relationship to account for these different trapping costs. In the Action Zone, trapping costs decline linearly as the distance from the beginning of the Action Zone increases (Fig. 6a and c). The intertrap distance of traps (approximately 2 km) within the Action Zone is fairly standardized; however, because more new gypsy moth colonies occur closer to the generally infested area, there are consequently more traps set near the beginning of the Action Zone (Fig. 6a) due to the use of pre- and post-treatment trapping delimits in which traps are set 500 to 1000 m apart. As a reference, the overall mean trapping cost for each 5 km width of Action Zone is \$152,000.

Table 3.—Summary of treatment options and their use in STS

Treatment option	Dose/acre × number of applications ^a	Cost/acre	Average acres treated/year
<i>B. thuringiensis kurstaki</i>	24 BIU × 1	\$22.00	10,062
	24 BIU × 2	\$44.00	68,984
	30 BIU × 1	\$22.00	422
	30 BIU × 2	\$44.00	1,988
	38 BIU × 1	\$28.00	8,729
Mating disruption	6 g × 1	\$8.34	273,741
	15 g × 1	\$13.73	145,532
Dimilin®	1 oz × 1	\$20.00	3,258
Gypchek®	5×10 ¹¹ PIB × 1	\$20.00	5,941

^aBIU, billion international units. PIB, polyhedral inclusion bodies.

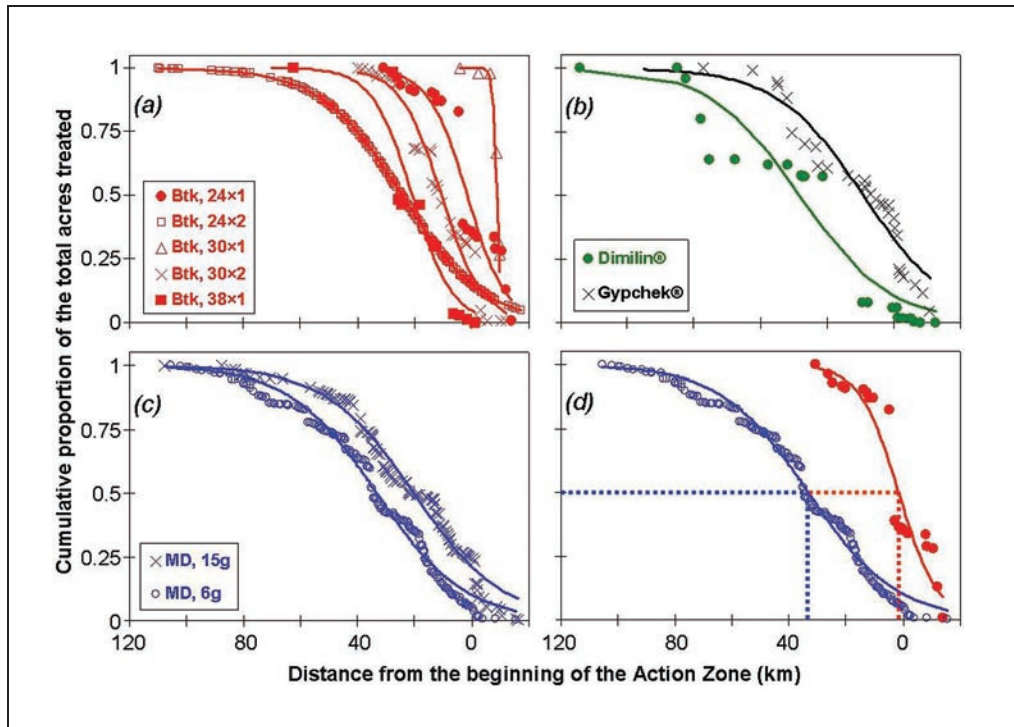


Figure 5.—Nonlinear relationships between the proportion of acres treated by each treatment tactic as a function of the distance from the beginning of the Action Zone (a-c). The utility of these relationships, using *B. thuringiensis kurstaki* (red; 24 BIU/acre × 1 application) and mating disruption (blue; 6 g/acre) are shown as examples (d). On average, half of the treated acreage for *B. thuringiensis kurstaki* (red dotted line) and mating disruption (blue dotted line) occurs within 2 and 33.2 km, respectively, of the beginning of the Action Zone. *Btk*, *B. thuringiensis kurstaki*; MD, Mating disruption.

Table 4.—Nonlinear regression parameter estimates (cf. Eq. 1) for the relationship between acres treated and distance from the beginning of the Action Zone

Treatment Option	Dose/acre × number of applications ^a	Parameter Estimates (SE)	
		Rate (<i>r</i>)	Lag (<i>B</i>)
<i>B. thuringiensis kurstaki</i>	24 BIU × 1	0.1478 (0.0195)	0.2301 (0.1295)
	24 BIU × 2	0.0704 (0.0010)	1.7203 (0.0258)
	30 BIU × 1	1.2586 (0.3673)	-11.2081 (3.3255)
	30 BIU × 2	0.1400 (0.0089)	1.4774 (0.1190)
	38 BIU × 1	0.1432 (0.0320)	2.9736 (0.6453)
Mating disruption	6 g × 1	0.0654 (0.0010)	2.1729 (0.0338)
	15 g × 1	0.0644 (0.0015)	1.3055 (0.0365)
Dimilin®	1 oz × 1	0.0753 (0.0106)	2.1292 (0.3182)
Gypchek®	5 × 10 ¹¹ PIB × 1	0.0770 (0.0068)	0.7015 (0.0860)

^aBIU, billion international units. PIB, polyhedral inclusion bodies.

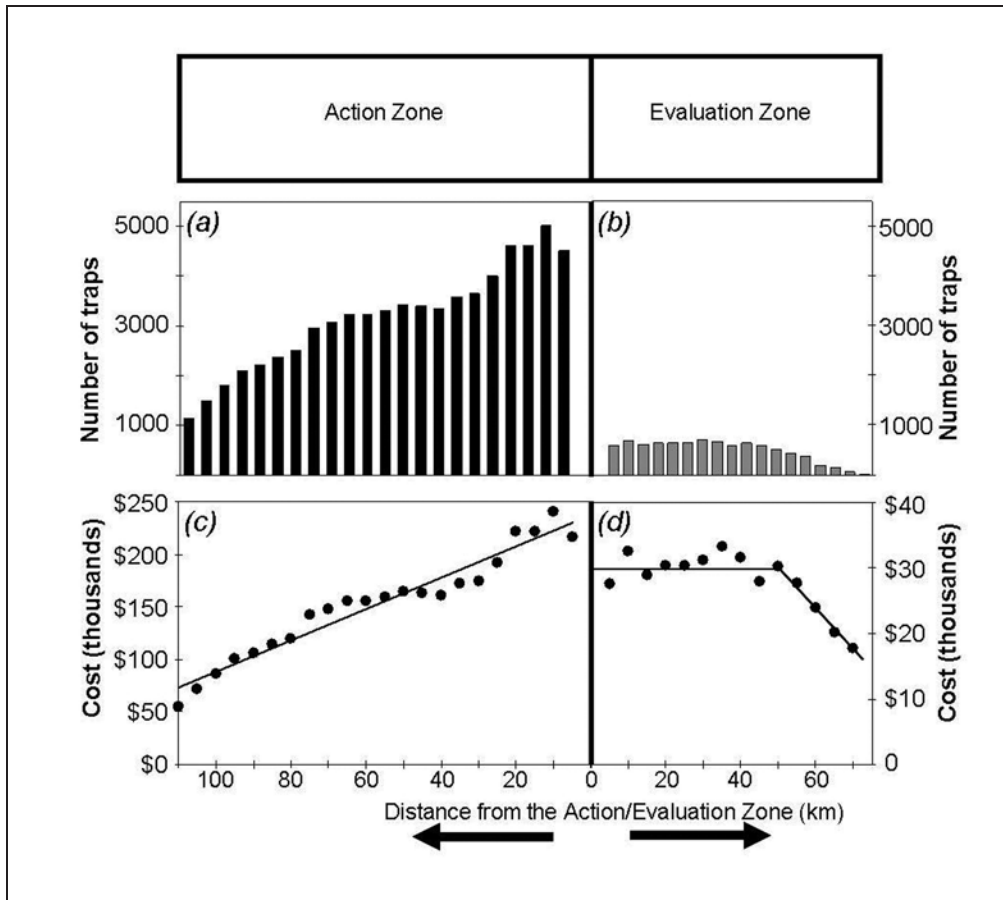


Figure 6.—Relationship between the number of traps deployed (a, b) and corresponding costs (c, d) for the Action and Evaluation Zones relative to the distance from the Action Zone/Evaluation Zone common boundary. Linear regression equations for the trap costs: (c) Predicted costs = $-1.50(\text{Distance}) + 237.95$; (d) Predicted costs = 29.92 and Predicted costs = $-0.81(\text{Distance}) + 72.43$.

Program Implementation and Gypsy Moth Spread

The combination of trapping and treatment costs, and the manner in which they are deployed, can be used to determine the extent that STS can be implemented at a given funding level. In this report, the assumption was made that annual budgets are more likely to decrease rather than increase. To examine the effect of increased financial constraints, I explored the feasibility of reducing the widths of the Action and Evaluation Zones.

Trap catch data from the Evaluation Zone are used primarily to estimate annual spread (Fig. 7), and this information is not trivial. The primary goal of the Slow the Spread Program is to slow the rate at which gypsy moth invades new areas. The displacement in moth population boundaries is used to estimate annual spread rates and thus is critically important in determining if the goals of STS are being achieved.

It becomes infeasible to eliminate or drastically reduce the width of the Evaluation Zone without jeopardizing the ability to estimate spread. Moreover, even if the Evaluation Zone were to be reduced in width, the Program costs would not greatly change since few treatments are deployed here (Fig. 5) and trap costs are minimal relative to other costs in the Program (Fig. 6).

The overall width of STS (Action and Evaluation Zones) would thus need to be maintained, at least in the near future, at roughly 170 km to estimate annual gypsy moth spread rates and to identify newly established populations ahead of the generally infested area. Trap grid densities are already optimized for detecting new colonies and estimating spread; thus, reducing the intensity of trapping deployments would be counterproductive. The primary, most biologically feasible manner by which STS could be implemented with budgetary constraints would be to decrease the width of the Action Zone (essentially reducing treatments) and increase the width of the Evaluation Zone (Fig. 8). This results in savings in both trapping (since trap grid density would be reduced) and treatment costs. An example of how treatments would be reduced with a corresponding reduction in Action Zone width is shown in Figure 9. Since gypsy moth spread occurs through stratified dispersal, the goal

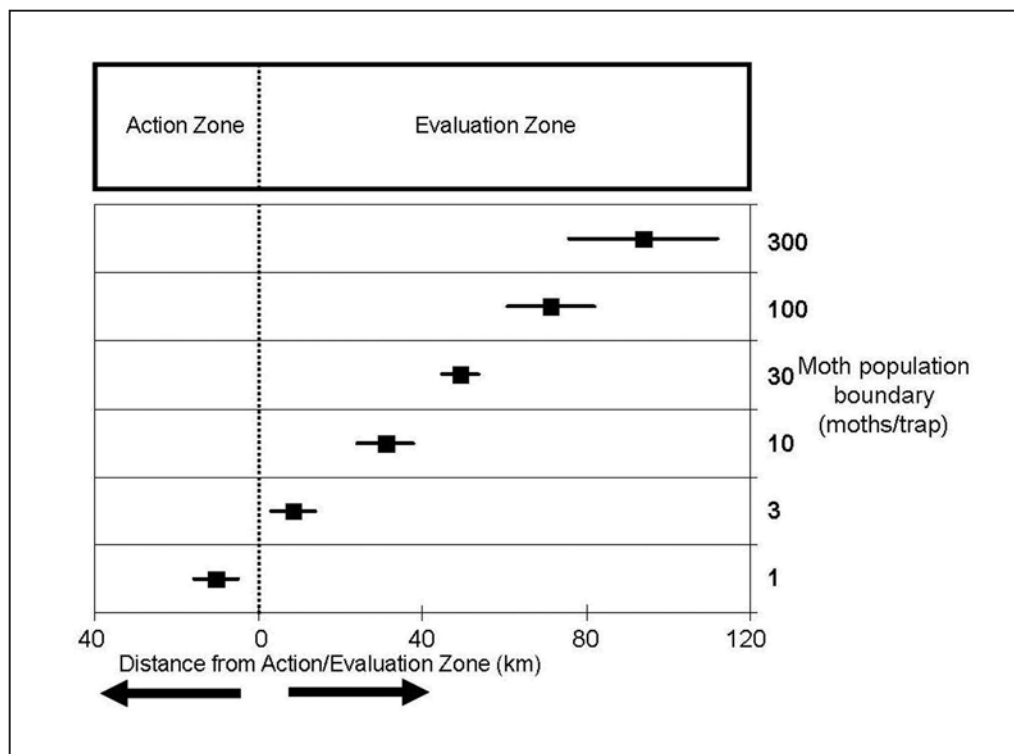


Figure 7.—Mean (\pm SD) locations of the 1, 3, 10, 30, 100, and 300 moth population boundaries (Sharov et al. 1997) relative to the common boundary of the Action and Evaluation Zones. All but the 1 moth/trap boundary are estimated using traps deployed in the Evaluation Zone.

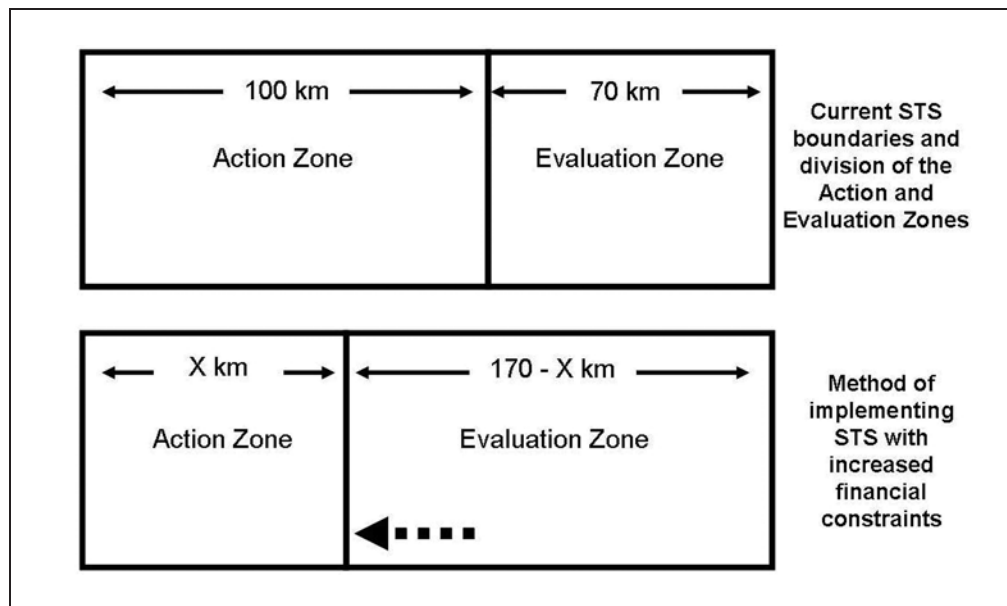


Figure 8.—Implementing STS with increased financial constraints.

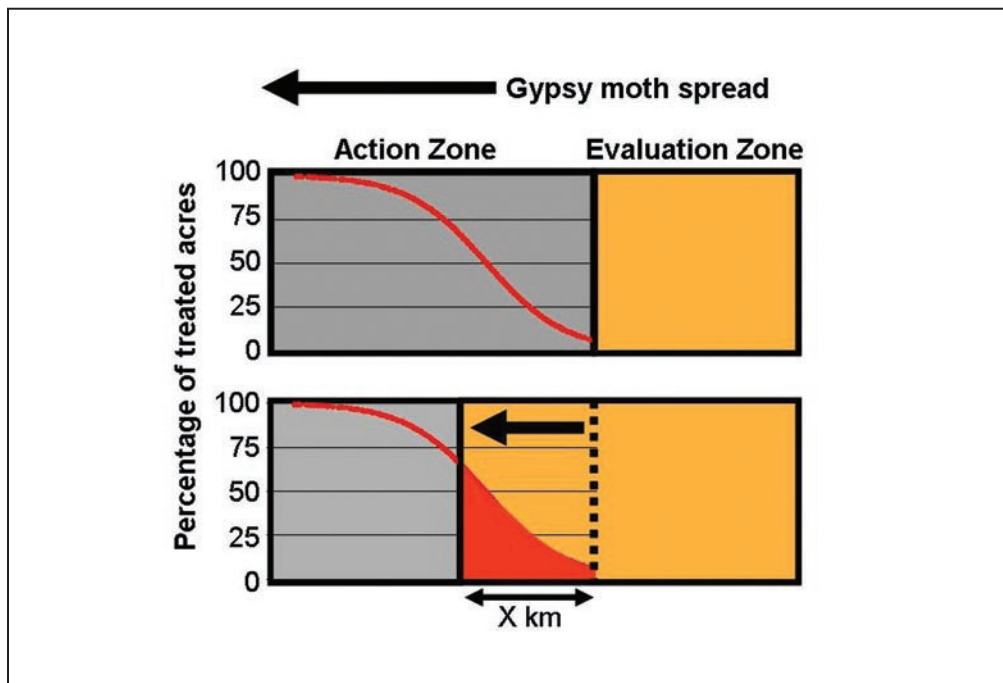


Figure 9.—Hypothetical example of the effects of a reduced Action Zone width on treatment acreage. The cumulative percentage of all acreage treated under STS (red curve) is shown across the length of the Action Zone. The top graph is the current implementation design, and the bottom graph illustrates the loss in treatment acreage (red area) when the Action Zone width is reduced by X km. This strategy ensures that the most distal colonies are still targeted for elimination since they would be the ones most likely to contribute to increased rates of spread under stratified diffusion.

of slowing its spread can still be achieved, albeit to varying levels of success, when the Action Zone is reduced in width providing that the most distal colonies are still targeted for treatment. However, since fewer colonies would be targeted, the rate of gypsy moth spread would increase because colonies left unmanaged would contribute to gypsy moth spread.

Using gypsy moth spread rate data observed during the current implementation of STS (Table 2) and data in the absence of STS (Liebhold et al. 1992, Sharov et al. 1998), linear regression was used to predict spread rates across varying widths of the Action Zone (Fig. 10). This relationship is challenging to predict given the lack of empirical or theoretical data on spread between the two extremes (i.e., a 100-km-wide Action Zone under STS, and no STS), but still the only empirical approach currently available to estimate the impact of reduced funding on spread. Moreover, it is still reasonable to assume that gypsy moth spread rates with some reduced level of STS would likely be between those spread rates observed in the absence of and in the presence of STS as currently implemented. In the event that future financial constraints force the Action Zone to be reduced, then spread rate data can be used to enhance the predictions displayed in Figure 10.

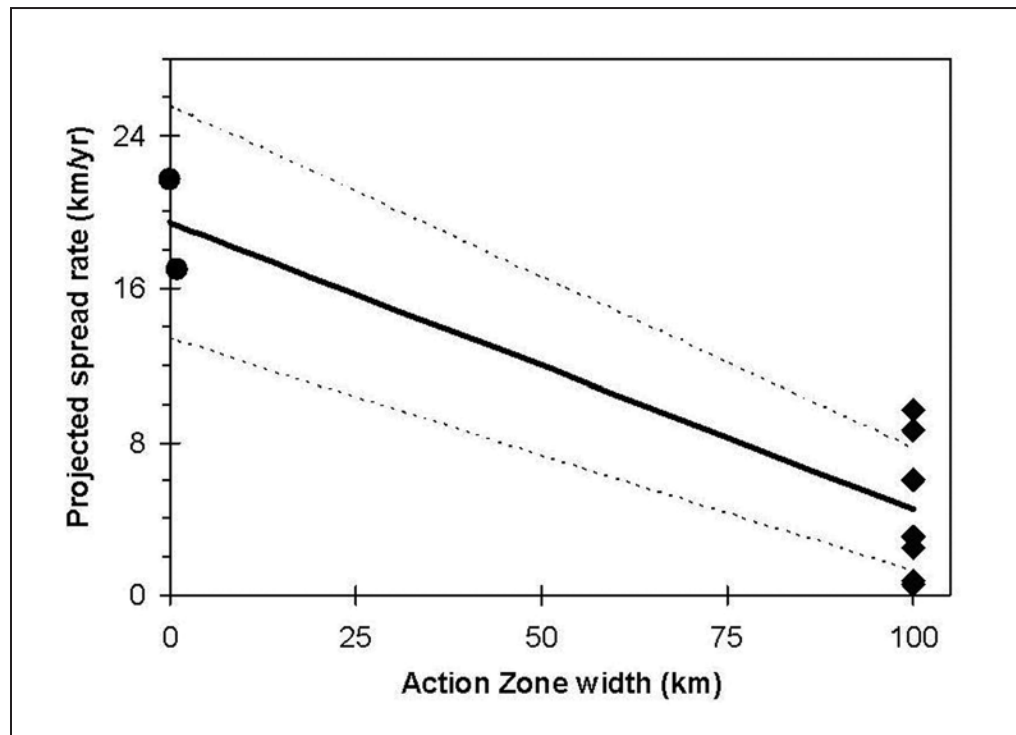


Figure 10.—Mean gypsy moth spread rates under current STS operating procedures (diamonds) coupled with spread in the absence of STS (circles; Liebhold et al. 1992, Sharov et al. 1998). Linear regression was fit (solid line; 95% CI as dashed lines) to these data to extrapolate the expected rate of spread over a range of Action Zone widths.

A combination of all treatment, trapping, and fixed costs across a range of widths for the Action and Evaluation Zones is presented in Table 5. The projected gypsy moth spread rates are also listed in Table 5. The total width of STS is constant, with the primary change being the gradual shift of area from the Action Zone into the Evaluation Zone (cf. Fig. 8). Costs in the Evaluation Zone are almost exclusively related to trapping costs, which are proportionally inexpensive. For example, a 70-km-wide Evaluation Zone would cost \$390,000 to implement, while a 130-km-wide Evaluation Zone would cost \$570,000. In contrast, corresponding changes in the Action Zone would decrease the costs from \$3.3 million (under a 100-km-wide Action Zone) to \$1.1 million (under a 40-km-wide Action Zone, Table 5). Using the estimated rates of gypsy moth spread across selected funding levels, I predicted long-term impacts on gypsy moth range expansion by determining the increase in the gypsy moth quarantined area from 2006 to 2025 (Fig. 11).

In this report, I presented an overview of the costs associated with STS and the biological ramifications of maintaining or modifying its extent. There are several additional points that could affect gypsy moth spread but are not easy to quantify.

Table 5.—Costs in millions \$USD and projected gypsy moth spread rates associated with the implementation of STS. Percent of the total program cost allocated to trapping, treatment, and fixed costs are noted in parentheses.

Width of zones (km)		Trapping costs			Fixed costs (%) ^c	Treatment costs (%) ^d	Total program cost ^e	Projected gypsy moth spread rate, km/yr (±95% CI) ^f
Action Zone (AZ)	Evaluation Zone (EZ)	AZ ^a	EZ ^b	Total (%)				
100	70	\$3.34	\$0.39	\$3.73 (28.7)	\$2.30 (17.7)	\$6.98 (53.7)	\$13.01	4.9 (2.2–7.7)
95	75	\$3.11	\$0.40	\$3.51 (28.3)	\$2.30 (18.5)	\$6.61 (53.2)	\$12.42	5.7 (2.9–8.4)
90	80	\$2.89	\$0.42	\$3.31 (28.2)	\$2.30 (19.6)	\$6.15 (52.3)	\$11.75	6.4 (3.7–9.1)
85	85	\$2.67	\$0.43	\$3.11 (28.2)	\$2.30 (20.9)	\$5.61 (50.9)	\$11.02	7.1 (4.4–9.8)
80	90	\$2.47	\$0.45	\$2.91 (28.5)	\$2.30 (22.5)	\$5.00 (48.9)	\$10.22	7.8 (5.1–10.6)
75	95	\$2.27	\$0.46	\$2.73 (29.1)	\$2.30 (24.5)	\$4.36 (46.4)	\$9.39	8.6 (5.8–11.3)
70	100	\$2.07	\$0.48	\$2.55 (29.8)	\$2.30 (26.9)	\$3.70 (43.3)	\$8.55	9.3 (6.6–12.0)
65	105	\$1.89	\$0.49	\$2.38 (30.7)	\$2.30 (29.7)	\$3.07 (39.6)	\$7.75	10.0 (7.3–12.7)
60	110	\$1.71	\$0.51	\$2.22 (31.7)	\$2.30 (32.9)	\$2.48 (35.4)	\$7.00	10.7 (8.0–13.5)
55	115	\$1.54	\$0.53	\$2.06 (32.5)	\$2.30 (36.3)	\$1.96 (31.0)	\$6.33	11.5 (8.7–14.2)
50	120	\$1.38	\$0.54	\$1.92 (33.4)	\$2.30 (40.1)	\$1.52 (26.5)	\$5.74	12.2 (9.5–14.9)
45	125	\$1.22	\$0.56	\$1.78 (34.0)	\$2.30 (43.9)	\$1.16 (22.1)	\$5.24	12.9 (10.2–15.6)
40	130	\$1.07	\$0.57	\$1.64 (34.0)	\$2.30 (47.7)	\$0.87 (18.0)	\$4.82	13.6 (10.9–16.4)

^aAverage cost/5km of Action Zone based on \$48/trap, and a linear function of trap density over width (Fig. 6).

^bAverage cost/5 km Evaluation Area based on \$48/trap, and a linear function of trap density over width (Fig. 6).

^cFixed costs include fulltime salaries and fringe, travel, audit and management services, database management, and NEPA and regulatory costs (Table 1).

^dEstimated by a cost function using yearly treatment data from 2001-2006 (Table 3, Fig. 5).

^eTotal assumes 75% federal contribution + 25% participating state contribution.

^fInterpolated from relationship presented in Figure 10.

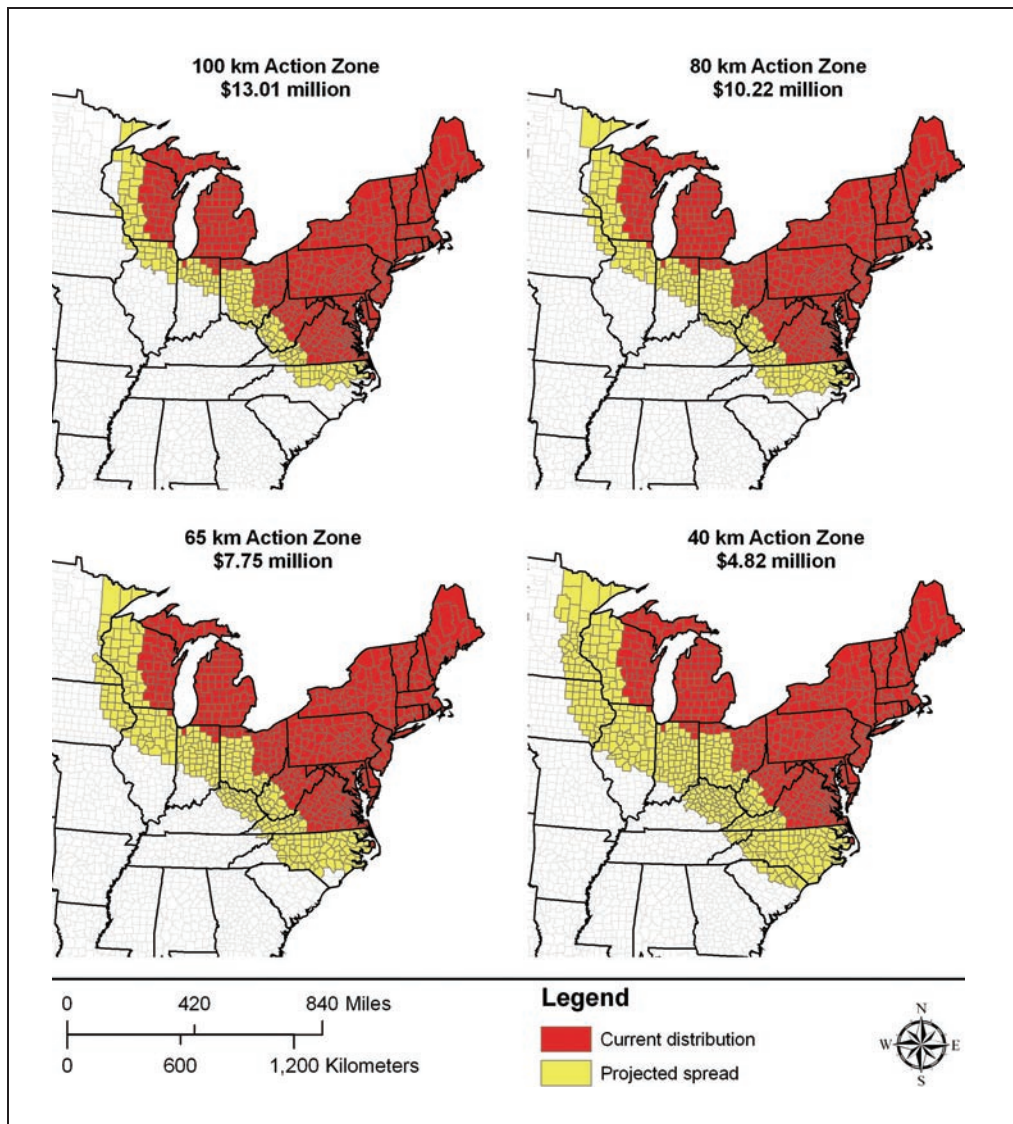


Figure 11.—Projections of gypsy moth range expansion over the next 20 years (2006-2025) at selected levels of STS funding.

First, STS is only one management program targeting gypsy moth. Others include cooperative suppression programs that operate within the generally infested area (Fig. 1) to mitigate gypsy moth outbreaks. The absence of gypsy moth suppression programs could affect gypsy moth spread since new gypsy moth introductions seem to be more frequent following outbreaks in source areas (Myers and Rothman 1995).

It is uncertain how potential future higher rates of gypsy moth spread, possibly resulting from a reduction in the extent of STS, will affect the degree of “boundary compression.” This phenomenon has been demonstrated both theoretically (Sharov et al. 1996) and empirically (Tobin and Whitmire 2005). Sharov et al. (1996) described

a model of gypsy moth spread that predicts when spread was reduced, the distance between moth population boundaries (i.e., boundaries representing low, intermediate, and high density populations) were likewise reduced or “compressed.” If moth population boundaries become less compressed due to higher spread rates, it is not clear what effect this could have on the ability to accurately estimate moth population boundaries, even within a wider Evaluation Zone. This could hinder the Program’s ability to accurately measure the rate of gypsy moth spread.

It is also unclear if reduced boundary compression would affect the abundance of natural enemies, such as the gypsy moth entomopathogens *Entomophaga maimaiga* (Hajek 1999) and the nucleopolyhedrosis virus (LdMNPV) (Elkinton and Liebhold 1990), and their regulation of gypsy moth populations. It is possible that when higher density populations are in closer proximity to intermediate density populations, then entomopathogens, especially *E. maimaiga*, could disperse from high gypsy moth population density areas and exert population control in intermediate density populations. In fact, any additional regulatory mechanism, whether through biological control agents or cooperative suppression programs, that operates within or near STS likely has some positive synergistic effect on the efficacy of STS.

Lastly, increased rates of gypsy moth spread will increase the rate at which new counties become regulated under the gypsy moth quarantine (U.S. Code of Federal Regulations, Title 7, Chapter III, Section 301.45). The movement of goods, including nursery stock and personal household items, from a quarantined area to an unquarantined area is regulated. Specifically, commercial products are required to obtain compliance prior to the movement of goods through interstate or intrastate commerce. This regulation obviously comes at a cost. An economic benefit of STS is to delay the costs associated with maintaining the quarantine (Sills and Bigsby 2007), as well as delaying the costs associated with gypsy moth outbreaks (Leuschner et al. 1996). Thus, reducing the implemented area of STS will have future additional management and regulatory costs that could eliminate any savings gained through budget reductions.

SUMMARY

The gypsy moth invasion in the United States proceeds through a process known as stratified dispersal. Local growth and dispersal are coupled with long-range, spatially disjunct “jumps” in the population (Hengeveld 1989, Andow et al. 1990, Shigesada and Kawasaki 1997). Newly founded populations can greatly contribute to the rate of gypsy moth spread when they grow and coalesce with the expanding population front (Fig. 2). The STS Program is implemented along the leading edge of the population front to identify and eliminate these new populations formed by these “jumps” before they contribute to the rate of spread (Tobin and Blackburn 2007). Future budgetary constraints could force STS managers at the state and federal levels to modify the relative widths of the Action and Evaluation Zones (Table 5), and hence the degree to which new populations can be managed. The less the gypsy moth is managed under STS, the greater the estimated rate of gypsy moth spread (Fig. 10) and the greater the rate at which the gypsy moth quarantined area is increased (Fig. 11).

The rationale behind STS could be applied in the development and implementation of other invasive species management programs. Any species that spreads according to stratified dispersal and does not yet fully occupy its susceptible host range could benefit from such a program, assuming that (1) there is a method for detecting low-density populations, which are more feasible to eradicate than higher density populations; (2) effective treatment tactics exist; and (3) the benefits of the program outweigh the costs. For example, there is currently an interest in developing a similar management program for the emerald ash borer, *Agilus planipennis* Fairmaire (Coleoptera: Buprestidae). Such an effort will undoubtedly incur many of the same types of costs reported here, and likewise would face parallel logistic and biological constraints. Consequently, costs and biological analyses from STS could serve as a valuable template when designing programs to reduce the spread of other nonindigenous species.

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The gypsy moth Slow the Spread Program aims to reduce the rate of gypsy moth, *Lymantria dispar* (L.), spread into new areas in the United States. The annual budget for this program has ranged from \$10-13 million. Changes in funding levels can have important ramifications to the implementation of this program, and consequently affect the rate of gypsy moth spread. This report presents a cost analysis for implementing the Slow the Spread Program across a range of funding levels, and predicts the consequent changes in gypsy moth spread rates. This work should be useful to program managers in implementing the Slow the Spread Program given yearly financial constraints, and more generally could serve as a template for barrier zone management programs against other nonindigenous species.

Key Words: *Lymantria dispar*, invasive species management, spread, biological invasions

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