AN INSECT OUT OF CONTROL? THE POTENTIAL FOR SPREAD AND ESTABLISHMENT OF THE GYPSY MOTH IN NEW FOREST AREAS IN THE UNITED STATES

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INTRODUCTION

The gypsy moth, *Lymantria dispar* L., was introduced from Europe into North America near Boston, Massachusetts, in 1869, and is now well established as a serious defoliator of forest, shade, and fruit trees over much of the eastern United States. Despite substantial efforts to eradicate, contain, or control this pest, the gypsy moth has persisted and continues to extend its range. The generally infested area currently extends from the northeast corner of North Carolina along a diagonal line that extends through Virginia, West Virginia, and the northeast corner of Ohio into Michigan. These five states are referred to as the transition zone, and states to the east of this line represent what is referred to as the generally infested area. A vast area of suitable habitat for the gypsy moth, much of which is valuable commercial hardwood forest, lies to the south and west of the generally infested area. This paper assumes that the gypsy moth will if not checked expand its range into that area and therefore proposes a management strategy for preventing this from occurring.

THE HISTORICAL RECORD

The original infestation increased and spread gradually until, by the summer of 1889 (30 years after its introduction), the insect was so abundant and destructive that it attracted public attention. The first outbreak encompassed forested lands that included 30 towns and cities in the greater Boston area and prompted the state of Massachusetts to implement an intensive program to eradicate the insect. The program was so successful in reducing the infestation that the state legislature chose to abandon the effort in 1900. Many people considered that action to be a fatal mistake.

During the next 5 years, gypsy moth populations increased tremendously in Massachusetts and new infestations were subsequently discovered in the neighboring states of Rhode Island, New Hampshire, Vermont, and Connecticut. From 1906 to 1912, the federal government financed the importation of natural enemies of the gypsy moth from several European countries and from Japan

BARANCHIKOV, Y.N., MATTSON, W.J., HAIN, F.P., and PAYNE, T.L., eds. 1991. Forest Insect Guilds: Patterns of Interaction with Host Trees. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. NE-153.

(Brown and Sheals 1944). Efforts to prevent the shipment of gypsy moth-infested products into outlying areas were intensified and led eventually to enactment of a federal domestic quarantine against the insect in 1912. The quarantine has been modified over the years, but remains in effect today and credited with greatly reducing the accidental long-range transport of gypsy moth on regulated commodities.

Between 1906 and 1920, the gypsy moth spread westward at an estimated rate of 9.6 km a year. Isolated infestations were discovered on estates in New York, New Jersey, and Ohio. In 1923, a barrier zone extending from Canada to Long Island and encompassing some 27,300 km^2 was established through a cooperative effort by the federal government and the state of New York to prevent the westward spread of the insect. Infested territory to the east of the zone was to be treated by the responsible state; infestations found within and to the west of the barrier zone were to be eradicated. Despite these efforts, the barrier zone became generally infested by 1939, and the effort was terminated in 1941.

Gypsy moth infestations seemed to explode in 1951-52, when 0.6 million ha were defoliated, as a result of which yet another thorough appraisal of the problem was made by state and federal officials.

A seven-point plan to re-establish the barrier zone was formulated in 1953, and the Congress made funds available to initiate an eradication program using DDT in 1956. By 1958, defoliation by the gypsy moth was recorded on only 50 ha within the totally infested area. However, concerns about the environmental persistence of DDT became paramount and use of the chemical was discontinued. Hopes of eradicating the gypsy moth were abandoned and a long-overdue emphasis was placed on research. The areas of infestation and defoliation increased substantially thereafter, which provided impetus for accelerated programs of research on the gypsy moth beginning in 1971 and continuing to the present.

MEANS OF SPREAD

Current distribution and spread of the gypsy moth in the United States (Fig. 1) is a product of both the natural spread of wind-blown first-stage larvae, and the inadvertent human transport of life stages from the generally infested area throughout the U.S. Historically, the extent of artificial introduction has probably been underestimated and the significance of natural spread overestimated. The following discussion offers a synthesis of what is known about both methods of spread.

Windblown Dispersal of Larvae

The distance that newly hatched larvae can disperse has been a controversial question for years. Early workers were convinced that long-distance dispersal of larvae was widespread in the Northeast and that larvae were readily blown up to 40 km by the winds (Collins 1917). However, Mason and McManus (1981) concluded that in nonmountainous terrain 99 percent of airborne larvae would be deposited within one km of their source. Even in mountainous areas, where mechanical turbulence and updrafts are more pronounced, an atmospheric dispersion model predicted that most larvae would be deposited within 3 km downwind.

Taylor and Reling (1986) conducted extensive aerial sampling of first-stage larvae over heavily infested ridges in Pennsylvania and suggested that 0.3 percent may get the opportunity to travel up to 19 km in one episode. More recently, Fosberg and Reling (1986) modeled the dispersal of gypsy moth larvae in mountainous terrain using a three-dimensional wind and dispersion model with real time climatological data from coastal California. Their model predicted that larvae would be carried aloft and transported more than a few hundred meters in only 2 percent of the cases. When long-range transport did occur, larvae were deposited 7 to 21 km away, but in very low concentrations. The

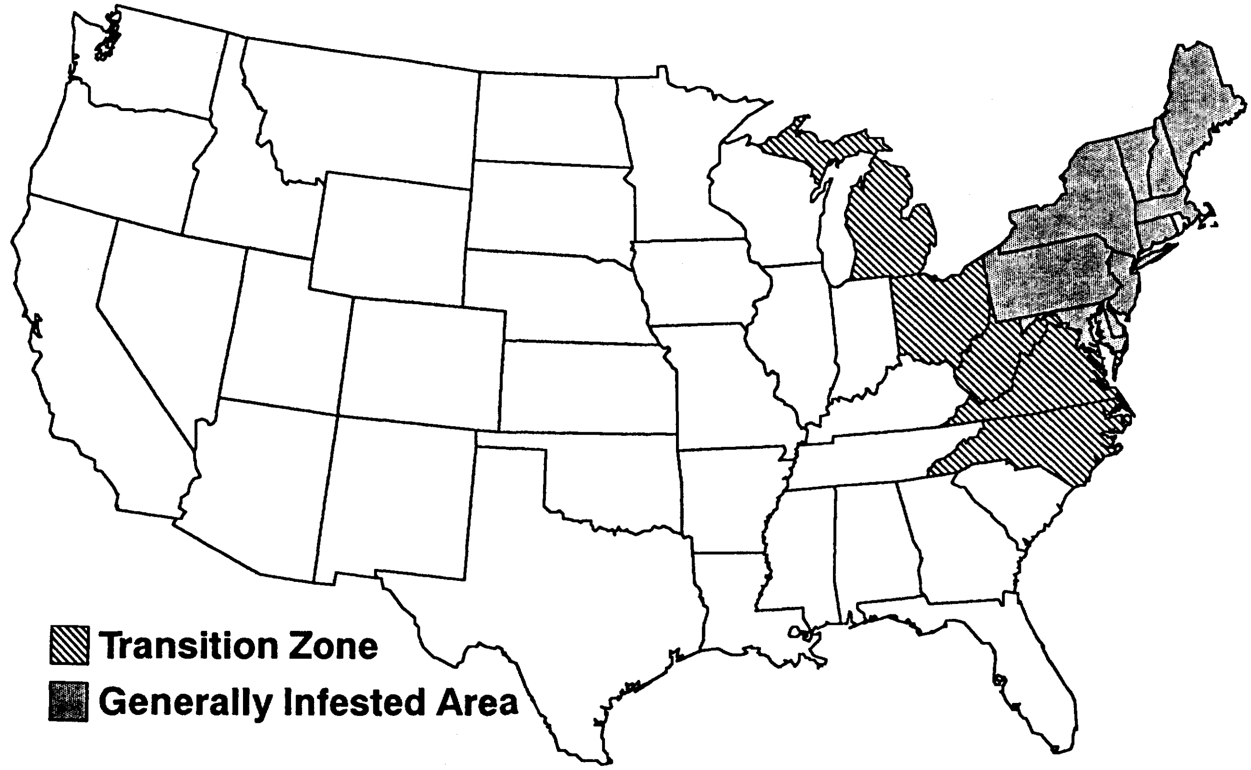

Figure 1. Current gypsy moth distribution

evidence suggests that although some larvae may be transported long distances when source populations are dense and hatch periodicity and optimal meteorological conditions are synchronized, most larval dispersal is a relatively short-range phenomenon. Support for this conclusion can be found in the documented record of isolated infestations that have occurred beyond the generally infested area. Of more than 264 isolated infestations that have been detected by the Animal and Plant Health Inspection Service, only 47 (18 percent) exceeded ca. 2.6 square km (1 sq mi) in area, even though these incipient populations may have persisted for several years prior to their detection. This suggests that under normal circumstances, the extent of larval dispersal and subsequent survival is minimal.

We recognize however that the Appalachian mountain range has been a factor in the accelerated rate of natural dispersal of the gypsy moth to the south. Susceptible ridgetop stands favor gypsy moth reproduction and survival, and complex wind fields associated with mountainous terrain increase the probability of greater dispersal. In the generally infested area, larval dispersal probably accelerates the redistribution and coalescence of local populations that have already begun to increase over broad areas.

Inadvertent Introduction of Life Stages

State and federal officials recognized in the early 1900s that spread of the gypsy moth out of the infested area around Boston was expedited by the transport of egg masses and other life stages on vehicles and commodities carried by major roads and thoroughfares. This led to enactment of a federal quarantine against the insect in 1912. Despite that regulatory effort, infestations were again discovered far beyond the infested area. In retrospect, it appears that the gypsy moth was probably introduced and reintroduced into both contiguous and distant areas and yet went undetected since there were no pheromone traps in those years and scouting for egg masses at low densities was and is an imperfect science.

The dimensions of the problem are best demonstrated by reviewing the circumstances of an isolated infestation detected in Somerville, New Jersey, in 1920. This infestation originated from a separate introduction of infested blue spruce trees from the Netherlands in 1910, prior to enactment of the federal quarantine. At the time it was discovered, the infestation was scattered over 1,040 km^2 around Somerville. A record of shipments of trees from the Somerville estate indicated that, prior to 1921, 261 shipments had been sent to 15 states from Connecticut south to Florida and west to Minnesota and Missouri. Follow-up inspections revealed that the shipments had led to new infestations in at least three of the states. The Somerville infestation was finally eradicated in 1931 at a total estimated cost of $2.5 million (Felt 1942). When one considers that this incident involved only commodity originating from a single small infestation at a time when transportation was somewhat limited, one can better appreciate the magnitude of the task to contain the gypsy moth today.

The regulatory quarantine is still in effect, although it has been modified over time to emphasize detection of life stages in commercial household moves. Historically, most new infestations have been traced to the transport of life stages on backyard furniture and related articles (dog houses, firewood, recreational equipment). Under new regulations implemented in 1983, shipments of household goods from designated high risk areas through or into nonregulated areas must be inspected at the point of origin and certified free of gypsy moth life stages.

Since 1980, California officials have initiated an aggressive program to supplant the federal quarantine on gypsy moth since they see the insect as a serious threat to the fruit and nut industry in the state. The California Department of Food and Agriculture maintains 16 border stations where personnel conduct inspections of recreational vehicles (campers, motorhomes, boat and house trailers) entering the state and identify shipments of household goods from states known to be infested by the gypsy moth. Recreational vehicles are known to be carriers of gypsy moth life stages. A survey conducted by APHIS in 1980 determined that 33 percent of all RVs leaving seven infested New Jersey campgrounds were carrying gypsy moth life stages. Under the California program, shipments of household goods are allowed to proceed through the border station but inspection of all outdoor items is conducted by destination county commissions after the moving van is unloaded. Documented results of this program are dramatic in that they illustrate the enormous potential for artificially introducing the gypsy moth into one of the most distant states from the generally infested area (Fig. 2). More than 2,000 interceptions of gypsy moth life stages from 14 states and Canada have been recorded since the program began in 1980. Most of the border interceptions occurred on recreational vehicles, although from 70 to 210 interceptions annually were recorded from county inspections of household goods at their destination. Egg masses were the life stage most frequently encountered, and in approximately 38 percent of the cases the life stages encountered were viable. As a result of this concerted effort to exclude the gypsy moth from California, the number of established infestations requiring treatment with pesticides declined from 10 in 1983 to only one in 1987, thus saving California taxpayers millions of dollars in treatment costs. The state estimated the cost of chemically treating the 10 infestations identified in 1983 at $1.5 million.

The increasing number of interceptions recorded since 1980 is obviously related to the extent and severity of the initial infestation in the generally infested area (Fig. 3). The number of interceptions recorded annually on recreational vehicles at California border stations, coupled with the fact that from 26 to 30,000 shipments of household goods from infested areas have been logged annually since 1984, demonstrates the potential for introduction of the gypsy moth into previously uninfested states (Fig. 4). These data also suggest that the gypsy moth is repeatedly being introduced into states both adjacent to and far removed from the generally infested region.

Since 1978, pheromone traps have been used extensively to detect isolated infestations throughout the United States and serve as the basic tool of the regulatory program. When pheromone traps are deployed according to APHIS protocols (1 trap/9 sq mi, depending on the terrain, setting, whether forest or residential, and so forth), new infestations are frequently detected and delimited within 2 to 3 years of their establishment and can then be more readily eliminated. As mentioned earlier, 72 percent of new infestations are less than 2.6 km in area when they are delimited. Those more extensive infestations that have been discovered in recent years in the states of Oregon (1984), Idaho (1987), and Utah (1988) apparently went undetected for several years because those states did not deploy a systematic grid of pheromone traps. The success of state detection programs is contingent upon the intensity of the trapping effort that each state initiates and maintains.

FACTORS THAT LIMIT ESTABLISHMENT IN NEW AREAS

Based on the statistics previously cited from the California gypsy moth exclusion program, there is no doubt that gypsy moth life stages have been transported to many uninfested states every year and that the number of such incidents has increased dramatically since the 1980-82 outbreak in the generally infested area. Yet judging from the relatively small number of infestations that have occurred and required APHIS to apply eradication treatments, we have to conclude that the probability of the gypsy moth becoming established in new areas is quite low. If this were not the case, the gypsy moth would by now, undoubtedly, have become entrenched in the oak-hickory and oak-pine forests throughout North America and in residential areas from coast to coast.

HOST AVAILABILITY AND SUITABILITY

In this section we attempt to elucidate those factors that affect the establishment of gypsy moth in new areas and will ultimately determine the future distribution of the insect in North America.

Unlike most other forest defoliators, the gypsy moth is a polyphagous insect that can feed successfully on over 200 species of trees that grow in the continental United States. Historically, however, outbreak areas have been characterized by an abundance of preferred host species, mainly oaks and aspen. Given the known distributions of oak-hickory and oak-pine types in the United States, the gypsy moth has the potential for establishing itself and thriving in several states to the south and west of the current generally infested area. The severity of the problem will be exacerbated by the availability of the contiguous forested area occupied by preferred food species, mainly oaks. The state of Pennsylvania, for example, contains over 4 million ha of oak forest, especially along the Appalachian mountain range that traverses the state. The state has experienced repeated outbreaks since 1970, as the gypsy moth has slowly spread to the south and west. Since oak remains the dominant species in Pennsylvania forests, the gypsy moth will be a recurring problem there in the years ahead. Similarly, the oak-pine forests on Cape Cod, Massachusetts, have sustained severe and repeated episodes of defoliation since the early 1900s and are still considered highly susceptible. Missouri, Tennessee, Kentucky, and West Virginia contain extensive areas of oak forests and have been identified as susceptible to the gypsy moth. The unglaciated regions of several midwestern states also contain extensive forests of oak and other susceptible species.

States further west and south have not been considered at risk to the gypsy moth because in them coniferous forests predominate. Hardwood species, including oaks, are scattered throughout these forests, however, especially along the waterways, and there they offer a suitable habitat for the gypsy moth. A case in point is Lane County, Oregon, where in 1987, 121,000 ha of mainly Douglas-fir forest were treated to eradicate an extensive but isolated infestation of gypsy moth that went undetected for several years. This infestation was successfully eliminated over a period of 3 years during which state/federal agencies applied multiple Bt treatments to the residual population.

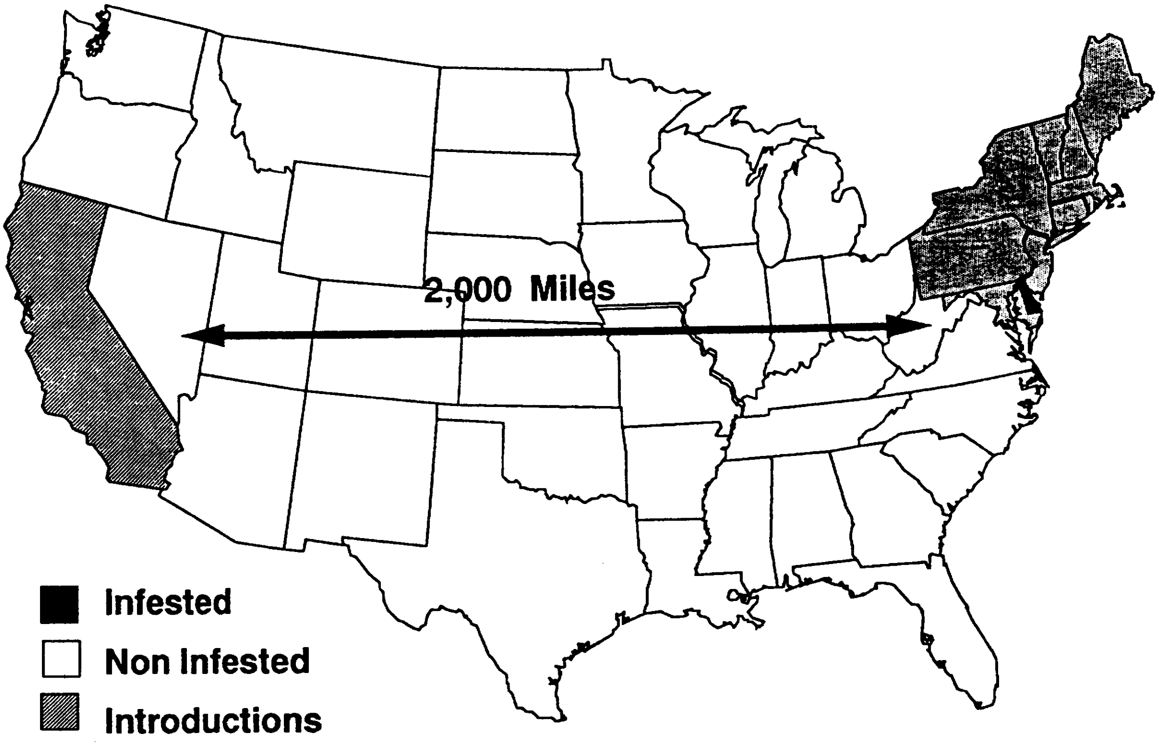

Figure 2. Introduction of gypsy moth into California

We must emphasize that although host availability may restrict the geographical extent of the problem when the gypsy moth is introduced beyond the natural range of oak, most successful establishments in places far removed from the generally infested region occur in urban residential areas and result from the introduction of life stages on household goods. In these areas, extensive plantings of preferred food species such as oaks, aspen, and ornamental fruit trees can support the establishment and expansion of gypsy moth populations.

Although considerable effort has been directed toward defining the range of host suitability for gypsy moth (Mosher 1915, Barbosa et al. 1983, 1986, Lechowicz and Mauffette 1986, Miller and Hanson 1989), most of these studies have been restricted to laboratory preference tests conducted on individual tree species common to the eastern United States. These studies confirm that although gypsy moth feeding preferences are extremely catholic, many tree species are not favored or rarely fed upon, such as black locust, *Robinia pseudoacacia*, ash, *Fraxinus* spp., and yellow poplar, *Liriodendron tulipifera*.

In general, the range of host suitability is narrowest for the early larval instars and broadest for the late larval instars, which can successfully feed and complete their development on most hardwoods and conifers. We do not fully understand the suitability of all species to all instars, especially when host switching occurs in the field. Gansner and Herrick (1985) reported on the preferences of gypsy moth for host species exhibited in the defoliation that occurred over a 5-year period on 575 plots in Central Pennsylvania. Although their data provide an index of preference, the results were somewhat compromised because less than half of the plots sustained moderate to heavy defoliation (> 30 percent), and that occurred in one year. Consequently, hemlock, a coniferous species readily defoliated

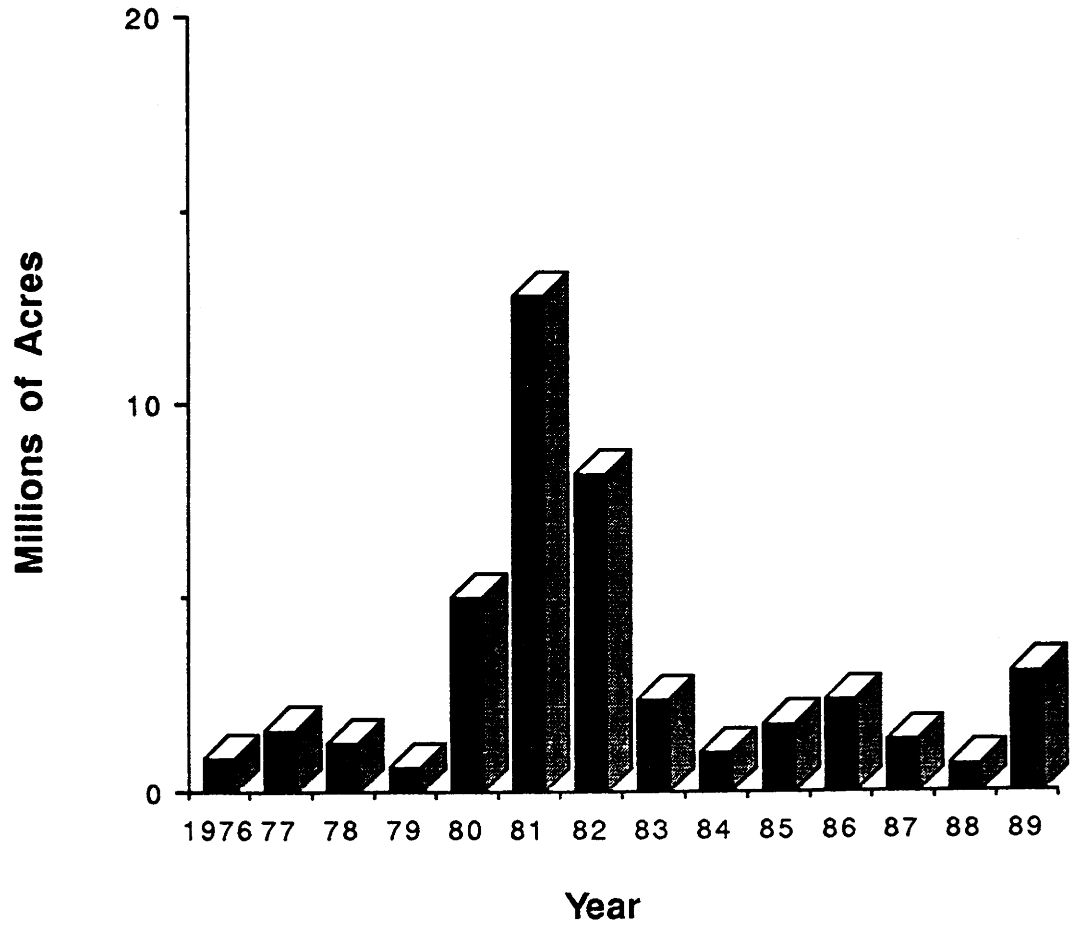

Figure 3. Acres defoliated by gypsy moth

by the gypsy moth and among which mortality often results, was the least preferred species in their study. This suggests that host preference in the field will be affected by initial distribution of the gypsy moth, relative density of the population, and proximity to other infested stands. There are still many unanswered and puzzling questions. For example, Barbosa et al. (1983) found that gypsy moth larvae reared on sweetgum, *Liquidambar styraciflua*, had the shortest developmental period, the highest pupal weights, and the largest mean fecundity, yet we observe mature native sweetgum trees in Maryland that are fully foliated while adjacent oaks are completely stripped. Obviously, more research is needed on gypsy moth/host plant relationships.

OTHER FACTORS

In addition to host availability and suitability, other variables such as climate, natural enemies, and losses due to dispersal affect the successful establishment of gypsy moth life stages that have been introduced into new areas. Given the known distribution of the gypsy moth worldwide (Giese and Schneider 1979), the insect is probably capable of surviving anywhere in the United States where

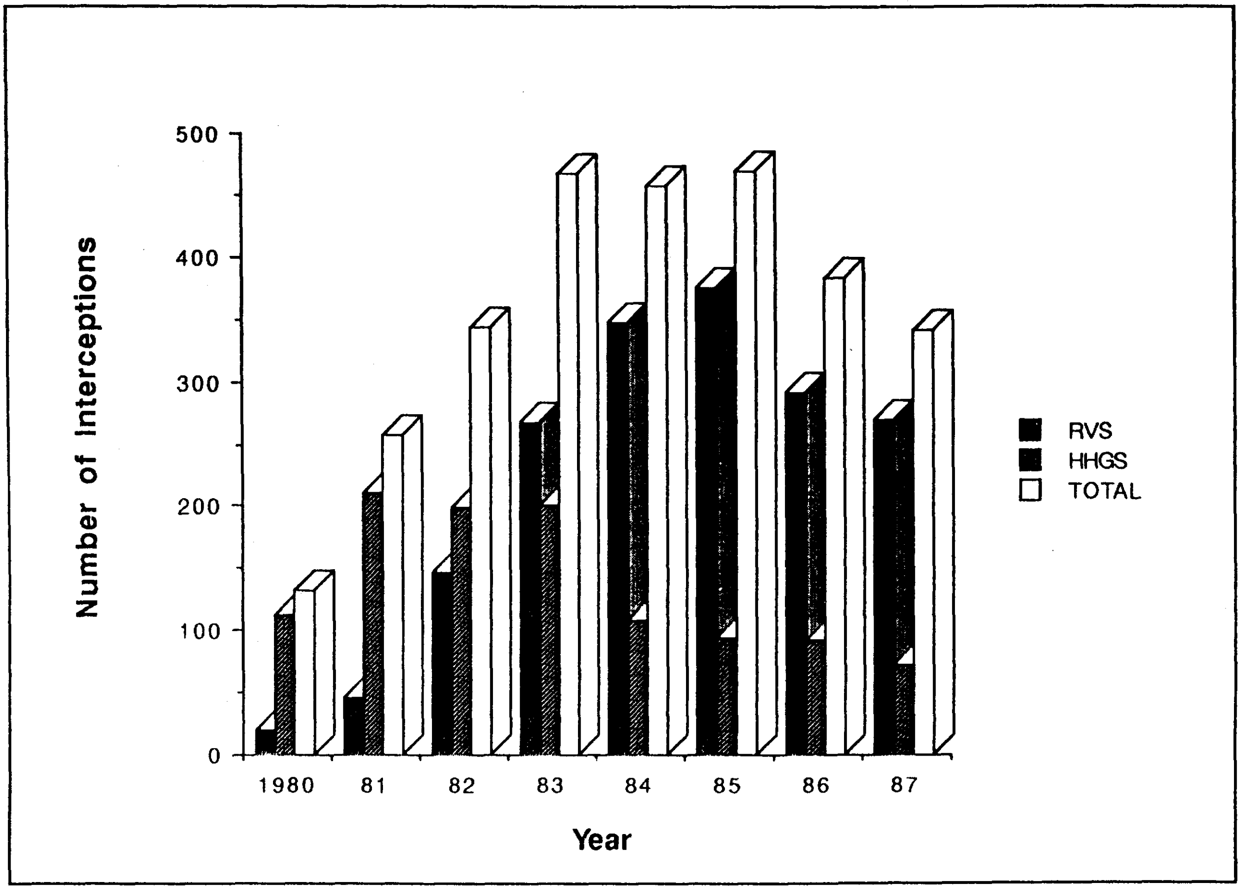

Figure 4. California interceptions from 1980-1987

suitable hosts exist. The gypsy moth is distributed as far north as Leningrad (60 N), as far south as North Africa (30-32 N) and the Far East (20 N). However, the area where periodic outbreaks occur lies between 0 and 50 E. longitude and 40-55 N. latitude and typically receives 25-100 cm of precipitation annually. Since the continental U.S. lies between 25 and 50 N. latitude, climate should not be a major factor limiting establishment by the gypsy moth.

The gypsy moth has an obligatory egg diapause whereby the egg stage must experience a period of exposure to chilling below a threshold temperature (ca. 5°C) in order to satisfy diapause requirements prerequisite to successful eclosion. The egg stage is better protected against severe cold than against mild or fluctuating temperatures. Outbreaks have occurred as far north as southern Quebec, where Madrid and Stewart (1981) concluded that lack of hosts in the province to the north are more limiting to the insect than extreme winter temperatures.

Experience with isolated infestations in the Pacific Northwest, Santa Barbara, California, and in Myrtle Beach, South Carolina, indicates that diapause requirements were satisfied in these climatically marginal areas. However, eclosion occurred much earlier in the spring and extended over a period of 4 to 8 weeks. This fact complicates the timing of eradication treatments and usually warrants repeated applications of pesticides at intervals throughout the hatch period.

Although we know little about the fate of gypsy moth life stages in new habitats, recently both parasitism and predation of life stages have been documented in instances where sterile insect releases were made to eradicate isolated infestations. In Berrien County, Michigan (1983), birds, especially blue jays, preyed heavily on releases of sterile male gypsy moths; in Bellingham, Washington (1985), where sterile eggs were released, 21 percent of the larvae collected had been parasitized by either *Cotesia melanoscelus* or *Compsilura concinnata*. Pending information from detailed studies, we can only assume that a complement of generalist parasites and predators or their ecological equivalents would attack the gypsy moth in isolated infestations.

One would think that passive dispersal of first-stage larvae would result in a high incidence of larval mortality. Hatching larvae frequently rest on or near the egg mass for hours if not days without feeding when meteorological conditions are not conducive to their dispersal. The longer they are prevented by adverse weather from dispersing, the more subject they are to predation and the lower their chances of successfully establishing on suitable foliage. Periods of rain can also drown the first-stage larvae. Windblown larvae must first survive the physical environment during the dispersal process, then locate and establish on suitable foliage after they are deposited. Airborne larvae are particularly vulnerable to desiccation. In a study by Taylor and Reling (1986), those larvae that had been collected aerially were all dead. Larvae deposited in hostile or nonforest environments obviously will not survive. The probability of establishment of those first-stage larvae that do reach forested environments is largely dependent upon the structure and composition of the vegetation in the area where they are deposited. Although estimates of gypsy moth mortality attributed to larval dispersal are not available, estimates are available for the eastern spruce budworm, another passively dispersed species. Miller (1958) estimated that the average mortality rate of first-stage budworm over a 6-year period was 64 percent and varied from 48 to 82 percent. Dispersal losses were greatest in open, mature stands and least in dense, middle-aged stands.

Many if not most introductions of gypsy moth life stages do not produce new infestations, and many factors acting in concert probably contribute to the demise of the gypsy moth in these remote situations. This conclusion is supported by the relatively few isolated infestations that have been reported in the past 13 years despite the large number of artificial introductions that apparently occur annually in states as far removed as California.

POTENTIAL IMPACT OF GYPSY MOTH ON FORESTS TO SOUTH AND WEST

On review of the approximate range of the oak-hickory and oak-pine forests beyond the currently infested area, it is apparent that there is abundant, highly suitable gypsy moth habitat to the south and west. A workshop held in West Virginia in 1987--"Coping with the gypsy moth in the new frontier"--was organized to provide the latest information on forest effects and management strategies to forest managers in states along the advancing front. This update was deemed necessary because the forests in the "new frontier," the Appalachian region, contain both a large oak component and a more valuable timber resource than those previously inhabited by the gypsy moth. In order to understand the potential impact of the gypsy moth on forests, we must shift our thinking from effects on individual trees to effects on stands of trees.

Stand Susceptibility

The term "susceptibility" refers to the potential for a forest stand to be defoliated by the gypsy moth, while "vulnerability" is the probability of mortality occurring after a stand has been defoliated. Bess et al. (1947) classified forest stands in New England as susceptible or resistant to defoliation on the basis of species composition and their history of disturbance. Species composition is the single most important factor that determines a stand's susceptibility; the higher the basal area in oaks and other preferred species such as aspen and birch, the more susceptible is the stand. Houston and

Valentine (1977) recognized the need to identify in advance of the gypsy moth those forest stands that are likely to be defoliated often and those where tree mortality is likely to be significant. They used ordination techniques to compare forest stands based on certain structural tree features known to influence gypsy moth larval behavior and survival and larval host food preferences. Later, Valentine and Houston (1984) developed discriminant functions for identifying mixed-oak stand susceptibility based on the measurement of diameters of preferred host trees and those trees that possess deep bark fissures or bark flaps between the ground and 1.83 m (6 ft). Herrick and Gansner (1986) also developed a rating system based on the basal area of oaks and that of trees with good crown condition. Mason (1987) reviewed both rating systems and provided an in-depth discussion of the merits of both approaches. It is important to recognize that susceptible stands are probably defoliated both more frequently and more severely than stands designated as resistant. However, Bess et. al. (1947) noted that resistant stands can be defoliated if they are adjacent to susceptible ones; furthermore, resistant stands that incur severe defoliation can themselves become more susceptible.

Stand Vulnerability

Stands defoliated by the gypsy moth have incurred tree mortality, growth loss, and changes in understory composition (Hicks and Fosbroke 1987). The magnitude of these impacts depends upon the number and severity of defoliations on individual trees. When trees are defoliated 50 to 60 percent or more, they respond by refoliating in midsummer. This creates stress on trees and predisposes them to attack by secondary agents (other insects and pathogens) that are the direct cause of subsequent mortality. Other stresses such as drought or frost along with site and stand conditions and incidence of secondary organisms, contribute to tree mortality and complicate the task of predicting the vulnerability of individual stands.

Although the results of studies to assess mortality after episodes of gypsy moth defoliation and to rate stand vulnerability have been somewhat variable, we can make some statements on which there is a consensus: 1) stands that contain the most oak incur the highest mortality; 2) trees that sustain two or more moderate to heavy defoliations (> 60 percent) are most likely to die; 3) trees with poor crown conditions are more vulnerable to defoliation than healthy trees; and 4) there is a "first wave effect" such that stands in newly infested areas realize the highest mortality rates after their first severe episode of defoliation. This pattern held true in New England (Campbell and Sloan 1977), New Jersey (Kegg 1973), and Pennsylvania (Quimby 1987) and appears likely to occur in the mid-Atlantic states of Maryland and West Virginia.

It is difficult to compare the published results of these studies because losses are expressed variably as value loss per acre, volume of pulpwood and sawtimber, dead trees per acre, or basal area per acre. Campbell and Sloan (1977) summarized results from the first major outbreaks in New England (1911-1931) and reported that the mortality of oak was 48 percent of total basal area and ranged from minor losses to catastrophic losses in some stands. In the aftermath, species composition of the stands was altered; they contained fewer oaks and more nonfavored species. Gypsy moth outbreaks still occur in these stands, but do not result so much in mortality as in deterioration of growth, yield, and wood quality.

The first severe outbreak in New Jersey occurred from 1968 to 1971 on the Newark watershed, where stands sustained 3 consecutive years of defoliation (> 75 percent). Net basal area loss was 44 percent; by 1972 oak mortality had reached 63 percent and another 28 percent of stems was left in declining condition (50 percent or more of canopy dead). Gansner et al. (1983) and Herrick and Gansner (1988) measured changes in forest conditions after gypsy moth defoliation in northeastern and central Pennsylvania and concluded that oak basal areas were reduced in both areas, but that timber stands outgrew most losses. These studies concentrated on the effects of defoliation on timber volume and value over a broad resource area rather than on individual stands, and since less than 40 percent of the plots in central Pennsylvania experienced even one year of moderate to heavy defoliation, mortality was properly not anticipated.

In another Pennsylvania study, where appraisals were conducted only on forest land known to have sustained repeated defoliations and tree mortality, Quimby (1987) reported tree mortality rates of 27.6 percent for pulpwood and 32.5 percent for sawtimber over nearly 350,000 acres, and 51.3 percent for both pulpwood and sawtimber over another 341,000 acres. Summer droughts during the period from 1980 to 1983 were thought to exacerbate the defoliation stress and resultant mortality. Preliminary reports on tree mortality in the ridge and valley system in western Pennsylvania and from the panhandle of West Virginia suggest that oak mortality is variable by species, but exceeds 25 percent in most areas (Twery, pers. comm.). Collectively, these studies indicate that oaks are most vulnerable to gypsy moth defoliation and incur the highest mortality rates. However, there is no consensus on which species of oak are most affected nor on whether trees growing on poor, stressed sites are more vulnerable to defoliation than those occupying better, mesic sites.

Although forest managers are primarily concerned about mortality, we should not discount the effects of defoliation on growth loss and regeneration. Hicks and Fosbroke (1987) have reviewed this subject and discussed the need to develop models from site and stand data that can predict mortality after episodes of defoliation. By linking stand vulnerability with susceptibility models, forest land managers can develop a basis for sound pest management decisions.

As the gypsy moth moves into the oak-pine forests of the South and the mixed-hardwood stands of the Midwest, questions arise about the dynamics of the insect in these stands and its ultimate impact. Several midwestern states are using available susceptibility models to rate their stands in advance of the gypsy moth. Although the species composition of these stands is more diverse, the native oak species are similar to those found in the generally infested area; consequently, these models may adequately classify stand susceptibility.

The picture in the South is more complex because oak-pine mixtures there consist of conifers and oaks that do not occur in the susceptible oak-pine stands of southern New Jersey and Cape Cod. At a recent conference on the management of pine-hardwood mixtures, presentations by Gottschalk and Twery (1989) and Montgomery et. al. (1989) synthesized what is known about the impact of gypsy moth on pine-oak stands to the north and discussed implications for management of these commercially important stands in the South.

In 1988-89, the Gypsy Moth Research and Development Program funded several projects designed to evaluate the suitability of native southern species to the gypsy moth both in the lab and in field plots established along the advancing front of the infestation. Similar evaluations are being conducted in the highly susceptible native aspen stands of central Michigan. These studies will provide data needed by forest managers to assess the potential susceptibility and vulnerability of stands in newly infested areas.

It seems likely that the gypsy moth will indeed continue to spread south and west until it runs out of suitable hosts. While large areas of southern pine will undoubtedly be resistant to defoliation, extensive commercial forest lands to the south and west of the currently infested zone are at considerable risk. Affected states must be prepared either to alter stand composition to reduce their susceptibility/vulnerability or to apply pesticide treatments more extensively than we are now capable of financing. If these management costs are deemed prohibitive, then we should consider initiatives to slow or even halt the spread of the gypsy moth in the immediate future.

CONTAINMENT: A VIABLE OPTION THEN AND NOW

Historically, there has been considerable debate on the merits of instituting a containment policy. Detractors say that since the natural spread of the moth cannot be halted, containment efforts would be futile and, furthermore, the cost of such a program would be prohibitive. Proponents argue that every year that a state remains uninfested translates into savings in pest management costs and spares the citizenry a year's worth of nuisance and damage.

Major programs have been undertaken to eradicate, control, or contain the gypsy moth since it was introduced into North America (Perry 1955). As mentioned earlier, the barrier zone that was deployed from 1923 to 1942 is credited with restricting distribution of the gypsy moth to New England east of the New York line. Felt (1942) estimated that maintenance of the barrier zone cost $210,000 annually. In 1940, the chief of the Bureau of Entomology and Plant Quarantine commissioned a blue ribbon committee to conduct a thorough appraisal of the gypsy moth problem. The committee's report strongly urged maintaining the barrier zone to prevent the spread of the moth to the central hardwood, southern Appalachian, and Piedmont regions (Korstian and Ruggles 1941), but funding for the barrier zone was drastically reduced in 1941, when resources were redirected to the war effort.

In 1952, a study group appointed by the Secretary of Agriculture initiated a program to assemble the facts needed for evaluation of the problem and for determining a future combative policy (Perry 1955). A seven-point plan for the prevention of spread and reduction in damage was formulated, including re-establishment of the barrier zone. The plan was implemented to the extent permitted by available funds, but eventually discontinued. In 1978 the Expanded Gypsy Moth Program initiated a contact with Ketron, Inc. to develop a cost/benefit analysis for gypsy moth containment. The report (Blacksten et al. 1978) concluded that significant expenditures are justified even to slow the spread of the moth and that the existing APHIS program projected a quite favorable benefit/cost ratio.

The advancing front of gypsy moth infestation is now located in the states of Michigan, Ohio, West Virginia, Virginia, and North Carolina. Any further advances into the next tier of states will greatly increase the cost of control and magnify proportionally the area from which artificial introductions can emanate. The 1952 appraisal documented that between 50 and 80 percent of the forest land in the states of Ohio, Tennessee, Kentucky, and Missouri was classified as susceptible to gypsy moth damage, based on proportion of favored food species, dry sites, poor stocking, and a history of land abuse. Clearly, there is much at risk beyond the advancing front.

A meeting of state and federal officials was recently held in Raleigh, North Carolina, to discuss the feasibility of containment given available technology and current distribution of the insect. A series of recommendations was drafted, one of which states that "a comprehensive research, development, operational plan should be developed that is specifically designed to culminate in a containment trial." The group concluded that containment is a potentially viable management strategy because of the limited mobility of the insect and because of the existence of a number of technologies that could be utilized in a containment program.

In essence, a containment program already exists. In 1988, the Appalachian Integrated Pest Management Program (AIPM) was implemented in a 38-county area of Virginia and West Virginia encompassing 5.2 million ha. One of the stated goals of this project is to minimize the spread of the gypsy moth through the AIPM area. A 2-3 km grid of pheromone traps is used to monitor populations throughout the project area. Data from these traps provide a measure of the distribution of the gypsy moth and identify areas where more intensive surveys are needed to detect possible outbreaks. Control tactics can then be deployed against spot infestations before they expand and cause economic damage. Treatments in the designated "transition zone" (Fig. 1) are analogous to the tactics used in the barrier zone in New England, though the pheromone traps now being used are far superior to the labor intensive practices used earlier. Furthermore, whereas treatments in the barrier zone consisted of creosoting egg masses and ground spraying with lead arsenate (neither of which is environmentally acceptable), we now have at our disposal biological and chemical pesticides, sterile insects, and pheromone technology that are environmentally acceptable by today's standards.

For those who may be skeptical that biological pesticides alone can eradicate an established infestation, three aerial applications of Bt coupled with intensive pheromone trapping to delineate residual populations were successful in eliminating the large infestation in Oregon over a 3-year period beginning in 1984. The area requiring treatment declined from 225,000 a in 1985, to 190,000 a in 1986, and to 12,000 a in 1987, when only 40 male moths were trapped. By expanding the existing AIPM pheromone trap network in Virginia and West Virginia through North Carolina to the east and through Ohio to the west, we could establish a containment zone within which gypsy moth populations could be delineated and suppressed as deemed necessary.

Perhaps the greatest deterrent to a containment strategy is the lack of a concerted federal commitment. At present, the Animal and Plant Health Inspection Service (APHIS) maintains the federal regulatory quarantine mainly by regulating the shipment of household goods out of the infested region and by detecting and eliminating isolated infestations, but funding for APHIS programs has not kept pace with inflation and their success has been compromised. APHIS programs must be continued and strengthened. As argued in the Ketron report, an effective containment strategy must be implemented to eliminate all artificial spread and eliminate natural spread. There must also be a federal commitment to provide the funds needed to suppress gypsy moth populations along the advancing front when densities exceed a threshold level. This is lacking in the current federal policy providing states only with matching funds. During actual outbreaks, funds available to the states are sufficient to treat only the highest priority forested lands.

To offset the high cost of containment, states in the second and third tiers beyond the advancing front should contribute to the effort as an investment in the future. A projected cost of $10 million per year is much more affordable when divided between 12 or more states as opposed to the five that make up the advancing front.

In the final analysis, if the costs are not prohibitive, the technology is adequate, and a shared state and federal commitment is made, there is every reason to believe that a containment program to slow the spread of the gypsy moth can be successful. Moreover, if we maintain the gypsy moth status quo for 5 to 10 years, there is a good possibility that ongoing bio-technological research will provide us with more effective tools for coping with the gypsy moth problem.

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