Chapter 1

Lymantria dispar and Progression of Management Strategies in the United States

Tom W. Coleman

Abstract

For more than 150 years, the exotic defoliator spongy moth, *Lymantria dispar* L. (Lepidoptera: Erebidae, formerly known as the "gypsy moth"), has impacted forests and been a nuisance to residents in the eastern United States. Management of this non-native, invasive species dates back to the late 1800s, and more recent eradication and suppression techniques have evolved from intensive, tedious management actions to integrated pest management programs that are coordinated by state and federal agencies. Five previous management programs dating from 1923 to 1999 have laid the framework for the current *L. dispar* management program. Specifically, three integrated pest management programs located in Maryland and the southern Appalachian Mountains developed the program structure and management actions used in the National Slow the Spread Program, which represents the main strategy of U.S. Department of Agriculture's National Spongy Moth Management Program.

Keywords: *Bacillus thuringiensis* var. *kurstaki,* defoliator, gypsy moth, integrated pest management, invasive insect, mating disruption, spongy moth

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BACKGROUND

Lymantria dispar L. (Lepidoptera: Erebidae), has been referred to by numerous common and scientific names since its initial species description in 1758 by C. Linneaus (Fig. 1). The literal translations of its common names in various languages include apricot-spinner, big head moth, brown arches, common caterpillar, dancing moth, dancing poison moth, deciduous nun moth, disparate silkmoth, dissimilar bombyx, dissimilar nocturnal-moth, dissimilar spinner, forest wool butterfly, fungus-caterpillar, fungus moth, fungus-spinner, garden nun moth, great fungus-caterpillar, great-head, great-head bear, great-head spinner, gubar moth, gypsy butterfly, gypsy moth, hairy caterpillar of cork, hairy lizard of the holm oaks, hairy oak caterpillar, hairy oak moth, leaf nun, large-headed nun, prairie moth, rose-spinner, silkspinner, silkworm unpaired, sponge knitter moth, spongy moth, spongy silk moth, stem caterpillar, stem-moth, thick-head, thick-headed bear, tree-caterpillar, two-fold, uneven moth, and zig-zag moth, and all make reference to its larval and adult appearance, behavior, and host preference (Forbush and Fernald 1896, Pogue and Schaeffer 2007). These names originate from the many countries across its native and introduced regions.

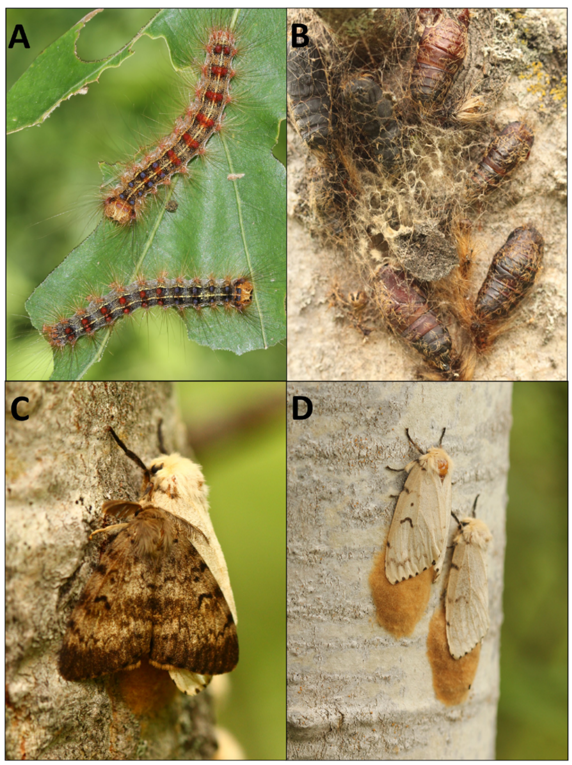

Figure 1.—Life stages of *Lymantria dispar:* (A) late instar caterpillars, (B) male and female pupae (note the smaller male pupa), (C) adult male and female mating, (D) females laying egg masses) of *Lymantria dispar* collected in the United States. (Photographs by T.W. Coleman, USDA Forest Service)

The species name has also undergone numerous revisions [*Palaena (Bombyx) dispar* 1758 Linn., *Laria dispar* 1801 Schrank, *Liparis dispar* 1810 Ochsenheimer, *Porthetria dispar* 1822 Hubner, *Ocneria dispar* Studinger 1822, *Hypogymna dispar* 1829 Stephens] (Forbush and Fernald 1896) prior to *Lymantria dispar* and subsequently *Lymantria dispar dispar* Linnaeus, distinguishing it from the Asian subspecies, *Lymantria dispar asiatica* Vnukovskij, and other Asian variants. *Lymantria dispar* remained in the genus *Porthetria* until it was returned to the genus *Lymantria* in the 1970s. Linneaus aptly named the species because the roots of the binomial name further align with its behavior [*lyma* (Greek) = "destruction, filth"] and sexually dimorphic adult stage [*dispar* (Greek) = "unequal, unlike"] (Borror 1960, Morwood 1990). The numerous common and species names also make reference to the ubiquitous nature and impact *L. dispar* has had on people throughout its native region, which encompasses regions throughout Europe, North Africa, central Asia, and east Asia including the Russian Far East (Giese and Schneider 1979, Pogue and Schaefer 2007). The impact and nuisance from *L. dispar* continue in its introduced region of North America. However, the common name of gypsy moth can be offensive to some groups, so is no longer recognized as the common name in the United States. In 2022, the Entomological Society of America adopted spongy moth as the new common name for *L. dispar*.

An accidental release of *L. dispar* in 1868 or 1869 by Étienne Léopold Trouvelot, a French artist, amateur entomologist, and astronomer with an interest in rearing silk moths, introduced the non-native species into the yard behind Trouvelot's home in Medford, Massachusetts (Forbush and Fernald 1896, Liebhold et al. 1989). Approximately 12 years later, the first report of defoliation and nuisance of caterpillars came from people living in Trouvelot's neighborhood and thus began the first large-scale eradication attempt against *L. dispar* and the start of a long history of *L. dispar* management in the United States. The U.S. Department of Agriculture (USDA) and state partners have successfully coordinated eradication efforts in 26 states since 1967, with the largest acreages treated in Wisconsin, North Carolina, Oregon, Utah, Tennessee, and Arkansas (Epanchin-Niell et al. 2021, Hajek and Tobin 2009, USDA FS 2021b), ultimately restricting the distribution of the population to 20 states in the eastern United States (Fig. 2). Since the early 1990s, an international program has been implemented to monitor east Asian *L. dispar asiatica* populations in an attempt to track introductions to North America (Mastro et al. 2021).

LIFE HISTORY

Lymantria dispar is univoltine, progressing from egg to larva to pupa and finally to adult (Fig. 1). Details on its biology and life history can be found in Doane and McManus (1981). Egg embryonation occurs shortly after oviposition, but larvae remain inside the egg chorion through the winter until spring, when hatch occurs. A chilling period and subsequent incubation period are needed for egg hatch (Giese and Casagrande 1981, Gray et al. 1991), which is synchronized with preferred host leaf expansion and can occur from April to May in eastern North America (Leonard 1981, Nealis and Erb 1993). First instar larvae can disperse short distances by "ballooning" on silk threads to surrounding areas (McManus and Mason 1983). Larvae progress through five to six instars in approximately 6 to 8 weeks and can be differentiated by head capsule width and coloration (Jobin et al. 1992). An instar feeds for 7 to 10 days before molting. Late instar caterpillars seek protected areas to pupate, usually under tree branches, logs, rocks, bark cracks, leaf

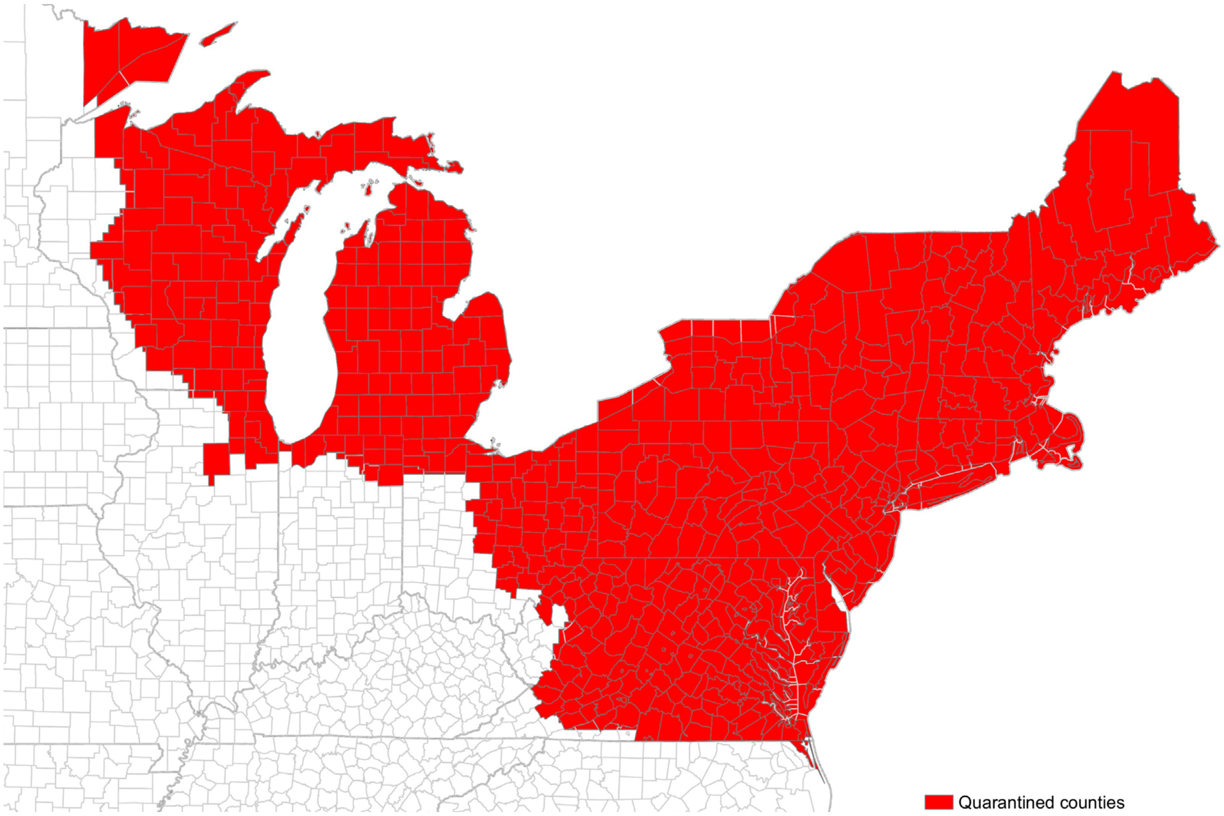

Figure 2.—*Lymantria dispar* is quarantined in 20 U.S. states. Counties are quarantined by local state agencies and USDA Animal and Plant Health Inspection Service.

litter, and human-made structures. Pupal development can last for 14 to 17 days before adult moth eclosion. Male moths commonly emerge 1 to 2 days prior to females and fly primarily from late morning into late afternoon, with a second, smaller crepuscular flight (Odell and Mastro 1980, Tobin et al. 2009). Adult moths do not feed and commonly live for about a week. Male moths can be trapped from late May to September throughout the moth's distribution in North America (Leonard 1981, Nealis and Erb 1993). The flightless females mate and subsequently lay eggs in a single mass near their pupal resting site, which is covered with buff-colored hairs from their abdomen. As a result, egg masses can be found on various items (e.g., tree branches and stems, rocks, walls, household articles, vehicles) and can contain a few hundred to a thousand eggs, facilitating the moth's capacity to travel and establish in other areas[1] (Fig. 3). Counts of egg mass densities in fixed-radius plots [e.g., 0.16 ha (1/40th acre)] may be the best tool to predict population densities, level of defoliation the following year, and, if necessary, additional management actions (Gottschalk 1993, Liebhold et al. 1994, Wilson and Fontaine 1978).

HOST SPECIES AND IMPACT

Lymantria dispar is extremely polyphagous and can feed on more than 300 tree and shrub species, which has likely contributed to its ability to establish and spread across various landscapes (Liebhold et al. 1995b). In North America, *L. dispar* larvae prefer feeding

[1] See Walter and Liebhold (2023) in this report for additional discussion about natural and human-assisted spread of *L. dispar* in the United States.

Figure 3.—A collection of *Lymantria dispar* adults and their egg masses during an outbreak in northern Michigan. (Photograph by T.W. Coleman, USDA Forest Service)

on oaks (*Quercus* spp. L.), poplars (*Populus* spp. L.), some birches (*Betula* spp. L.), apples (*Malus* spp. Mill.), sweetgum (*Liquidambar styraciflua* L.), basswoods (*Tilia* spp. L.), hawthorns (*Crataegus* spp. Tourn. *ex* L.), and willows (*Salix* spp. L.) in North America. Liebhold et al. (1995a) and USDA FS and APHIS (2012a) provide an extensive host list of susceptible, resistant, and immune species. First instar larvae require susceptible host species to survive, whereas later instar larvae can feed on susceptible and immune host species. Immune host species will escape high levels of herbivory even during high population pressure.

Since the 1920s, cumulative defoliation attributed to *L. dispar* has surpassed 39 million hectares with over 5.2 million hectares defoliated in a single year (1981), impacting all land ownerships (Figs. 4 and 5) (USDA FS 2021a, USDA FS 2021b, Williams 1982). *Lymantria dispar* populations progress through four phases (innocuous or endemic, release, outbreak, and decline) and can remain at endemic levels for several years. Mortality caused by small mammals and introduced parasitoids and predators contribute to sustaining populations in the endemic phase but have little effect on controlling larger population densities (Elkinton and Liebhold 1990). During the release phase, populations can build to high levels for 1 or more years then reach outbreak levels that can persist for 1 to 3 years before declining and returning to endemic levels. At a regional scale, outbreaks exhibit a statistical periodicity with 5 to 10 years between outbreaks (Johnson et al. 2005). Two pathogens, *Entomphaga maimaiga* Humber, Shimazu, and R.S. Soper (Entomophthorales: Entomophthoraceae) and *L. dispar* nucleopolyhedrosis virus (NPV), regularly contribute to the collapse of outbreaks. In the past 10 years, outbreaks and high levels of defoliation have occurred in 2021 in Maine, Maryland, Massachusetts, Michigan, New Jersey, New York, Pennsylvania, Vermont, and Ontario, Canada; in 2010 and from 2019 to 2021 in Michigan and Pennsylvania; from 2013 to 2015 in Pennsylvania and New York; from 2015 to 2017 in Connecticut, Massachusetts, and Rhode Island; from 2015 to 2016 in West Virginia; and from 2015 to 2018 in Virginia. During these outbreaks, defoliation ranged from tens of thousands to hundreds of thousands of hectares annually (USDA FS 2021). Low and moderate levels of defoliation can injure trees, reducing radial growth, reducing the amount and size of leaves the following year, causing crown dieback, killing fine roots, and inducing epicormic shoots on injured trees (Gottschalk 1993). Tree mortality often results after several consecutive years of severe defoliation (>75 percent) and tends to increase rapidly during the second year after defoliation (Fig. 6) (Davidson et al. 2001). Defoliation from *L. dispar* occurs early in the growing season, and although heavily defoliated trees can often refoliate in the same season, doing so is energetically costly and can quickly deplete a tree's resources. Forest stands with a higher proportion (>50 percent) of oak species (e.g., chestnut oak, *Q. prinus* Willd. and white oak, *Q. alba* L.), abundant refuges for larvae, unfavorable habitat for small mammals, and those that are located on poorer sites often experience the highest levels of tree mortality (Gottschalk 1993, Herrick and Gansner 1986, Houston and Valentine 1977). In the northeastern United States, susceptible, or favored, host and oak species experienced higher defoliation and tree mortality following a *L. dispar* outbreak (Davidson et al. 1999). Trees with intermediate and suppressed crowns and poor crown conditions have higher mortality rates compared to dominant canopy trees (Campbell and Sloan 1977, Campbell and Valentine 1972). As defoliation intensity, duration, and frequency increase, tree mortality likewise increases (Davidson et al. 1999), but stands with greater tree species diversity reduced the impact of *L. dispar* defoliation. Pines, *Pinus* spp. L., that experienced high levels of defoliation (81 to 100 percent) succumbed following a single bout of injury (Baker 1941). Coniferous species, including pitch pine, *Pinus rigida* Mill., white pine, *P. strobus* L., red pine, *P. resinosa* Sol. Ex. Aiton, and spruce, *Picea* spp. Mill., are often consumed by late instar caterpillars, which will feed on old and new foliage. A single year of severe defoliation can cause mortality of these conifer species. Trees weakened by drought, late spring frosts, secondary insects and diseases, and other stressors will succumb to high levels of defoliation often several years after an outbreak has subsided (Campbell and Sloan 1977, Campbell and Valentine 1972, Davidson et al. 2001, Gansner and Herrick 1984, Gottschalk and MacFarlane 1992).

Figure 4.—Defoliation caused by the *Lymantria dispar* during an outbreak in Wisconsin. Note the varying levels of defoliation with several areas of severe injury (brown coloration). (Photograph by M. Roberts, USDA Forest Service)

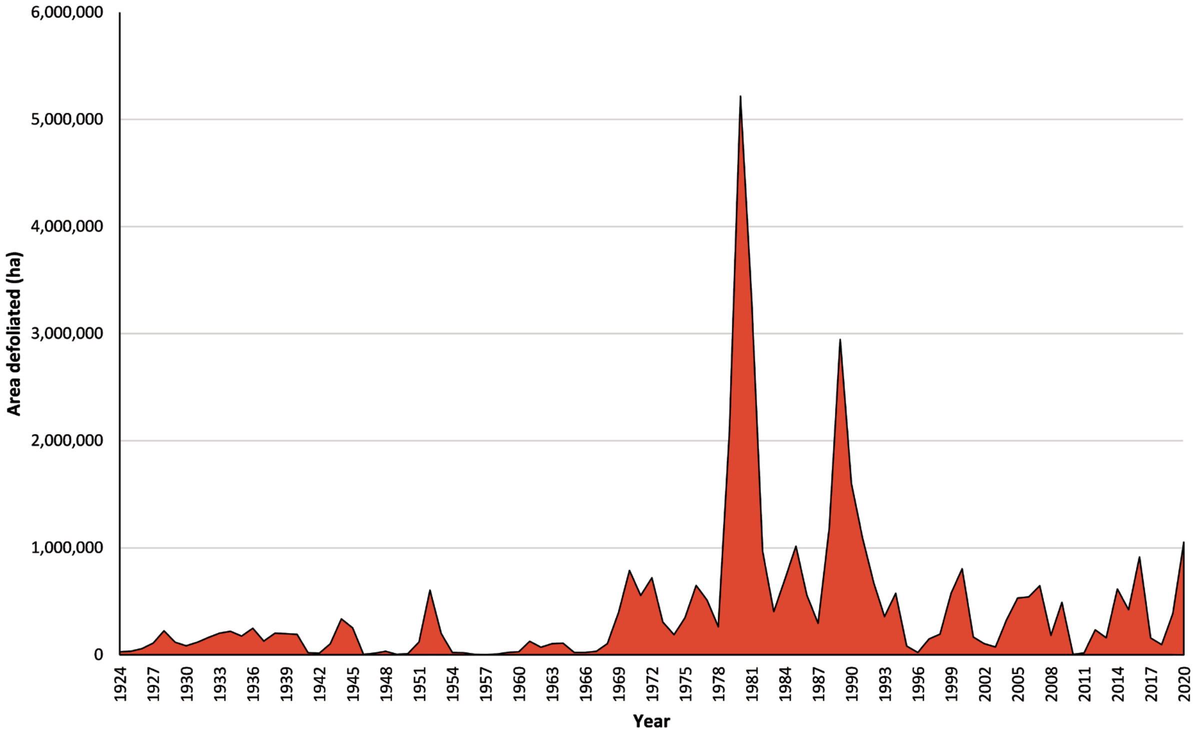

Figure 5.—*Lymantria dispar* defoliation mapped by detection surveys from 1924–2021 in the United States. Regional outbreaks occur every 5 to 10 years and commonly persist for 1 to 3 years.

Oak-hickory and oak-pine forest types represent optimal habitat for *L. dispar* outbreaks (Morin and Liebhold 2015) and those stands with 60 percent, 40 percent, or 15 percent of preferred host species represent high, medium, or low susceptibility to injury, respectively (Fig. 7) (Campbell 1974, Gottschalk 1993, Herrick and Gansner 1986). Many susceptible forest types located throughout the southern United States are still uninvaded (Liebhold et al. 1997). Leuschner et al. (1996) details the ecological and economic impacts on timber (e.g., reduced yield, increased rotation timing, decreased wood quality or negative changes in species composition, regeneration, or a combination of these factors); recreation (e.g., visits lost, postponed, substituted, or less enjoyable, as well as suppression costs and cleanup, removal, and replacement expenditures); and residential areas (e.g., suppression costs and cleanup, removal, and replacement expenditures) when the spread of *L. dispar* outbreaks are unmanaged.

Short-term changes in microclimate can result from moderate and severe defoliation, increasing temperature, light, nutrients, and moisture reaching the forest floor (USDA FS and APHIS 2012a). These changes can lead to subsequent increases in shrub and herbaceous cover (Gansner 1985, Hix et al. 1991, McEwan et al. 2009). Water quality can be affected by increased runoff and direct contamination from the deposition of frass, but these changes are typically short-lived (Smith-Tripp et al. 2020, USDA FS and APHIS 2012a). Tree injury and mortality to oaks can affect mast production for animals that rely on acorns for food but increase the availability of nesting and foraging resources for several bird species that utilize snags and dense shrub cover (Showalter and Whitmore 2002).

Figure 6.—Tree mortality as a result of consecutive years of severe *Lymantria dispar* defoliation and consecutive years of drought that impacted several states from 2015 to 2017 in the northeastern United States. In the image, oaks (*Quercus* spp.) experienced the highest levels of injury and mortality. (Photograph by K. Dodds, USDA Forest Service)

Presence of outbreak populations can lead to aesthetic and nuisance concerns and health issues due to the densities of caterpillars often aggregating on structures, the presence of frass raining down from defoliated trees, caterpillars falling from the canopy, and injury and mortality of trees. Aesthetic and nuisance concerns commonly arise in public parks and recreational areas in forested communities where tree cover is abundant. Nuisance and defoliation were the primary concerns noted by private landowners and land managers in the northeastern United States during *L. dispar* outbreaks (Moeller et al. 1977). Dense, late-instar caterpillar populations are very noticeable and apparent and can cause stress and anxiety to the public. Furthermore, skin contact with hairs from the caterpillar can cause wheals and rashes, leading to severe itching and allergic reactions that may require medical treatment (Gooderham et al. 2021, Marshall 1981, Montgomery and Wallner 1988).

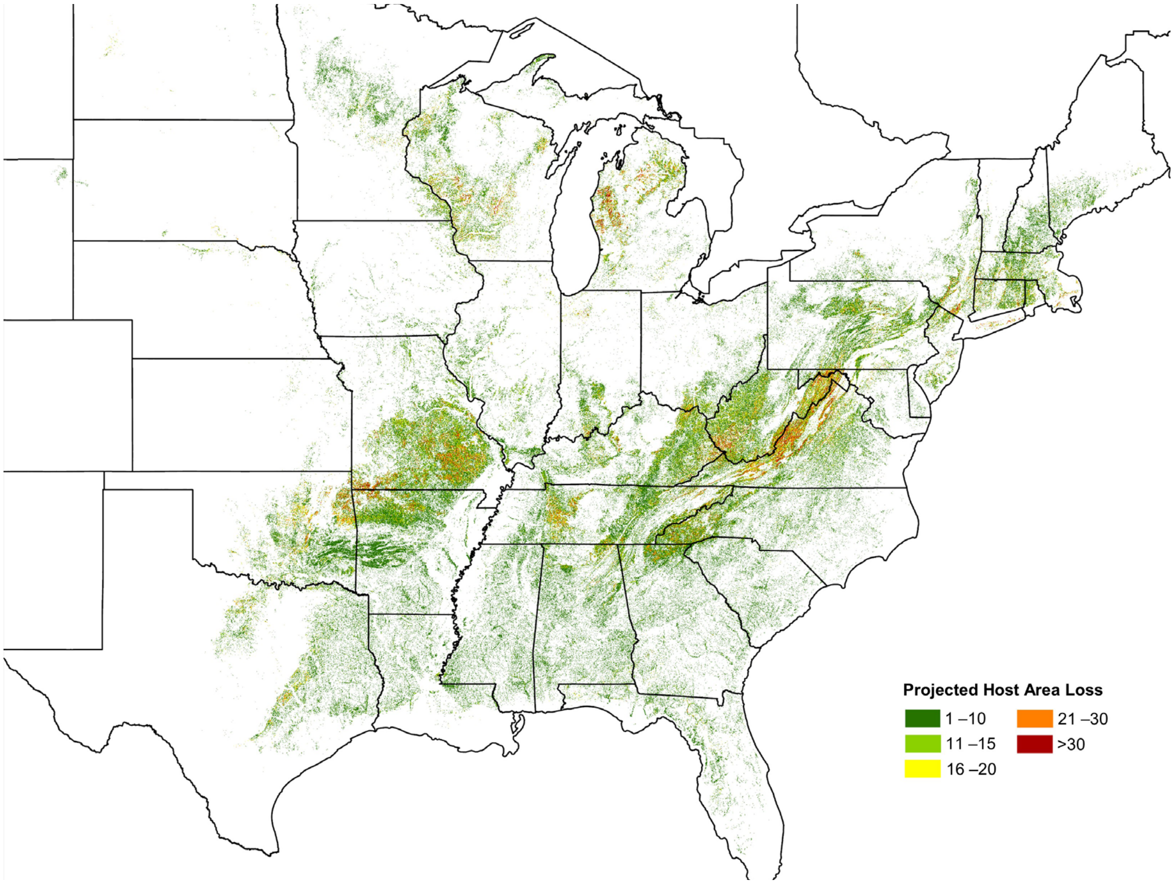

Figure 7.—Forest stands at risk (percent host basal area loss) to *Lymantria dispar* injury in the eastern United States. Risk data was developed by Krist et al. (2014) for the 2013–2027 National Insect and Disease Risk Map. Uninfested areas in the southern United States represent widespread risk to *L. dispar,* but regions of the Cumberland Plateau, Southern Appalachian Mountains, and Ozarks possess the highest risk (>30% basal area loss).

MANAGEMENT STRATEGIES

Numerous management strategies, including intensive monitoring, biological control, physical control, cultural control, and chemical control were used in the early 1900s to reduce the rate of spread and impact of *L. dispar* in the United States (Forbush and Fernald 1896, McManus and McIntyre 1981, USDA FS and APHIS 2012a). McManus (2007) provides a detailed timeline of *L. dispar* events from 1869 to 2005 in the United States. The initial eradication and New York barrier programs in the late 19th and early 20th century relied heavily on ground and aerial chemical applications, including copper acetoarsenite, lead arsenate, dichorodiphenyltrichoroethane (DDT), and carbaryl to suppress outbreaks (Fig. 8) (Liebhold and McManus 1999, White et al. 1981). Early efforts of cultural and physical control focused on the destruction of egg masses by removing and burning them, pouring boiling water on them, or treating them with creosote (Fig. 8). Infested trees and shrubs were also burned (Forbush and Fernald 1896). Trees were banded with burlap skirts to trap larvae moving up and down trees, and caterpillars found under the bands were killed daily. Egg mass counts, burlap bands, and primitive pheromone traps (baited with live, caged females) were used to monitor the presence and density of populations (Forbush and Fernald 1896, Kolodny-Hirsch 1986). The U.S. Civilian Conservation Corps

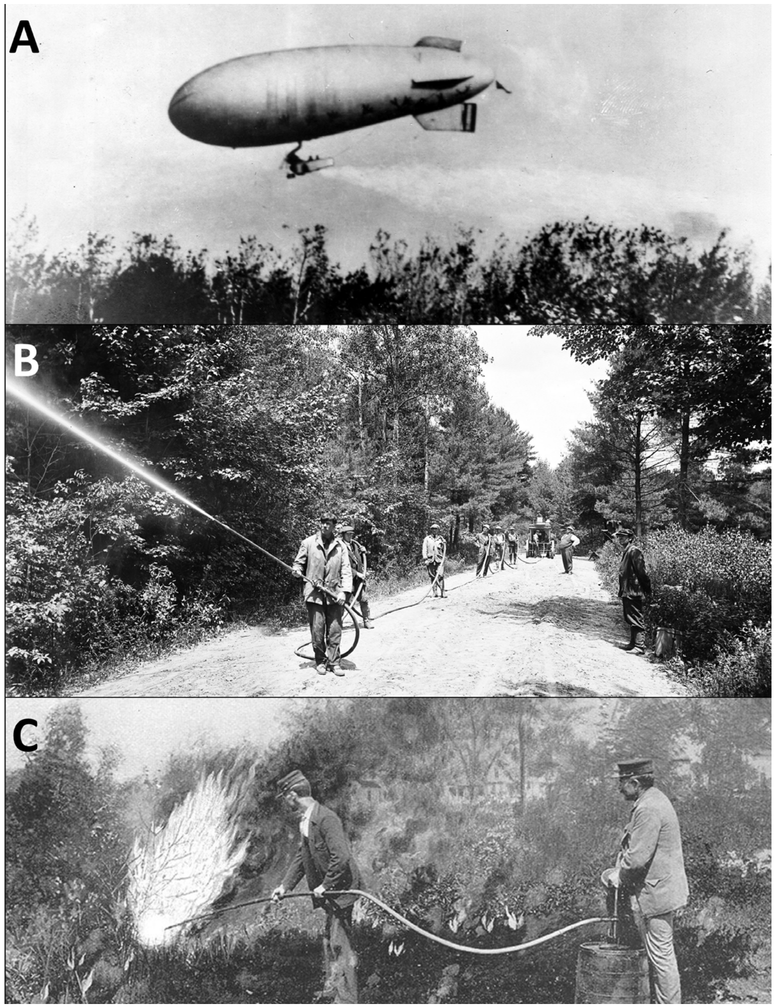

Figure 8.—Aerial applications were used to suppress *Lymantria dispar* populations with an U.S. Army blimp following World War I in New Hampshire (A). Arsenate of lead was used to treat the populations. Ground applications were also utilized to treat (B) and destroy (C) populations. (USDA archive photographs)

provided labor for much of these management activities in the 1930s and 1940s, which made such tedious tasks feasible (Fig. 8).

The identification of the *L. dispar* sex pheromone [cis-7, 8-epoxy-2-methyloctadecane (disparlure)] significantly enhanced monitoring techniques, which initially used caged female moths or crude extracts from the tip of female abdomens (Bierl et al. 1970, Forbush and Fernald 1896). Subsequently, the plus enantiomer or (7R,8S)-cis-7,8-epoxy-2-methyloctadecane [(+)-disparlure] was shown to possess exclusive and elevated attractiveness to male *L. dispar* in North America (Cardé et al. 1977, Plimmer et al. 1977). The synthetic sex pheromone and use of delta and milk carton traps are invaluable for detecting newly established, low-density populations and directing treatment decisions for eradication efforts.

During the early 1990s, 34 species of parasitoids and predators were released in classical biological control programs (Blackburn and Hajek 2018, Elkinton and Liebhold 1990, Fuester et al. 2014, Reardon 1991). However, only 12 species have established, and their impacts on *L. dispar* population dynamics are not clear (Fuester et al. 2014, Kenis and Lopez Vaamonde 1998). As a result, and because virtually all of the good candidate agents have already been introduced, classical biological control options have been abandoned. At least one of the parasitoid species introduced during these early programs, *Compsilura concinnata* Meigen (Diptera: Tachnidae) is polyphagous and utilizes other Lepidopteran species as hosts, which may have adverse impacts on populations of some of these species (Blackburn and Hajek 2018, Elkinton and Boettner 2012).

Environmental concerns in the 1950 and 1960s led to changes in forest pest management tactics and the development of integrated pest management (IPM) strategies and utilization in *L. dispar* management programs over the next two decades. In the early 1970s, the need for *L. dispar* management intensified because the moth's range increased dramatically and caused defoliation over approximately 809,000 hectares (McManus 1978). Collectively, two research programs, the Accelerated Program (1971–1974) and USDA Expanded Gypsy Moth Management Program (1975–1978), focused on the following goals (Doane and McManus 1981):

- developing and evaluating the synthetic sex pheromone and microbial controls for suppression and eradication
- increasing foreign exploration for classical biological control and evaluating effectiveness
- refining population prediction models, sampling methodology, and impact assessments
- evaluating *L. dispar* NPV testing and registration and evaluating new chemical insecticide candidates
- assessing sterile male release techniques
- developing mass rearing protocols

These programs benefited from cooperative studies that involved the USDA Forest Service (USDA FS), the USDA Agricultural Research Service, the USDA Animal and Plant Health Inspection Service (USDA APHIS), the Cooperative State Research Service, universities, and state agencies.

The Expanded Gypsy Moth Management Program was part of the Combined Forest Pest Research and Development Program, which also addressed research gaps for the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough) (Lepidoptera: Erebidae), in the Pacific Northwest and southern pine beetle, *Dendroctonus frontalis* Zimmermann (Coleoptera: Curculionidae), in the southeastern United States.

From the early 1970s through the late 1980s, chemical applications for suppression of outbreak populations relied on organophosphate (trichlorfon) and carbamate (carbaryl) insecticides for suppression of *L. dispar* outbreaks (Liebhold and McManus 1999, USDA FS 2021b, White et al. 1981). Insect growth regulators became a viable option for *L. dispar* management in the late 1970s. Diflubenzuron, a chitinase inhibitor, was used heavily from the early 1980s to the early 2000s in state and federal *L. dispar* suppression projects, whereas tebufenozide, which disrupts molting, has been used more predominately since 2013. Tebufenozide is typically favored more than Diflubenzuron in applications because it has fewer non-target impacts and is less toxic to aquatic invertebrates (USDA FS and APHIS 2012a).

Biopesticide options for *L. dispar* began to flourish in the 1980s. In 1980, *Bacillus thuringiensis* var. *kurstaki (Btk),* a naturally occurring soil bacterium, was first used as a microbial biopesticide and has been used continuously since 1980 for state and federal suppression and eradication projects (Fig. 9) (USDA FS 2021). Its effectiveness at suppressing high population densities of *L. dispar* along with its limited non-target effects (i.e., only impacting caterpillars that ingest the bacteria), and short environmental persistence (less than 1 week), make *Btk* an excellent management tactic (USDA FS and APHIS 2012a). Since the 1980s, it has been the most widely used *L. dispar* larvicide in government-administered operations (Hajek and Tobin 2010, USDA FS 2021b).

Lymantria dispar NPV is hypothesized to have been unintentionally introduced to North America in the early 1900s with parasitoids introduced for classical biological control (Howard and Fiske 1911). The virus spreads when larvae ingest viral bodies on leaves or the egg surface after eclosion. Like other NPVs, the effect on caterpillars depends on density: the virus spreads easily through high-density populations and impacts early instar larvae and late instar larvae within a year (Blackburn and Hajek 2018). Caterpillars infected by NPV can be found hanging dead by their abdominal prolegs, creating an inverted V shape with their limp body (Blackburn and Hajek 2018). The infected caterpillar eventually ruptures, raining viral particles on plant material below. Nucleopolyhedrosis virus is specific to *L. dispar* and has been formulated into a microbial biopesticide, Gypchek (Podgwaite 1999). Gypchek has been used in government management programs since the late 1980s (USDA FS 2021b) and is predominantly used in treatment applications where sensitive, threatened, or endangered Lepidoptera species are present because its impacts are limited only to *L. dispar.* Gypchek is not commercially available and is only used in treatment operations sponsored by the Forest Service. The product is costly and time-intensive to produce because it requires the mass rearing of NPV-infected caterpillars. *Lymantria dispar* NPV and *Btk* applications are most effective

Figure 9.—*Bacillus thuringiensis* var. *kurstaki (Btk)* applications for *Lymantria dispar* in western Virginia. Double applications of *Btk* are commonly used for slow the spread and eradication treatments. (Photograph by T.W. Coleman, USDA Forest Service)

when targeting first and second larval instars, whereas some insect growth regulators are more effective when treating older instar larvae (Coleman et al. 2020).

The fungal pathogen *E. maimaiga* is widespread in Japan, where it is an important mortality agent in *L. dispar* populations (Hajek et al. 2021). It was introduced to North America in 1910 or 1911 but never detected. However, in 1989 it was found causing high levels of infections in *L. dispar* populations in Connecticut (Hajek 1999). The details on the introduction of this fungus remain unclear, but most likely it was inadvertently introduced from Japan sometime between 1979 and 1989. Following the initial emergence of *E. maimaiga* in southern New England in 1989, the fungus rapidly spread across the range invaded by *L. dispar* (Hajek et al. 1995, 2021). Cool, wet springs are highly conducive for spread and proliferation of *E. maimaiga* spores, and the fungus is density independent (Reilly et al. 2014). *Entomophaga maimaiga* is ubiquitous in the infested areas and often results in the collapse of *L. dispar* populations (Hajek et al. 2015). Infected caterpillars hang head down in a vertical position on tree stems and branches, facilitating the spread of two spore types that can either re-infect the current population or remain dormant in the soil for up to a decade (Blackburn and Hajek 2018).

The use of semiochemicals has been a fairly recent management option for *L. dispar.* In 1972, Beroza and Knipling proposed the use of pheromones to suppress mating. However, transforming this concept into a practical tactic required many years of methods development. Thorpe et al. (2006) and Onufrieva (2023, this report) outline the development and operational use of mating disruption for low density populations. Hercon® Disrupt® II (Hercon Environmental, Emigsville, PA) was used predominantly in the National Slow the Spread (STS) Program and its pilot program from 1995 to 2017 (USDA FS 2021b). SPLAT GM and SPLAT GM-Organic (ISCA Technologies, Riverside, CA) was subsequently developed and used operationally from 1998 through the present (Coleman et al. 2023, this report page 45; USDA FS 2021b).

Silvicultural control has been implemented on public and private lands, but in recent years it has not been an area of focus for forest management on federal lands. The lack of silvicultural control may be attributed to the success of slowing the rate of spread of *L. dispar* at the advancing front and the changing management objectives on public lands. Gottschalk (1993) recommends silvicultural prescriptions that focus on reducing stand susceptibility and host vulnerability by increasing stand vigor, removing trees most likely to die, reducing *L. dispar* habitat and susceptible hosts, improving predator and parasitoid habitats, and regenerating stands that are close to maturity or understocked. Additional management options that have been considered but deemed ineffective, too costly, or inappropriate for large-scale integrated pest management (IPM) programs include inherited sterility or sterile insect technique, entomophagous nematodes, microsporidia, phytochemicals, and systemic insecticides (Doskotch et al. 1981, Kononchuk et al. 2021, Reardon et al. 1993, White et al. 1981, Xu et al. 2021).

Recent work on new *L. dispar* and *L. dispar asiatica* suppression tactics have focused on either gene silencing with RNA interference (RNAi) or DNA insecticides that block anti-apoptotic genes as biopesticides (Ghosh and Gundersen-Rindal 2017, Nyadar et al. 2016, Oberemok et al. 2019, Oberemok and Nyadar 2015, Oberemok and Skorokhod 2014, Wen et al. 2020). RNAi and DNA insecticides have the benefit of being potentially more species-specific to *L. dispar* than *Btk* and bypass resistance to insecticides and biopesticides (Nydar et al. 2016, Oberemok et al. 2019). Uptake of RNAi by caterpillar feeding (continuously) and absorption in the midgut is likely a promising method for an effective control strategy (Nyadar et al. 2016). Fogging applications have been proposed for use with DNA insecticides to thoroughly cover late-instar larvae in Asia (Oberemok et al. 2019). Reductions in body weight and egg masses, impaired development, and mortality have been observed in RNAi laboratory studies (Ghosh and Gundersen-Rindal 2017, Nyadar et al. 2016, Sun et al. 2022, Wen et al. 2020), and larval mortality (~47 percent) has been reported in tests with DNA insecticides (Oberemok et al. 2019). Terenius et al. (2011) report that RNAi has had varying levels of success in Lepidopterans. However, neither of these biopesticides has been field tested against *L. dispar* because of production costs, concerns about non-target impacts, and complications with delivery methods (Nyadar et al. 2016, Oberemok et al. 2019).

PEST MANAGEMENT PROGRAMS

The U.S. Department of Agriculture has had an active role in managing *L. dispar* since 1906, when Congress appropriated funds to manage an outbreak in Massachusetts and fund exploration and importation of natural enemies for *L. dispar* control (Forbush and Fernald 1896, McManus 2007). Ever since the passage of the Plant Quarantine Act in 1912, the USDA has implemented a quarantine aimed at limiting the spread of *L. dispar* in the United States by regulating the movement of plant material (Liebhold et al. 1992). Since the early 1900s, two barrier zone programs were implemented in the northeastern United States to actively stop the movement of *L. dispar:* the Barrier Zone (1923–1941) from Canada to Long Island along the Champlain and Hudson River Valleys, and the Gypsy Moth Appraisal Program (1953–1958) along the Adirondack mountains in New York to the Allegheny Plateau (Fig. 10). The Maryland Integrated Pest Management Project (MD-IPM Project, 1983–1987) was established in the southern part of that state. The Appalachian Integrated Pest Management Project (AIPM, 1988–1992) was modeled somewhat on previous IPM strategies and implemented in the Allegheny Mountains in Virginia and West Virginia. The Slow the Spread Pilot Project (1992–1999) continued one of the objectives of the AIPM project—to slow *L. dispar* spread—and demonstrated that an area-wide strategy was cost effective. Finally, the National Slow the Spread (STS) Program began in 2000 and implemented this strategy across eight states—Indiana, Illinois, Michigan, North Carolina, Ohio, Virginia, West Virginia, and Wisconsin—to reduce the rate of spread of *L. dispar* along the leading edge of the infestation (Fig. 10).

Previous *L. dispar* IPM programs helped provide a solid foundation for the STS Program. The barrier zone concept utilized in 1923 in New York was effective at reducing the rate of spread of *L. dispar,* even though the zone became generally infested in 1939, and funding and treatments were eliminated in 1941 when the United States entered World War II (Liebhold et al. 1992). The 1923 Barrier Zone implemented practices that remain part of USDA's current National Spongy Moth Management program, where individual states treated populations east of the barrier zone (i.e., suppression), and state and federal agencies treated in the transition zone (i.e., slow the spread). The 1953 Gypsy Moth Appraisal Program, involving New York, Vermont, and Connecticut, was initiated to prevent additional spread and damage from *L. dispar* and relied heavily on the application of DDT. These applications were heavily criticized, notably by Rachel Carson in the book "Silent Spring," published in 1962. Ultimately, the environmental effects associated with DDT led to its elimination. The barrier zone became infested, and the program ended.

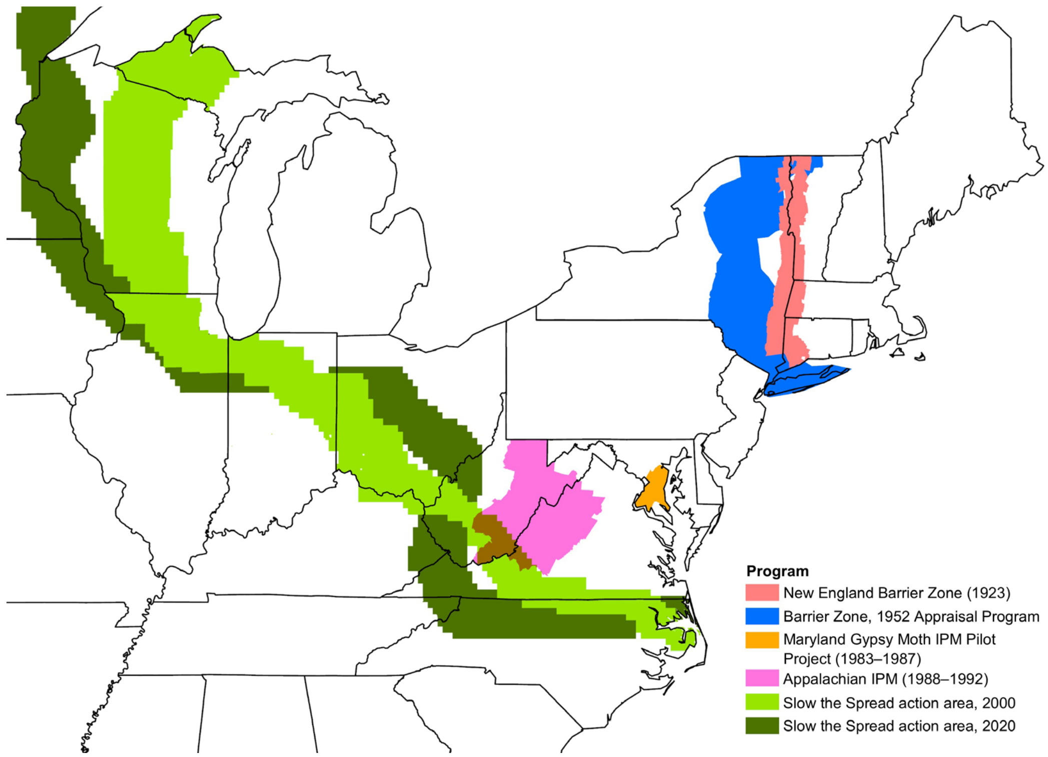

Figure 10.—Progression of *Lymantria dispar* management programs in the eastern United States. The program boundary from 2000 and 2020 for the National Slow the Spread Program highlights the success of the most recent integrated pest management program.

The two IPM programs that followed, the MD-IPM project and the AIPM project, initiated several activities that are still implemented in the STS Program. These include monitoring *L. dispar* populations along the leading edge with an extensive network of pheromone-baited traps, treating low-density *L. dispar* populations at a landscape scale with environmentally sensitive methods, and utilizing a centralized database to manage trap data and to inform land managers of potential trapping and treatment applications (McManus 2007, Reardon 1991, Reardon 1996, Reardon et al. 1993).

Maryland Integrated Pest Management (MD-IPM) Project

The MD-IPM Project was a five-year cooperative pilot project to determine the feasibility of managing *L. dispar* populations using an IPM approach over a diverse landscape (Reardon et al. 1993). The MD-IPM project was also used as a comparison to Maryland's current Gypsy Moth Cooperative Suppression Program. A project coordinator and technical committee were appointed to direct the project and develop a five-year plan, which was implemented by federal, state, county, and local agencies and organizations. The average annual budget for the MD IPM program was $441,200 and supported full-time (three entomologists) and seasonal staff (15 to 25 employees).

The program managed low- (<62 egg masses/0.4 ha) to moderate-density (<617 egg masses/0.4 ha) *L. dispar* populations in a 20,234 ha area that spanned five Maryland counties (Anne Arundel, Calvert, Charles, Howard, and Prince George's). Pheromone-baited milk carton traps monitored at 1 km grids, egg mass surveys in 1 km^2 cells, and tree banding provided population data, yearly trends, and phenological data. The project utilized decision making criteria (e.g., no action, preventive action, and suppressive action) to direct intervention techniques that relied on egg mass and male moth densities and trends, size and proximity of the infestation to other infestations, stand susceptibility, percent defoliation, environmental sensitivity, social and economic value, and land use (Reardon et al. 1993). Various techniques were tested or implemented alone or in combination with other techniques in the MD-IPM project, including ground (individual tree and broadcast applications) and aerial (*Btk,* Gypcheck) treatment techniques, inherited sterility (i.e., sterilized male and F1 sterile egg mass releases), ground applied mating disruption [i.e., Hercon® Luretape® GM (Hercon Environmental, Emigsville, PA)], augmentative and classical biological control with parasitoids and entomogenous nematodes, insect growth regulator (e.g., Diflubenzuron), contact insecticides (e.g., Bendiocarb), and systemic insecticides. Life stage and various other stand-specific data were used to evaluate treatment efficacy. Database management for the project was hosted at Virginia Polytechnic Institute and State University (VT), Blacksburg, Virginia, and VT staff assisted the decision-making process by developing computer-aided maps with population trend and density data. The MD-IPM project treated 3,203 ha (IPM area: 2,465 ha, comparison area: 739 ha) and 17 isolated, heavily infested individual trees during the five-year period using eight treatment methods. The majority of the treated area utilized aerial applications of *Btk* (Table 1). However, low population densities in both the IPM area and a comparison treatment area did not allow an efficacy assessment of the IPM work. Nevertheless, the program was instrumental for developing and testing biopesticides (*Btk* and Gypchek) against *L. dispar* because it demonstrated that an IPM program was feasible over a diverse landscape and provided the prototype for the AIPM Project.

Appalachian Integrated Pest Management (AIPM) Project

With support from Congress, the 5-year AIPM Project was implemented across 20 counties in West Virginia and 18 counties in Virginia, encompassing approximately 5.19 million hectares and playing a crucial role in the development of the framework ultimately adopted by the STS Program. Among its innovations, the AIPM program applied varying decision-making practices among different monitoring zones that were established to align with varying moth capture levels and management objectives. Decision-making tools helped guide trapping and treatment activities, and geospatial tools were developed to manage low-density populations (Reardon 1991).

The AIPM Project was established along the leading edge of the *L. dispar* invasion with four objectives: (1) to minimize the spread and adverse effects in the *L. dispar* project area; (2) to develop a prototype IPM structure consisting of standardized sampling protocols, decision matrices for intervention activities of low-level *L. dispar* populations, computer based geographical information systems (GIS), and an educational program; (3) to continue the development of intervention activities for the management of isolated low-density infestations; and (4) to assess the feasibility of implementing a coordinated federal and state program over a large area (Reardon 1996).

The project area was divided into four monitoring areas that spanned heavily infested areas (>500 male moths/trap) to low-density areas (<10 male moths average/trap), with each zone possessing its own intervention tactics. State and federal agencies monitored pheromone-baited traps at either a 2 or 3 km base grids, with delimiting surveys at smaller grids, and surveyed forest stands to assess defoliation and egg mass densities.

Table 1.—Treatment accomplishments from previous *Lymantria dispar* integrated pest management (IPM) programs

Project	Treatments	Area treated
A. MD-IPM Project (1983–1987)	Aerial application of *Bacillus thuringiensis* var. *kurstaki (Btk)*	2,342
	Aerial application of *Btk*/parasite release	768
	Ground application of *Btk*/Hercon® Luretape®	74
	Parasite release	2
	Aerial application of Diflubenzuron	14
	Ground application of Gypchek	4
	Ground application of Bendiocarb	0
	Ground application of Diflubenzuron	0
Total treated		**3,204**
	mean cost/trap: $13.35	
	mean *Btk* cost/0.4 ha: $62.07	
	mean Hercon® Luretape® cost/0.4 ha: $155.67	
	mean egg mass survey cost/0.16 ha: $7.00	
B. AIPM Project (1998–1992)	Aerial application of *Btk*	123,172
	Aerial application of Diflubenzuron	113,898
	Aerial application of Gypchek	2,648
	Aerial application of mating disruption	7,887
Total treated		**247,605**
C. STS Pilot Project (1992–1999)	Aerial application of *Btk*	58,386
	Aerial application of Diflubenzuron	1,412
	Aerial application of Gypchek	1,805
	Aerial application of mating disruption	28,594
Total treated		**90,196**

Notes: Data was compiled from Reardon et al. (1993), Reardon (1996), and VT (2021). Cost information for the MD-IPM Project was obtained from Reardon et al. (1993).

Project data (i.e., moth trap data, egg mass counts, defoliation data, proposed treatment areas, and forest cover types) were compiled in a geographical information system by VT to develop maps for project decision-makers and evaluate subsequent intervention methods (Liebhold et al. 1996). The AIPM Project focused suppression treatments on varying densities of *L. dispar* with aerial applications of *Btk*, Diflubenzuron, Gypchek, and mating disruption (Hercon® Disrupt® II) (Table 1). Reardon (1996) outlines the successes of the AIPM Project with technology development, evaluation of data, technology transfer, and their use in the STS Pilot Project.

Slow the Spread (STS) Pilot Project

As AIPM ended in 1992, the STS Pilot Project was initiated along the transition zone in 21 counties of Virginia, North Carolina, and West Virginia, and three counties in the Upper Peninsula of Michigan. The goal of the pilot program was to demonstrate that new and current technology could slow the rate of spread of *L. dispar* populations; assess the technological, economic, ecological, and environmental viability of implementing an operational STS program; and implement a plan for integrating STS technology into a national strategy for *L. dispar* management (McManus 2007). With an overall goal of reducing the rate of spread of *L. dispar* by approximately 50 percent, the pilot project had a mean annual funding of $2,678,636 (±643,454) for data available from 1993 to 1995. State and federal agencies along with a newly formed steering committee would implement the project, whereas a technical committee comprised of state, federal, and university scientists would provide expert recommendations (McManus 2007). Pheromone-baited traps were deployed in 1 km base grids with delimit-trapping at 250 m and 500 m grids in a 100 km wide action zone and in an adjoining evaluation zone. A centralized database remained at VT. During the pilot project, increases in federal funding allowed for an increase in treatment hectares, supporting the feasibility of a national program. Applications of *Btk,* Diflubenzuron, Gypchek, and mating disruption (Hercon® Disrupt® II) comprised the treatments, totaling 90,196 ha (Table 1). Continued spread and outbreaks of *L. dispar* threatened oak forests in the southern United States and provided justification for a *L. dispar* containment program. In 1995, federal agencies developed a memorandum of understanding to define responsibilities for the program; this document has since been updated but still directs *L. dispar* management in the United States (USDA FS and APHIS 2012a, 2012b). The USDA National Spongy Moth Management Program has provided a national strategy comprised of four components—suppression, slowing the spread, eradication, and regulatory—to reduce the rate of spread and lessen the impact of *L. dispar* (USDA FS and APHIS 2012b). A cost-benefit ratio of 2.78 for one-time impacts and 21.60 for yearly impacts for reducing the rate of spread by 60 percent justified the *L. dispar* containment strategy across the entire transition area for a national program (Leuschner 1991, Leuschner et al. 1996).

During the pilot program, Sharov and Liebhold (1998) conducted a study using a mathematical model to predict the efficacy of the STS Program. The spatially explicit model described spread via stratified dispersal (i.e., formation of isolated populations ahead of the invasion front that grow and coalesce). They parametrized the model for *L. dispar* spread using trap data from the AIPM and STS Pilot Project and predicted that a 100 km action area (where isolated populations are identified and treated) would cause a 54 percent reduction in spread, which closely approximated the observed 59 percent reduction in spread during these programs. These results, along with the economic analyses by Leuschner et al. (1996), provided further evidence that the STS strategy is viable and established a scientific basis for the program.

National Slow the Spread (STS) Program

The National STS Program was formally adopted in August 2000 with an updated goal of reducing the rate of *L. dispar* spread by 60 percent (from an unrestricted rate of spread of 19.6 km/yr to less than 7.8 km/yr). The steering committee of the pilot project was replaced with a board of directors and a non-profit foundation, the Slow the Spread

Foundation (Leonard 2007). Coleman et al. (2023, this report page 28) outline the roles of the three committees (operations, regulatory, and technical) and the general structure and workflow of the national program.

For 20 years, the National STS Program has successfully achieved its goal (Coleman et al. 2023, this report page 45), and the program represents one of the largest and most comprehensive IPM programs in the world (Liebhold et al. 2021). Sills (2008) compared the benefits of the reduced rate of spread and additional management and quarantine costs when *L. dispar* reaches outbreak populations, estimating a cost-benefit ratio at 1-to-3 for the STS Program and a net present value of $21 to $33 million from 2006 to 2026, depending on which benefits were included. A similar economic analysis conducted in British Columbia, Canada, determined that the expected annual benefits of a prevention program in the province ranged from 3.4 to 8.3 times the annual estimated cost of the program (Sun et al. 2019).

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