Management of the Gypsy Moth through a Decision Algorithm under the STS Project

Patrick C. Tobin, Alexei A. Sharov, Andrew A. Liebhold, Donna S. Leonard, E. Anderson Roberts, and Matthew R. Learn

The gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae), has been gradually expanding its range in North America since its accidental release into Massachusetts approximately 135 years ago (Liebhold et al. 1989). Gypsy moth is a highly polyphagous herbivore that can exploit more than 300 species of deciduous and coniferous hosts (Elkinton and Liebhold 1990), although some tree species, such as those in the genera *Quercus*, *Populus*, and *Salix*, are more preferred than others (Martinat and Barbosa 1987). The ecological and economic costs, indirect and direct, from gypsy moth damage are severe (e.g., Doane and McManus 1981, Thurber et al. 1994, Leuschner et al. 1996, Sample et al. 1996, Redman and Scriber 2000).

The USDA Cooperative Management Programs for gypsy moth populations fall into one of three categories:

(1) eradication, which is implemented in uninfested regions located distant from the expanding population front;
(2) suppression (i.e., reducing outbreak population abundance), which is implemented in regions that are generally infested; and
(3) barrier-zone management (i.e., limitation of range-expansion), which is implemented in the transition zone between the uninfested and infested areas, and which is currently realized through the STS project (Sharov et al. 2002b).

In this article, we focus on the Decision Algorithm used in the STS project. This Decision Algorithm is the realization of several years of work and relies on extensive areawide survey data and computationally intensive data processing to objectively quantify spatial and temporal population patterns to achieve areawide management of expanding gypsy moth populations.

Philosophy of the STS Project

Gypsy moth populations do not spread continuously along the population front. Instead, individual colonies become established beyond the expanding front either through dispersal or more commonly through the inadvertent transportation of life stages by humans (Schwalbe 1981). Thus, the area near the population front can be separated into the "infested zone" that is continuously occupied, the "transition zone" where isolated colonies become established, and the "uninfested zone" (Fig. 1).

As individual colonies grow within the transition zone, they coalesce and contribute to the range expansion of the gypsy moth. Liebhold et al. (1992) modeled gypsy moth range expansion and found that if windborne larval movement was the only form of dispersal (i.e., no accidental transport of life stages), then range expansion should occur at a rate of roughly 3 km/yr. They found, however, that from 1965 to 1990 in the northeastern United States, the average spread rate was ≈21 km/yr. They hypothesized that this greater rate of spread was due to the formation, growth and coalescence of isolated populations ahead of the population front. Thus, an efficient approach to reducing gypsy moth spread would be to retard or eradicate these isolated populations.

In 1988, the USDA Forest Service initiated the Appalachian Integrated Pest Management Project (AIPM) along a portion of the expanding gypsy moth population front in Virginia and West Virginia. One of the objectives of the program was to slow gypsy moth spread by identifying isolated gypsy moth populations in the transition zone and applying site-specific treatments to these populations (McFadden and McManus 1991, Reardon 1991). Because of the success of AIPM, the USDA Forest Service then initiated, in 1993, the STS (STS) pilot project over a larger portion of the expanding front in Virginia, West Virginia, North Carolina, and Michigan to determine the feasibility of extending the use of area-wide integrated management tactics to control gypsy moth spread (Leonard and Sharov 1995). Based on the success of the pilot project, STS was integrated into the USDA's national strategy to manage gypsy moth and was implemented along the entire expanding population front. The program represents one of the largest and most comprehensive programs to manage an invasive forest insect pest.

The STS program focuses on populations in the transition zone that are not targeted by traditional eradication and suppression efforts. In this zone, populations are recently established, still at low abundance, and discontinuous from one another. Trapping male moths through pheromone traps is the primary method of sampling because other life stages are difficult to find. The strategy applied in STS is to use grids of pheromone traps to locate and delimit isolated populations. Once these populations have been delimited, they are eradicated or retarded before they grow too large. Thus, the basic premise of STS is to locate and retard isolated populations in the transition zone to prevent them from growing, coalescing, and contributing to the progression of the population front.

Principles of Monitoring

STS is a management program that uses a barrier zone located along the expanding population front. Because the objective of STS is to slow the spread, as opposed to stopping the spread, the location of the barrier zone shifts over time. The extent of the zone is determined relative to population boundaries that are estimated by interpolating moth counts from grids of pheromone-baited traps (Sharov et al. 1995). Sharov et al. (1997) showed that the boundary based on the 10 moths/trap threshold was most stable in space and time relative to population boundaries estimated using other thresholds; therefore, the location of the project area is adjusted relative to the 10 moths/trap line.

The STS project area is set on both sides from the 10 moths/trap boundary, from at least 50 km before the boundary and at least 120 km beyond the boundary (Fig. 1). Isolated gypsy moth colonies also become established beyond the STS area, but their frequency declines rapidly in the area that is more than 170 km from the 10 moth/trap boundary (Sharov and Liebhold 1998b). The areas behind and beyond the STS area are monitored as part of suppression or detection/eradication, respectively, and administered cooperatively by USDA and state agencies.

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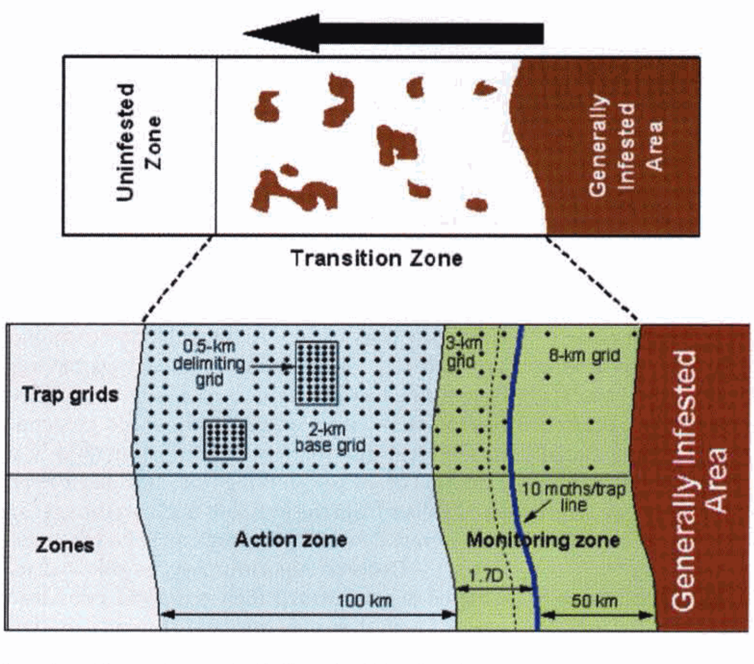


Fig. 1. Diagram of the STS project area, trap grids, and trap types used in various parts of the project. D is the distance between 10 and 30 moths/trap lines. Within the transition zone, pheromone-baited traps are used to monitor, detect, and set treatment boundaries around isolated colonies.

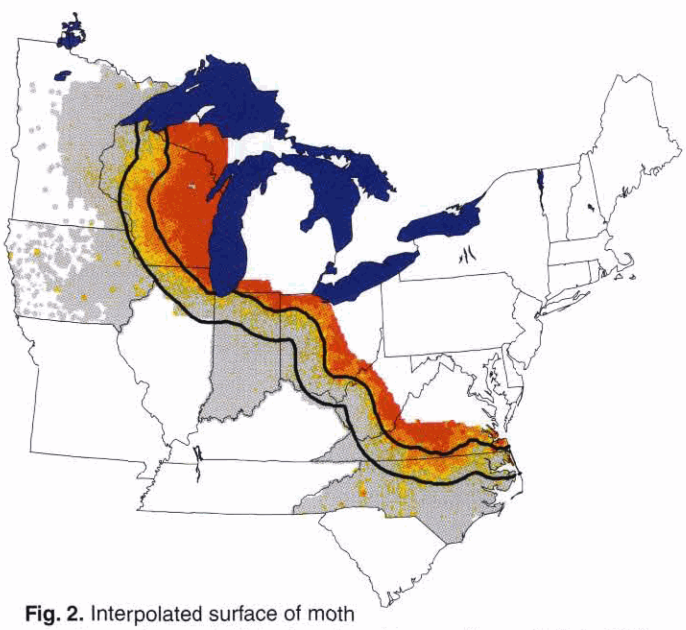


Fig. 2. Interpolated surface of moth abundance, from red (high abundance) to grey (no moths), in 2003. The thick black lines outline the Action Zone for 2003.

The project area is subdivided into two zones: the monitoring zone is located in the proximal portion of the area, and the action zone is located in the distal portion of the project area (Fig. 1). The action zone is where active management is implemented (i.e., detection and treatment of low-abundance colonies), whereas the monitoring zone is used to delineate population boundaries, evaluate the project's effect on spread, and to adjust the project area's boundaries each year in response to gypsy moth spread.

The purpose of delimitation is to determine the spatial extent of the isolated population so that treatments can be targeted more precisely.

Collecting Data under STS

Gypsy moth populations are monitored throughout the STS project area using pheromone-baited traps (Fig. 2). STS is a cooperative effort among 10 states, two universities, and USDA. Each state is responsible for placing and monitoring pheromone traps used to detect male moths. The effort is coordinated on a national level so that the data are collected uniformly. A phenology model derived from the BioSIM software (Régnière and Sharov 1998) is used to predict the timing of male emergence, which is a guide for timing trap placement and removal. States employ a varying number of employees or contractors to deploy and retrieve traps. These surveyors are equipped with handheld dataloggers with Global Positioning Systems receivers that are used to record trap captures, along with the spatial coordinates of trap locations. The data are then uploaded to a database that is accessed and processed by the Decision Algorithm. Based on the yearly fluctuation of action and monitoring zone boundaries, the number of traps can vary. Generally, more than 50,000 traps are placed in the action zone in a year.

In most of the monitoring zone, pheromone traps are set in grids with an intertrap distance of 8 km (Fig. 1), which is sufficient for estimating population boundaries (Sharov et al. 1997). In the area of the monitoring zone adjacent to the action zone, a higher trap density is needed, and the intertrap distance is 3 km. Finally, in the action zone, the intertrap distance is 2 km (Fig. 1); this trap density was found to be sufficient for detecting isolated colonies (Sharov et al. 1998). Beyond the STS area, states place traps in cooperation with USDA APHIS Gypsy Moth Detection and Eradication Programs (Gypsy Moth Program Manual 2004).

The Decision Algorithm

The Decision Algorithm for the STS project evolved during the STS pilot project. During the first year of the pilot project, decisions were made through visual interpretation of the trap grid data, but the Decision Algorithm was developed to automate this process. The algorithm is largely based on the optimization of intervention action in a model of gypsy moth spread (Sharov et al. 1998). In essence, trap catch data from grids are used by the Decision Algorithm to objectively locate presumptive isolated gypsy moth populations, or "Potential Problem Areas" (PPAs) within the transition zone. These PPAs are then evaluated to recommend a course of action, which can include treatment, more intensive monitoring to delimit the extent of the population, or the recommendation can be to do nothing (Fig. 3). In most cases, isolated populations are delimited the year following detection; and if they persist, then they are treated in the third year. The purpose of delimitation is to determine the spatial extent of the isolated population so that treatment activities can be targeted more precisely. Whereas baseline detection trapping in the action zone is conducted using a 2 km grid, delimitation trapping is conducted on a 0.5–1 km grid, or equivalent mile-based spacing.

Selection of Potential Problem Areas. The Decision Algorithm uses three methods to select PPAs. All three are based on analysis of a 40 × 40 km localized spatial neighborhood in the trapping grid, and all three are designed to locate "hot spots" in the neighborhood. The first method identifies traps for which the moth count, after transformation using $\log_e(Z + 1)$, exceeds the 98th percentile of the local distribution of $\log_e$-transformed moth counts over the 40 × 40 km neighborhood. The other two methods use smoothed interpolated surfaces (on a 1 km grid) derived from trap data using median indicator kriging (Isaaks , E. H., and R. M. Srivastava 1989. An introduction to applied geostatistics). The second method uses the $\log_e$-transformed kriged values to locate areas where interpolated values exceeded the 92nd percentile of the local distribution. The third method is an extension of the previous method, in which interpolated values from the previous and current year are considered. By overlaying trap catch data from two years, the Decision Algorithm may be able to detect isolated areas through their temporal persistence even though they may not be sufficiently spatially

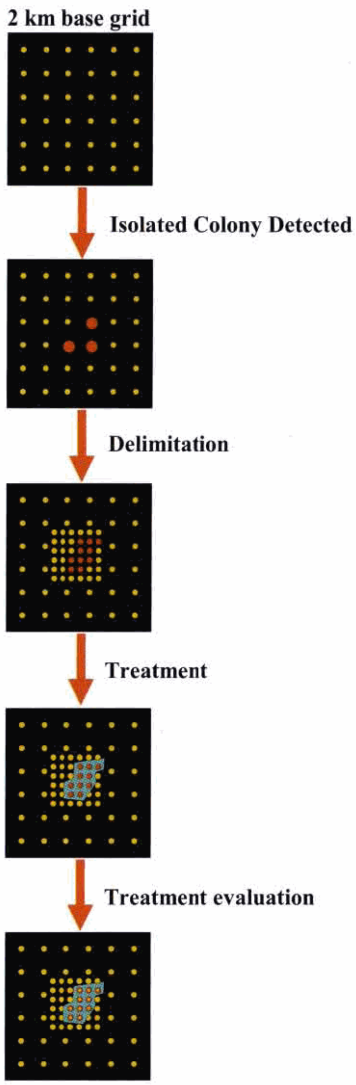


Fig. 3. Simplified flow chart of the STS strategy process. When an isolated colony is detected within the action zone, the area around the colony is delimited the next year using a 0.5 – 1 km grid to outline the infestation, which will then be treated the following year.

distinct to detect on the basis of data from a single year. The three methods are used collectively and in concert, so that the results from all three methods are jointly and equally considered in the selection process.

Assigning a Course of Action to Potential Problem Areas. The Decision Algorithm calculates two indices, a delimiting index and a priority index, for each PPA to assist in objectively assigning an appropriate action. The delimiting index is used as a guide to indicate the need for more intensive monitoring to delineate the extent of the infestation before treatment. The delimiting index, D, is a function of trap density per square km (K) and the area of the colony (A),

$$D = K \times Z(A) \quad (1)$$

In large colonies (≥9 km^2), trap density, K, can be estimated simply as the number of traps in the colony divided by its area. For smaller colonies, however, there are too few traps to estimate a trap density. For these colonies, trap density is calculated by including nearby traps that are within 3 km of the PPA.

The function $Z(A)$ is an adjustment coefficient that depends on the colony area. The reason behind this adjustment is that small colonies require a higher trap density for delimiting than large colonies do because of the difference in spatial resolution. In small colonies, a 0.5 km trapping grid should be used to delineate colony boundaries, but in larger colonies, a 1.0 km grid is sufficient because of a larger total number of traps. We use the following function for $Z(A)$:

$$Z(A) = 4 - 3\exp\left[\frac{-(A-1)^2}{900}\right] \quad (2)$$

When colonies are small, $Z(A)$ is close to 1 so that $D \approx K$. However, in larger colonies, $Z(A)$ approaches 4, so that D is about equal to a quadruple trap density in larger PPAs to compensate for a 4-fold decrease in trap density.

The priority index, P, is the most complex aspect to the STS Decision Algorithm. It is used to

(1) identify PPAs in which treatments against isolated gypsy moth populations may be necessary during the next year,
(2) identify PPAs in which additional, higher density trapping is conducted during the next year to better delimit the population, which then may be treated in the year after that, and

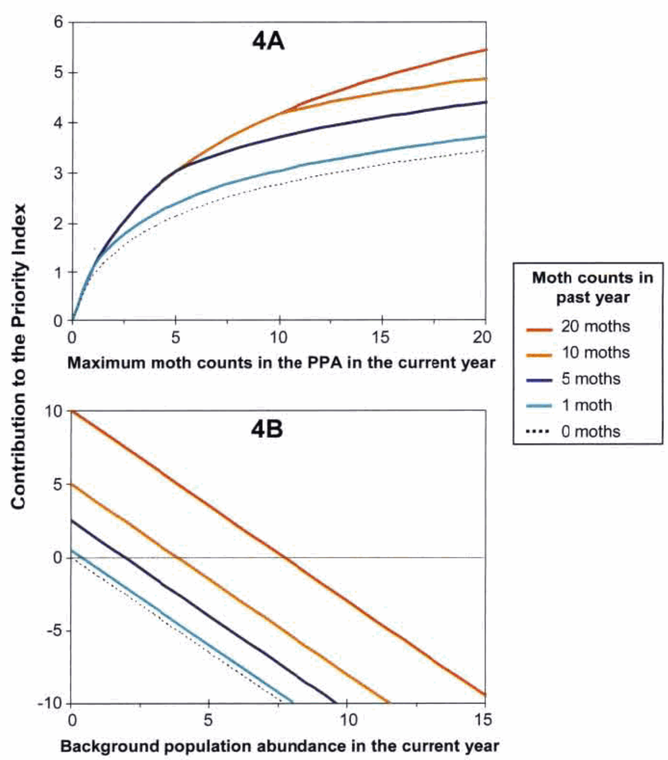


Fig. 4. Contributions to the priority index of maximum moth counts in the PPA in the current and past year (**4A**, *F1* Component), and the contributions based on background populations (**4B**, *F3* Component).

(3) rank the importance of each PPA so that the more critical PPAs can be targeted first given constraints on available STS resources.

The priority index comprises four primary components,

$$P = F1 + F2 + F3 + F4 \quad (3)$$

Each component represents a different aspect in assigning the priority to each PPA (Table 1).

The function $F1$ represents the maximum moth counts in the PPA in the current (N_t) and previous year (N'_{t-1}),

$$F1 = \log_e [N_t + 0.5N_t (\min(N_t, N'_{t-1}) + 1) + 1] \quad (4)$$

This component makes it possible to consider population abundance and persistence when assigning priority. Thus, PPAs with a previous history of a high moth count are assigned higher priority index values relative to those in which the maximum moth count was lower; penalties are not applied to those PPAs in which the counts increased from few-to-no moths to high moth counts (Fig. 4A).

The second component considers the Euclidean distance, d, between the PPA and the population front, which is assumed to coincide with the proximal border of the STS action zone.

$$F2 = \min (0.002d, 0.222d - 3.3) \quad (5)$$

This is a piece-linear function that applies a lower priority to those PPAs that are ≤15 km from the population front (Fig. 5). For example, when d = 10, $F2$ = –1.08; for d = 15, $F2$ = 0.0. When the PPA is located > 15 km from the population front, a small additional priority is given to distant colonies.

Component $F2$ is conceptually based on the rate of gypsy moth spread. Historically, populations have moved at a rate of ≈20 km/yr (Liebhold et al. 1992, Sharov et al. 1997, Sharov et al. 1999). Based upon this, in part, a target spread rate of 10 km/yr, or a 50% reduction, is used in the overall planning of the STS program (Leonard and Sharov 1995, Leuschner et al. 1996). Therefore, a threshold of 15 km in $F2$ was used as a compromise between historical and expected rates of spread, based on the notion that PPAs located within 15 km of the population front would soon be within the generally infested zone. Thus, the impact of their treatment under STS would be too ephemeral to be economically viable

The third component, $F3$, considers the neighboring background populations around the PPA in the current (Nb_t) and previous year (Nb_{t-1}),

$$F3 = 0.5\, Nb_{t-1} - 1.3\, Nb_t \quad (6)$$

This component decreases the priority of a PPA if the background moth abundance is high, thereby

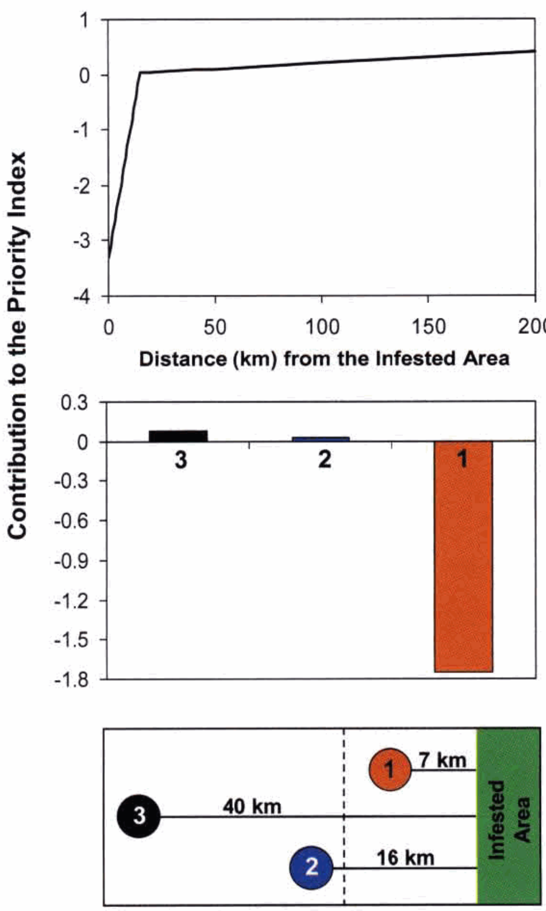


Fig. 5. Effects of distance between the PPA and the infested area on the priority index. This component (*F2*) places a substantial penalty on PPAs close to the population front (i.e., PPA 1), whereas those located >15 km from the front (i.e., PPAs 2 and 3) are given only minor additional priority points.

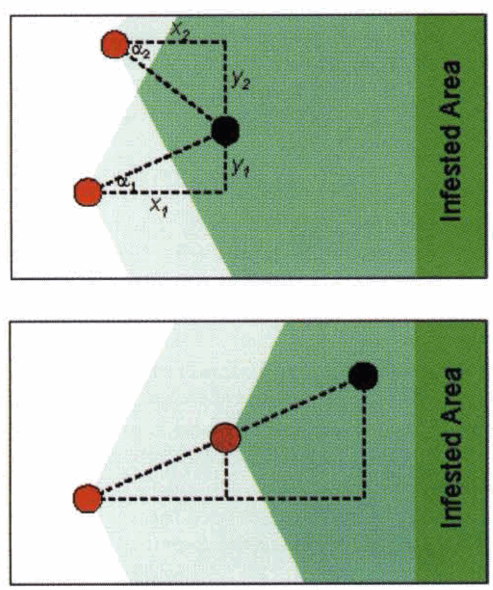


Fig. 6. The shadow of influence (*F4* Component). In the top graph, two PPAs (in red) each influence the same PPA (in black) located closer to the infested area without affecting each other. In the bottom graph, the PPA farthest from the infested area influences the other two, and the middle PPA in turn influences only the one closest to the infested area.

decreasing management priorities in years characterized by intensive moth dispersal (Fig. 4B). On the contrary, high background moth abundance in the previous year can increase the priority of the PPA, if there was a decrease in background moth abundance in the current year. This component, for example, would allow for an increase in the priority in cases when the background populations declined from year *t-1* to year *t*, while the PPA persisted.

The last component is the most complex and considers the influence PPAs have on each other when assigning priority,

$$F4 = -0.1\sum_i w(x_i, y_i) \quad (7)$$

where x_i is the distance from a PPA of interest with respect to the *i*-th PPA measured in the direction perpendicular to the population front, and y_i is the distance between these PPAs in the direction parallel to the population front (Fig. 6).

The logic is that any PPAs located in back of (proximal to) other PPAs should have decreased priority because there is no point in addressing proximal populations if other populations exist at more distant locations. In other words, these more distal populations have greater potential for increased spread and should receive higher priority. The function $w(x, y)$ is

$$w(x,y) = \begin{cases} 0.5(1-\exp(z \div 10))(\cos(3\alpha)+1) & \text{if } |\alpha| < 60^\circ, \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

where z is the Euclidean distance between PPAs, and $\alpha = \tan^{-1}(y \div x)$.

The sum in equation (7) is taken over all other PPAs that are (a) located farther away from the population front than the PPA being evaluated, (b) located within the STS action zone, and (c) have a priority index P > 2.5 (Fig. 7). If a PPA is located in the intersection of several PPAs, then its priority index is reduced by the sum of effects of all these PPAs (Fig. 6). In essence, a PPA can decrease the priority index of other PPAs that are located closer to the infested area and are within this "shadow" of influence.

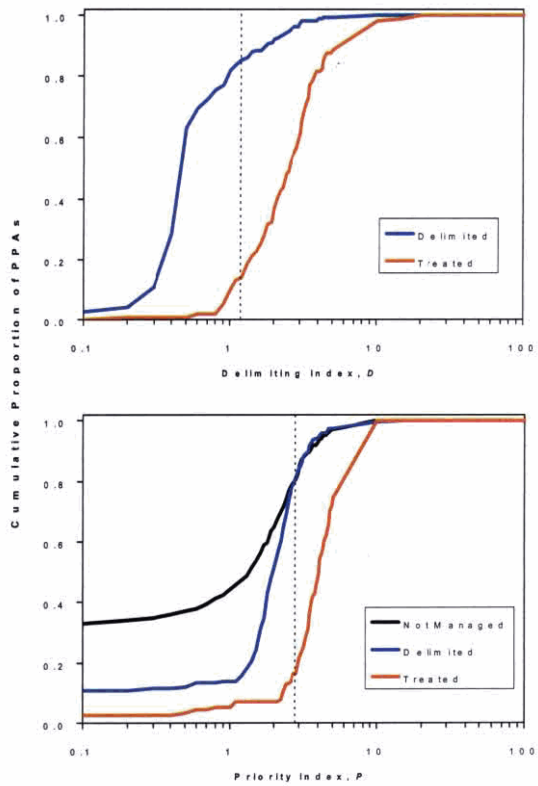


Fig. 8. (**A**). Cumulative proportion of PPAs that were actually delimited or treated in Virginia, West Virginia, and North Carolina in 1996–2000 over the delimiting index calculated by the Decision Algorithm. (**B**). The same relationship but for values of the priority index and including those PPAs that were left unmanaged. These two relationships were used to optimize the thresholds of each (vertical dashed lines).

Thresholds of the Delimiting and Priority

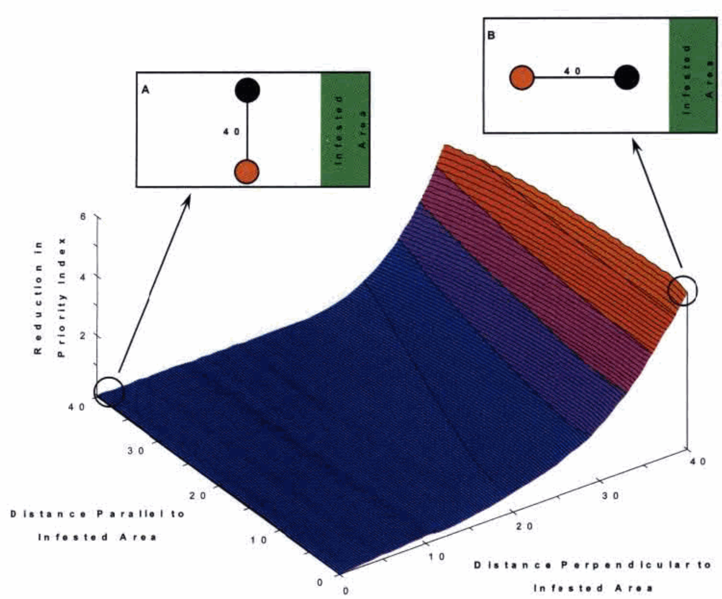


Fig. 7. The function w(x, y) calculates the reduction in the priority index depending on the distances measured perpendicular and parallel to the infested areas. For example, when two PPAs are aligned side-by-side (**A**), neither PPA influences the other and results in no reduction. However, when one PPA is aligned in front of the other (**B**), the priority index of the one closest to the infested area is reduced.

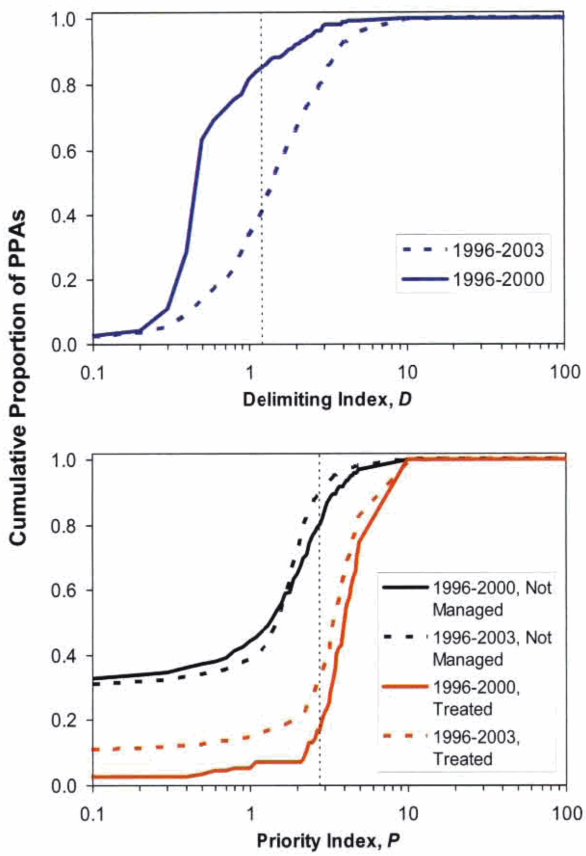


Fig. 9. Comparison of decisions for PPAs and values of the delimiting index (**A**) and priority index (**B**) using data from which thresholds were calibrated and optimized (1996–2000, solid lines), and how their performance currently measures (1996–2003, dashed lines).

Indices. Thresholds of the delimiting and priority indices for recommending a course of action were calibrated on the basis of the actual, implemented actions for PPAs from Virginia, West Virginia, and North Carolina from the STS Pilot Project during1996–2000, because the actions taken in these areas reduced spread by 60% over historical levels (Sharov and Liebhold 1998a, Sharov et al. 2002b). Frequency distributions were used to determine optimal thresholds for each index. The delimiting index was thus set at 1.2, which was successful in identifying >80% of PPAs that were actually delimited (Fig. 8). The priority index was set at 2.8, which had the dual effect of eliminating >80% of PPAs in which no treatment was implemented, while including >80% of PPAs in which treatment was implemented (Fig. 8). Furthermore, the threshold of priority index used in past decisions, in particular, has remained fairly stable to date across space and time despite its complexity. For example, when considering PPAs from 1996 to 2003 from all states in which a PPA has been identified (Iowa, Illinois, Indiana, Kentucky, Michigan, Minnesota, North Carolina, Ohio, Virginia, Wisconsin, and West Virginia, for a total of 5516 PPAs), this threshold still eliminates >80% of PPAs that are eventually not treated, while still including ≥70% of PPAs that are (Fig. 9).

Project Evaluation

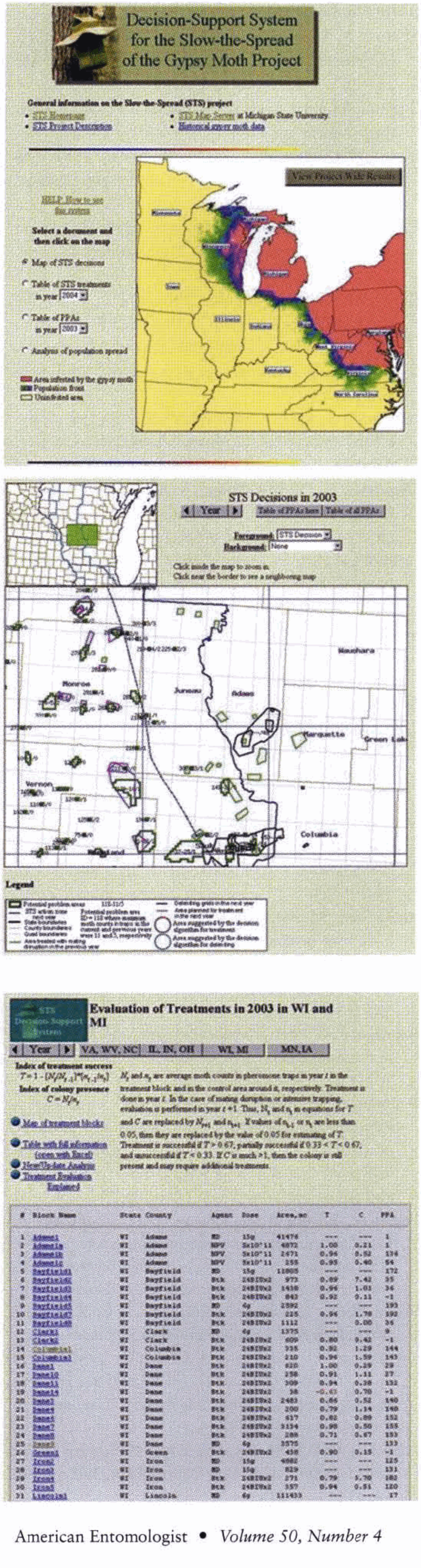
Two principle evaluation components are calculated by the Decision Algorithm and used to evaluate STS. The first calculates the rate of spread between consecutive years. The entire STS area is divided into subregions; for example, Wisconsin is partitioned into three subregions, north to south, to account for changes in climate. The first step in estimating the rate of spread is to delimit the boundaries of the estimated 1-, 3-, 10-, 30-, 100-, and 300-moth abundance thresholds using the "Best Cell Classification Method" (Sharov et al. 1995). For each subregion, the distance between each moth line in consecutive years (e.g., the distance between the 10-moth line in year *t* and *t+1*) is calculated, and then the distances for each of the six moth lines are averaged to determine the rate of spread. The rate of spread is then compared with the historical, pre-STS average of 20 km/yr to determine the reduction; STS has a target spread rate of 10 km/yr, or a 50% reduction.

The second component to the evaluation process is the evaluation of gypsy moth control treatments that are used in STS. The project primarily relies upon the use of mating disruption (disparlure) and *Bacillus thuringiensis* var. *kurstaki* (Berliner) against gypsy moth population in treated PPAs.

The Decision Algorithm calculates two indices to measure the success or failure of treatments. The first, called an Index of Treatment Success (Sharov et al. 2002a), is based on the philosophy of Abbott's formula (Abbott 1925) and uses data on population abundance in the PPA before and after treatment, as well the change in abundance in nearby, untreated areas that serve as a "control." In this manner, the change in abundance in the treated area is considered while adjusting for changes in the background population. For example, if treated populations in the PPA declined at nearly the same rate as those in the untreated areas, then the treatment would not be considered successful though from a management perspective, the goal in STS is still achieved. The second index, an Index of Colony Presence, is the ratio of abundance in the treated population to the background population. A primary goal of STS is to reduce colony population to the background level in the neighboring areas.

Linking the Output to a Web-Based Geographic Information System

During the gypsy moth trapping season (June–October), trap counts are submitted to a centralized STS Oracle database where data integrity checks are made. The Decision Algorithm is configured to automatically access the Oracle database and process the catch data three times a day. All PPAs are given a unique identification number so they can be traced throughout the survey season. The recommendations generated by the Decision Algorithm are automatically exported to the STS geographic information system (GIS) (implemented in ArcGIS) for use in mapping and decision making tools other than those in the Decision Algorithm.



The Decision Algorithm generates a series of web pages that can be used for browsing maps of trap locations, interpolated trap capture surfaces, phenological predictions, and recommendations (Fig. 10). Analyses of treatments are provided for each treatment block, and evaluation of spread rates in each region are provided in tables. These web pages exist for each year of trapping data at http://da.ento.vt.edu (Decision-Support System for the Slow-the-Spread Project 2004). The Decision Algorithm is currently implemented in the C++ language and runs on a dual-Xeon 2.0 GHz Dell Computer with 1 GB of RAM running under the Red Hat Linux V.8 operating system. Complete code documentation is available at http://da.ento.vt.edu/Documentation. The algorithm takes about 15 minutes for analysis, and then roughly 2 hours to generate GIF images that are uploaded to the web page (Fig. 10). The display of all trap data, analyses, and decisions for easy viewing on the web is a valuable asset for state participants to view their own data, and for the public to be aware of the program that is being implemented in their area.

Project Planning

Upon completion of final trap catch data uploading and quality control measures, results from the Decision Algorithm are used as a guide in the actual implementation of STS strategies. Delimiting and treatment blocks identified by the Decision Algorithm are discussed in each participating state through a series of "Road Shows." During these Road Shows, state representatives meet with USDA Forest Service personnel to discuss the decision-making process by reviewing each PPA and deciding which blocks will be delimited or treated during the following year. Map and reports generated by the Decision Algorithm are reviewed, and sometimes actions suggested by the algorithm are overridden, in part because of information about the presence of, for example, life stages and habitat. As a result of this human input, decisions can be modified if needed, for example, based on economical or ecological considerations. Also, the boundaries of the proposed action area are finalized, digitized, and then entered back into the Decision Algorithm.

The Decision Algorithm then processes these edited recommendations and generates a report comparing these recommendations with the final action that was decided during the road shows. In this report, errors and discrepancies in treatment or delimiting decisions are classified and sorted according to the priority index. In this manner, we merge the results from both a human and artificial intelligence perspective so that all decisions are made as objectively as possible across

The display of all trap data, analyses, and decisions for easy viewing on the web is a valuable asset for state participants to view their own data.

Fig. 10. Results of the Decision Algorithm are automatically generated and then uploaded to the World Wide Web (http://da.ento.vt.edu/) to facilitate the dissemination of information.

a large spatial scale, without ignoring real-world constraints.

Implications of the Slow-the-Spread Project

Results indicate that most treatments in the STS program have been successful; and that in most regions, the overall objective of the program (i.e., 50% reduction in spread rates) is being achieved (Sharov et al. 2002b). It is noteworthy that this is being accomplished in a program in which the bulk of the resources are allocated to monitoring (Mayo et al. 2003), and that treatments are conducted in relatively small areas using the most environmentally sound methods. The Decision Algorithm is used to mine through the voluminous quantity of pheromone trap data and incorporates rapid advances in technologies, particularly geospatial ones (e.g., GPS, GIS, spatial statistics) in support of areawide management of gypsy moth. The success of the program demonstrates the benefit of areawide integrated pest management in a variety of landscapes. Regardless of whether one agrees or disagrees with the costs and benefits of the STS project (Leuschner et al. 1996, Sharov and Liebhold 1998a, Mayo et al. 2003), this Decision Algorithm can be used as a template for the processing and analyzing large sets of spatially- and temporally-referenced data.

Acknowledgments

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Roles of the Primary Components to the Decision Algorithm Priority Index

Function	General Role
F1	Considers the population abundance in the PPA in the current and previous year
F2	Considers the distance of the PPA from the generally infested areas, or population front
F3	Considers the abundance in nearby, background populations
F4	Considers the effects other nearby PPAs may have on the PPA being evaluated

"What is it?" Answer.

This is the seventh tergite of the male (top) and female (bottom) *Hylurgus ligniperda* (Fabricius) (Coleoptera: Scolytidae). The top photograph shows the heavily sclerotized bands of the integument that lead to the plectrum (pick), which is used to strike the pars stridens (file), which is on the interior surface of the elytra. This "What is it?" photograph was submitted by David L. Mausel, Department of Entomology, Virginia Tech State University, 217 Price Hall, Blacksburg, Virginia Tech University 24061-0319.

If you have a photograph you would like to submit for consideration as a "What is it?" photo, then please e-mail it as a 300 dpi tiff to the editor at cdarwin@aol.com.

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Patrick C. Tobin is a Research Ecologist with the USDA Forest Service, Northeastern Research Station, 180 Canfield Street, Morgantown, WV 26505. His primary research interest is the study of the factors that influence the abundance of forest insect populations over spatial and temporal scales, and he chairs the Slow-the-Spread Project Technical Advisory Committee. **Alexei A. Sharov** is a staff Scientist with the Developmental Genomics and Aging Section at the National Institute on Aging/National Institutes of Health in Annapolis, MD. **Andrew A. Liebhold** is a Research Entomologist with the USDA Forest Service, Northeastern Research Station. **Donna S. Leonard** is with the ESDA Forest Service, Forest Health Protection in Asheville, NA, and is the Project Manager for Slow-the Spread. **E. Anderson Roberts**, is a Senior Research Associate with Department of Entomology, Virginia Tech University. **Mathew R. Learn** is a former Computer Programmer for the Slow-the-Spread Project, Department of Entomology, Virginia Tech University.