Chapter 32

Gypsy moth IPM

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Over the last 50 years, North American forests have been inundated by a multitude of alien pest invasions. Among these, noteworthy invaders include the hemlock woolly adelgid (*Adelges tsugae*), emerald ash borer (*Agrilus planipennis*), chestnut blight and Dutch elm disease. These species have greatly altered both the ecological and economic values associated with forests and their management, representing perhaps the most demanding challenge facing state and federal forest pest management personnel. In this chapter, we provide an overview of the gypsy moth (*Lymantria dispar*) problem and describe the various approaches to managing this species, which serve as a model system for understanding the management of non-indigenous forest pests.

32.1 Gypsy moth in North America

Gypsy moth was accidentally introduced to North America over 130 years ago, but it has spread relatively slowly, currently occupying less than one-third of its potential habitat in the eastern USA. It is possible to observe at any time areas where the species has not yet established, where introduced populations are occasionally eradicated, areas at the leading edge of the expanding range where concerted efforts are directed to slow its spread, and areas where the species has been established for many years and where considerable resources are expended to suppress defoliating populations. Because the gypsy moth has a dramatic and continuing impact on the public, this species has been the target for many intense research and management programs. Consequently, the technology being applied to manage this species is particularly advanced and thus elucidates the possibilities for managing other non-indigenous species.

The gypsy moth is native to virtually all temperate forest regions of Europe, Asia and North Africa. The northern limit of its range proceeds from southern Sweden and Finland through Europe and across Russia, and the southern limit begins in northern Morocco, Algeria and Tunisia and proceeds east to include all of the Mediterranean islands on a line through Israel, Iran, Central Asia and finally into China and Japan. Though many non-indigenous pests are considered to be innocuous species in their native ranges, the gypsy moth periodically causes outbreaks over much of Europe and Asia where it is regarded as a pest. The gypsy moth was first introduced to North America in 1868 or 1869 by Étienne Léopold Trouvelot, a French artist who was living in Medford, Massachusetts. Trouvelot was engaged in the amateur study of native silkworms and other silk-producing insects on his property when the gypsy

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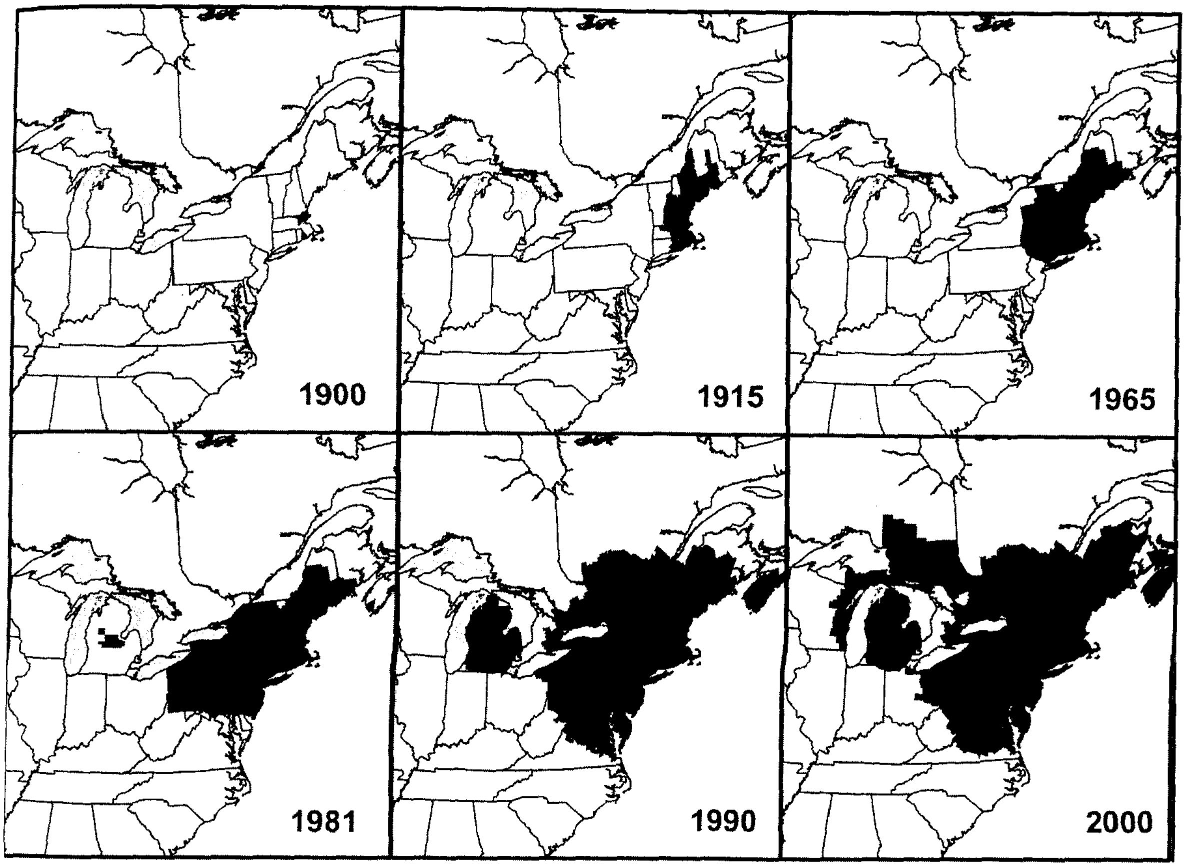

Fig. 32.1 Historical gypsy moth spread in North America (from Liebhold *et al.*, 2007).

moth larvae that he was cultivating escaped from containment (Forbush & Fernald, 1896; Liebhold *et al.*, 1989). About 20 years after the accidental introduction, larvae of the insect became so abundant and destructive on fruit and shade trees that it attracted public attention; the extensive defoliation and nuisance created by hordes of larvae prompted the state of Massachusetts to embark on an intensive program to eradicate the gypsy moth, an effort that ultimately failed. By 1912, infestations were detected in the neighboring states of Vermont, New Hampshire, Rhode Island and Connecticut. The current distribution of the species includes most of the northeastern USA and southeastern Canada (Fig. 32.1). Populations in the Great Lakes region originated from a secondary population that was accidentally introduced into Michigan in the 1960s.

The relatively slow spread of the gypsy moth in North America can be attributed to the fact that the female moths are incapable of sustained flight. Through most of Asia and portions of Eastern Europe, gypsy moth females are capable of extended flight. But in Western Europe, though female moths have fully developed wings, they are incapable of directed flight. Apparently Trouvelot's population was collected from France where females are flightless. Adults emerge, mate and oviposit in mid to late summer. Egg masses, which may contain 50–1000 eggs, are laid on tree trunks, branches, as well as objects on the forest floor such as logs, stumps and rock outcroppings. Populations remain in the egg stage throughout winter and are well protected from extreme conditions by an obligate diapause. Eggs hatch in the spring and young larvae engage in wind-borne dispersal on silken threads, which facilitate the redistribution of local populations. Upon locating suitable hosts, larvae feed and complete five (male) or six (female) instars before pupating. In low- to moderate-density populations, late-instar larvae exhibit diel behavior whereby they feed at night and descend from the tree canopy at dawn, resting in cryptic sites on the tree or on the forest floor.

32.1.1 Host range

Gypsy moth larvae are polyphagous and are known to feed on hundreds of tree species. Late instars are more polyphagous than early stage larvae. Completion of early larval development is largely restricted to oak (*Quercus*), poplar (*Populus*), willow (*Salix*) or larch (*Larix*) in North America. Liebhold *et al.* (1995) provide a comprehensive list of preferred species collated from various sources in the literature. As a result of the more specific host requirements by early instars, outbreaks generally do not develop in stands that are composed of less than 20% of these preferred genera. In North America, most such susceptible forests are dominated by oak. Outbreaks are most frequent in dry sites such as on ridge top stands characterized by poor, shallow soils, rock outcroppings, and preferred species such as chestnut oak.

32.1.2 Population dynamics

During outbreaks, populations reach extremely high densities (e.g. egg mass populations exceeding 1000/ha) such that they may consume most or all of the foliage on trees prior to reaching the last instar. Gypsy moth outbreaks are common events both in the species' native and alien ranges, and the temporal patterns of outbreaks are similar. Most populations exhibit periodicity with outbreaks recurring every eight to 12 years (Johnson *et al.*, 2005). It has also been noted that in the highly susceptible sites, however, the very dry sites described previously, populations exhibit a "doubled" frequency such that outbreaks recur every four to six years (Johnson *et al.*, 2006). Despite considerable research devoted to gypsy moth population dynamics (Elkinton & Liebhold, 1989), there remains considerable uncertainty about the causes of gypsy moth population oscillations. Perhaps the most plausible explanation advanced to date is that by Dwyer *et al.* (2004) who hypothesized that periodic oscillations are the combined result of strongly density-dependent mortality caused by a nucleopolyhedrosis virus at high densities coupled with predation by generalist small mammal predators at low densities.

Of course these periodic oscillations are not precise and at any one location; outbreaks rarely recur with regularity. However, there is considerable synchrony in the development of outbreaks over large areas and regional defoliation levels exhibit statistical periodicity (Peltonen *et al.*, 2002; Johnson *et al.*, 2005). Since 1924, over 35 million ha of forest land in North America have been defoliated. The extent of outbreaks, measured by the total forested area defoliated, has worsened dramatically as the area infested has increased. Annual defoliation exceeding 500 000 ha occurred in 20 years between 1970 and 1995, a period when the distribution of gypsy moth populations expanded significantly in the South and West. Over 5.2 million ha were defoliated in 1981, 3 million ha in 1990. Over the last decade (1997–2007), the area of annual defoliation in North America has declined slightly, coinciding with the appearance in 1989 of a previously unknown fungal pathogen, *Entomophaga maimaiga*, which has caused extensive larval mortality in gypsy moth populations throughout their current range. Unfortunately, there is little certainty that this pathogen has significantly impacted regional defoliation levels; nor is it known how it may affect gypsy moth populations in the future because fungal epizootics are closely associated with specific environmental conditions (i.e. rainfall, high humidity).

32.1.3 Losses due to defoliation

The effects of defoliation on trees is highly variable and depends on both the frequency of defoliation, the condition of the stand prior to defoliation, and the presence of other factors that influence tree growth (Twery, 1991). For example, considerable tree mortality can occur following only one year of heavy defoliation in trees in poor crown condition, particularly if the defoliation occurs in a drought year. In other stands, trees in good condition may be able to survive after one or more years of total defoliation. Maximum tree mortality usually occurs three to five years after an episode

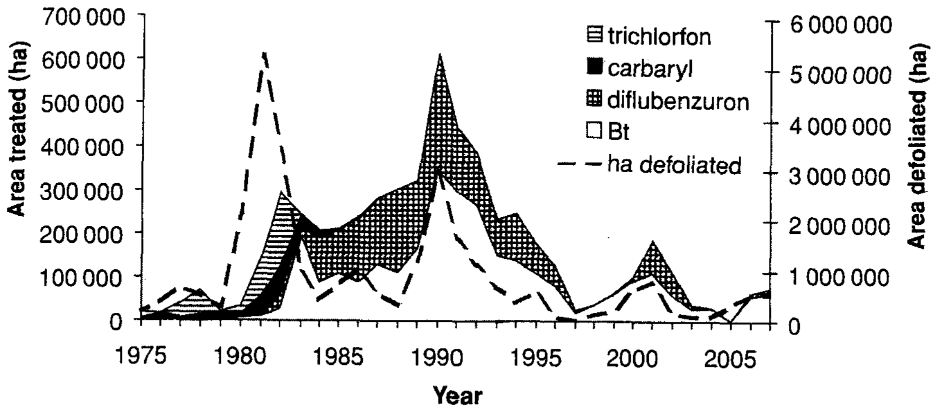

Fig. 32.2 Historical suppression of gypsy moth populations via aerial application of pesticides, and defoliation (from US Department of Agriculture, 2007).

of defoliation and is usually caused by secondary agents such as the pathogenic fungus *Armillaria mellea* and the wood-boring beetle *Agrilus bilineatus*, which readily attack severely weakened trees.

Probably the most comprehensive analysis of socioeconomic impacts of gypsy moth outbreaks was provided by Leuschner *et al.* (1996) who concluded that impacts of tree mortality on timber values were dwarfed by the much greater residential costs associated with gypsy moth defoliation and nuisance. The area currently invaded by the gypsy moth encompasses about 864 475 km^2, an area that coincides with the most heavily populated region in the USA. Therefore, the interaction between the public and the gypsy moth has been frequent and, at times, intense. During the outbreak phase, when the density of gypsy moth populations can increase 100-fold in successive years, larvae can pose a hazard to human health and disrupt the public's enjoyment of outdoor activities. In extreme situations such as the severe outbreak of 1981, there were hundreds of documented reports where individuals suffered severe allergenic reactions to airborne hairs and scales that originated from gypsy moth life stages. Further, defoliation of trees in residential areas and the possibility of their loss detract from aesthetic and property values such that homeowners are willing to go to great expense to protect their trees and combat nuisance populations of larvae.

32.2 Suppression

Given the propensity for gypsy moth populations to periodically reach high levels and the general adversity of the public towards these outbreaks, there has been a long history of direct control using ground and aerial applications of pesticides to suppress high-density populations. In 1956, 222 000 ha were aerially sprayed with DDT followed by 1.2 million ha in 1957. Although this spraying was highly effective in eliminating gypsy moth populations and preventing defoliation, the use of DDT was phased out in 1958 because of public concern about residues on food and feed crops and adverse effects of DDT on species of beneficial organisms, fish and wildlife. It was replaced by other broad-spectrum synthetic pesticides such as carbaryl and trichlorfon. However, the use of these products eventually declined because of their negative impacts on species of parasitoids and bees (Fig. 32.2). Diflubenzuron (Dimilin®), an insect growth regulator, was registered by the US Environmental Protection Agency (EPA) in 1976 for use against the gypsy moth and was extremely effective against all larval stages at very low dosages. Despite its efficacy, its use has been somewhat limited because it is toxic to aquatic invertebrates and crustaceans and thus cannot be applied near bodies of water or in areas where surface water is present.

Beginning in the 1970s, research and methods improvement was accelerated towards developing microbial pesticides for use against the gypsy moth, specifically *Bacillus thuringiensis* (*Bt*), to address the public's concerns about the environmental effects of aerially applied chemical pesticides. Although the pathogenicity of *Bt* against gypsy moth was well known, its efficacy in the field was erratic until a more potent strain called *Btk* (*Bacillus thuringiensis* variety *kurstaki*) was isolated in 1970. Since then there has been a dramatic improvement in commercial *Btk* formulations so that it is currently one of the most widely used materials in gypsy moth suppression programs. Gypchek, the naturally occurring gypsy moth nucleopolyhedrosis virus, was one of the first viral pesticides registered in 1978 by the EPA. Because it is produced in vivo, the process is labor intensive and more costly than conventional pesticides, thus only 5000–8000 ha equivalents are produced annually. Because it is specific only to gypsy moth, Gypchek is highly sought after for use in environmentally sensitive habitats where application of broad spectrum products is not acceptable.

Most efforts to suppress outbreak gypsy moth populations are carried out as part of the Cooperative US Department of Agriculture Forest Service–State Gypsy Moth Suppression Program which facilitates suppression of gypsy moth populations on federal, state and privately owned land. The cost of suppression is typically shared by the Forest Service, state/local governments and the landholder, though the cost share varies considerably among states. Participation is voluntary and proposals for funding must meet established criteria and include treatments approved by the Federal Environmental Impact Statement for gypsy moth. Monitoring plays an important role in any pest management program and is especially critical in gypsy moth suppression. Traditionally, treatment decisions are driven by counts of overwintering egg mass populations (Ravlin *et al.*, 1987; Liebhold *et al.*, 1994). Several statistical models are available which predict defoliation based upon egg mass densities (Gansner *et al.*, 1985; Liebhold *et al.*, 1993) and most states use egg mass density thresholds (e.g. 100 egg masses/ha) as part of their decision-making criteria for suppression. Unfortunately, the relationship between pre-treatment egg mass density and subsequent defoliation is not precise and this can lead to substantial error in predicting defoliation. Part of the uncertainty in these predictions is due to the high sampling error encountered in estimating egg mass densities (Liebhold *et al.*, 1991); additionally, the collapse of high-density populations is difficult to predict due to the complexity of the trophic interactions between gypsy moths and their natural enemies, such as the nucleopolyhedrosis virus and *E. maimaiga*. The uncertainty in these predictions detracts from the efficiency of large-scale suppression programs (Liebhold *et al.*, 1996; Weseloh, 1996).

32.2.1 Eradication

The gypsy moth currently occupies less than one-third of the forested region in the USA that is capable of supporting a gypsy moth outbreak (Morin *et al.*, 2004). As the gypsy moth slowly expands its range, life stages are occasionally transported accidentally well beyond the expanding population front and these are capable of founding new isolated populations. It has long been recognized that the tendency for larvae to pupate and for emerging female gypsy moths to oviposit in cryptic locations often results in accidental movement of egg masses over long distances via commodities, e.g. nursery stock, household goods or recreational vehicles. A federal domestic quarantine was enacted in 1912 to minimize the rapid expansion of the insect to the remainder of eastern USA and Canada, and still in effect today, is credited with reducing the accidental long-range transport of gypsy moth life stages on regulated commodities.

Unfortunately, domestic quarantines are rarely perfect and thousands of gypsy moth life stages are probably transported into uninfested regions every year. For example, California recorded more than 2000 interceptions of gypsy moth life stages (mainly egg masses) from recreational vehicles and shipments of household goods that originated from 14 states and Canada between 1980 and 1990, a period of high population density in the eastern USA (McFadden & McManus, 1991). While most of these individuals do not successfully colonize new areas, populations frequently arise in favorable habitats outside of the generally infested region. As part of the Cooperative Agricultural Pest Survey (CAPS), thousands of gypsy moth pheromone-baited traps are placed annually in uninfested states in order to detect incipient populations (US Department of Agriculture, 2006). These traps are highly efficient, and consequently, each year, there are many locations in the uninfested area where males are detected. The typical response to new detections is to deploy more traps in the following year in and around the site of initial detection at a rate of 40/km^2 in order to (1) determine that the population has persisted and (2) spatially delimit the population. Only about one-tenth of populations that are initially detected survive the following year because of Allee and random effects that naturally cause extinction (Liebhold & Bascompte, 2003); therefore it is important to confirm the persistence of populations prior to any attempt to eradicate them. Once a population has been adequately delimited, multiple aerial applications of pesticides (typically *Bt*) are applied in order to achieve eradication. Following these treatments, pheromone traps are once more deployed to confirm the presence/absence of gypsy moth populations. Any evidence of residual populations is followed by cycles of delimitation/treatment over subsequent years until no male moths are trapped. While most current eradication programs utilize aerial applications of *Bt*, a mass trapping is also carried out in some locations when the area infested is small and well delineated. In these cases, pheromone traps are deployed at rates of 9–25 traps/ha.

The above description of gypsy moth eradication efforts is based upon the assumption that the population detected is of typical European genetic origin. In the USA, trapped males detected from new locations far removed from the infested area, particularly from the west coast, are routinely subjected to a DNA analysis in order to evaluate the genetic origin of the population. In recent years, there have been several incidents in which gypsy moth life stages of Asian origin have been accidentally transported to ports on the east coast of the USA and western USA and Canada. The current US Department of Agriculture policy for response to the detection of Asian strains of the gypsy moth demands a more rapid and aggressive response than that employed for detection of the European strain. Instead of waiting a year for delimiting populations, any detection of Asian individuals is typically followed by multiple aerial applications of *Bt* in the following year.

Though eradication is sometimes a controversial subject because of some well-publicized failures to eradicate certain alien species (Myers *et al.*, 2000), the gypsy moth is a good example of a species for which eradication is almost always successful when isolated populations are discovered and delimited. Much of the success in gypsy moth eradication can be attributed to the low cost yet high efficiency of utilizing pheromone traps as a first line of defense to detect and delimit incipient populations.

32.2.2 Containment

Given the immense public concern about gypsy moth over the last century, the concept of containing its spread has arisen repeatedly. In 1923, federal and state officials began a program to halt gypsy moth spread by establishing a barrier zone that encompassed more than 27 300 km^2 and extended from Canada to Long Island along the Champlain and Hudson River valleys. The territory east of this zone was treated by the individual states while infestations within the zone were eliminated by joint state and federal actions using mainly chemical and mechanical methods. The barrier zone became generally infested by 1939 and the effort was terminated in 1941. Although this program failed to stop the spread of gypsy moth, it has been credited with slowing the rate of spread (Liebhold *et al.*, 1992) despite the fact that only labor-intensive methods for control were available during that period.

Gypsy moth populations in North America are slowly expanding their range and while it is probably impossible to stop this spread, slowing the rate of spread is a more realistic goal. Leuschner *et al.* (1996) performed an economic analysis that indicated that expenditure of funds to slow gypsy moth spread would result in net savings, primarily because of the reduction of funds and resources that would be required to suppress outbreak populations in subsequent years should the insect become established in new areas. As a result, the gypsy moth Slow the Spread (STS) program was initiated in 1999 as a cooperative

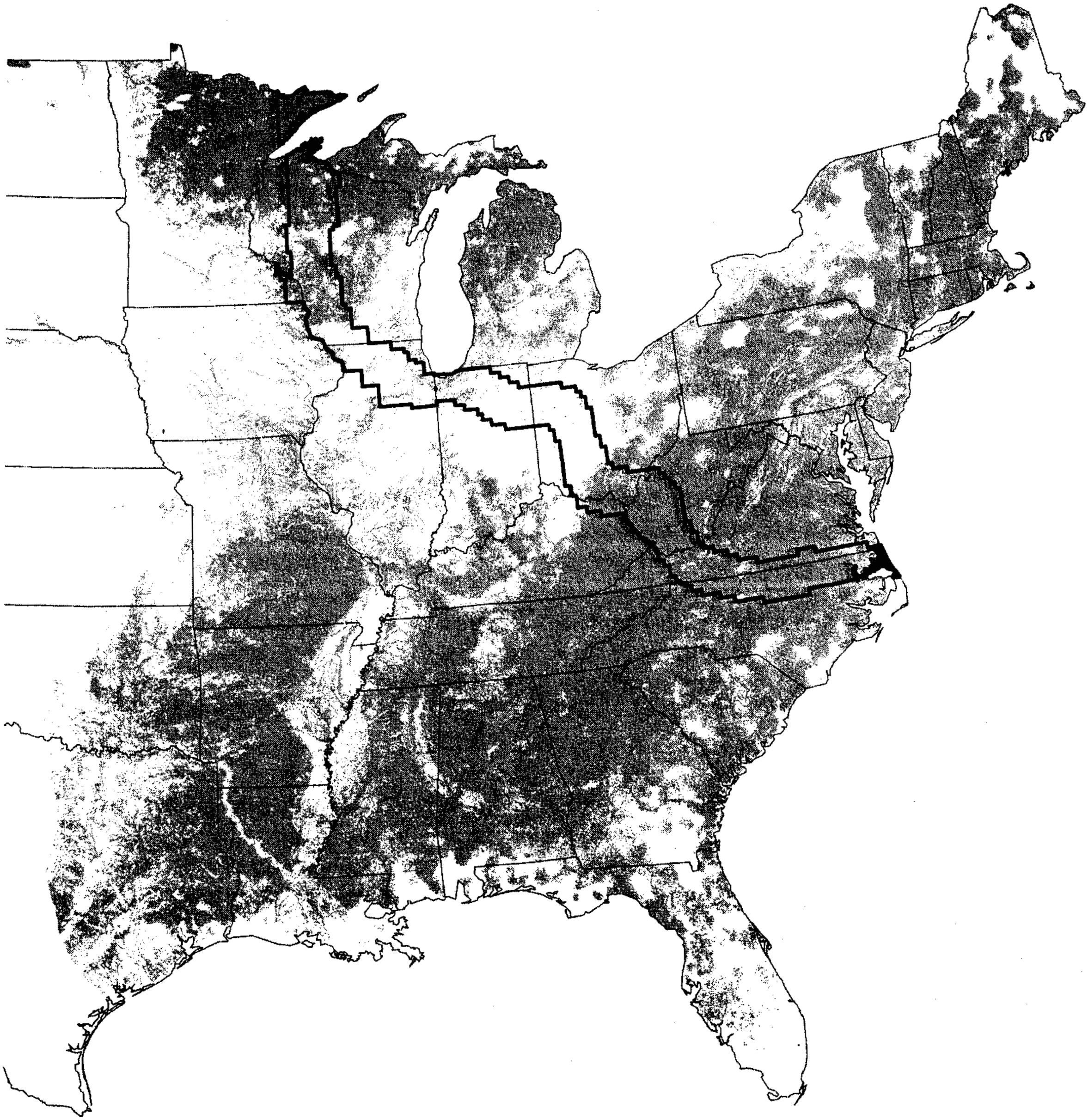

Fig. 32.3 Location of the gypsy moth "Slow the Spread" action area, a ~100-km band along the expanding gypsy moth population front. Areas shaded in gray represent forested areas that are susceptible to defoliation as predicted by the presence of >2 m^2/ha basal area of preferred gypsy moth hosts estimated from forest inventory data (Morin *et al.*, 2004).

federal/state program located along the expanding population front (Sharov *et al.*, 2002) (Fig. 32.3). The program is based upon the scientific finding that gypsy moth spread is exacerbated because isolated colonies form ahead of the advancing population front usually as a result of accidental movement of life stages; over time, these colonies grow, coalesce and thereby promote their expansion (Sharov & Liebhold, 1998). The strategy in STS is to locate and eradicate these isolated colonies before they expand and coalesce. This is accomplished by annually deploying over 100 000 pheromone-baited traps in a 2-km grid along a 100-km band ranging from northern Wisconsin to coastal North Carolina. When colonies are detected within this grid, a more intensive 1-km grid is deployed in the subsequent year to better delimit the population; finally in the third year, the colony is treated (Fig. 32.4). Most colonies are treated using mating disruption which is accomplished by aerially applying a formulation of pheromone flakes. Extensive research has demonstrated that mating disruption is not effective when trap captures exceed 100 males/trap; therefore colonies that exceed this population level are usually treated with aerial applications of *Bt*. Results to date indicate that the program has been successful at reducing rates of spread by well over 50% (Tobin & Blackburn, 2007).

The STS program relies heavily on new technologies and serves as a model system for managing alien invasions. Trap locations are recorded via GPS technology and all data are assembled in a GIS that is used to process trap count data, which is the basis for decision making, for planning treatment areas and for web delivery of summary information (Tobin *et al.*, 2004). Actual costs associated with applying treatments comprise less than 50% of the ~$US 12 million that the program costs annually. To put the cost of this program in perspective, it's important to note that in the outbreak of 1990, aerial spraying of biological and chemical pesticides through the cooperative federal–state suppression program was conducted on 0.65 million ha at an estimated cost of $US 22.5 million. In addition to the environmental concerns associated with spraying, expenditures by the public for spraying pesticides on private forested land and in urban residential areas were astronomical.

32.3 Conclusions

The prognosis for the gypsy moth and its associated impacts in the USA is not encouraging. Based on an analysis conducted by Liebhold *et al.*, (1997), there are 19 states currently not infested by gypsy moth that contain more than 1 million ha of forests that are classified as susceptible to gypsy moth defoliation and damage. This suggests that costs associated with managing this pest will continue to escalate which is a strong justification for slowing the spread of the pest. In addition to the benefits that will accrue from delaying

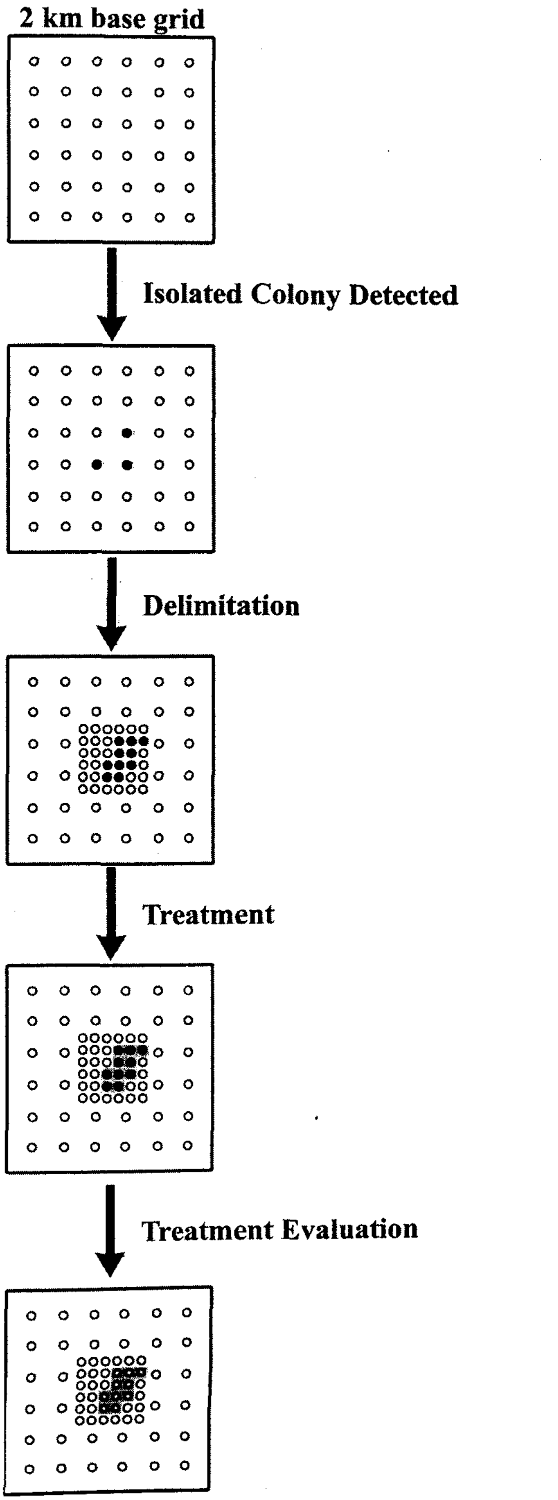

Fig. 32.4 Diagrammatic representation of the gypsy moth "Slow the Spread" strategy (modified from Tobin & Blackburn, 2007).

impacts and costs associated with management programs, STS, like most IPM programs, is based on a strong foundation of intensive monitoring and deploys only environmentally acceptable treatments when such actions are deemed necessary. Additional information on the strategies discussed in this chapter can be found in the programmatic Environmental Impact Statement *Gypsy Moth Management in the USA: A Cooperative Approach* (US Department of Agriculture, 1995).

Acknowledgements

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