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Lloyd C. Irland

John B. Dimond

Judy L. Stone

Jonathan Falk

Ellen Baum

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Lloyd C. Irland, John B. Dimond, Judy L. Stone,
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Maine Agricultural Experiment Station
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Orono, ME 04469

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Lloyd C. Irland
The Irland Group, Forestry Consultants
Augusta, Maine

John B. Dimond
Entomology Department
University of Maine
Orono, Maine

Judy L. Stone, Jonathan Falk, and Ellen Baum
The Irland Group, Forestry Consultants
Augusta, Maine

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INTRODUCTION

This report was initiated by the Maine Forest Service (MFS) in response to concerns that a serious effort was needed to capture the experiences and lessons learned during the 1970–85 spruce budworm outbreak in Maine. The MFS retained The Irland Group to conduct the work and prepare this report.

Our objective is to synthesize the observations and experiences of land managers, as well as the principal results of recent scientific research on spruce budworm in Maine. We have tried to provide a one-stop synthesis volume useful for land managers, students, and scientists. This volume does not replace the several excellent scientific compendia that are available. Nor is it a cookbook of detailed management recommendations, but we hope our specific recommendations will be useful. Rather, it is an effort to provide a "time capsule" that will enable future forest managers to come to grips quickly with what we believe has been learned about budworm and Maine's forest from 1970–85 during a severe outbreak. It is the book that we wish we had had in 1970.

Clearly, what is summarized here cannot be uncritically applied to a future outbreak. Future forest and insect population conditions may differ markedly. We cannot generalize to future outbreaks from our sample of one. But equally clearly, future managers will want some place to begin, some overview and assessment of knowledge as of 1987.

This report briefly reviews budworm population dynamics and interactions with the forest, then describes the budworm's impacts in detail. It then reviews the three principal responses: survey and detection; spraying; and silviculture and salvage. It then offers an overview of the outbreak's effects and provides a summary of conclusions and recommendations for the future.

We focus on the budworm outbreak, changes in the forest, forest management practices, and protection programs employed. We do not offer a full history or state of the art treatment of policy, financing, survey and detection, and aircraft and spray technology, but only enough to complete a general picture. We do not consider the changing knowledge and policies in the areas on environmental and human health concerns.

One cautionary note should be expressed. No reader should assume from the title of this monograph that a "spruce budworm outbreak in Maine" had any biological reality. The outbreak in Maine was a portion of a much larger, subcontinental event, and in the biological sense, we must consider that larger picture. What is unique to Maine are the specific responses we made to the outbreak, and discussing these responses is the only strong justification for writing about an "outbreak in Maine". Most of our responses started as technology or ideas

borrowed from Canadian or other US sources, then molded to fit our unique social, political, and geographic characteristics.

In preparing this report, we began with an extensive interview survey to capture experiences, ideas, and questions from forest managers and scientists who worked in Maine's forest during the outbreak. Interviews were conducted in person by skilled researchers with experience in the budworm field. The responses were collated and have been noted as appropriate in the text. A detailed summary of the interview responses is on file with the MFS. We then reviewed pertinent literature, emphasizing local reports and the principal synthesis volumes recently issued.

CHAPTER I

BUDWORM-FOREST DYNAMICS IN MAINE

The spruce budworm, *Choristoneura fumiferana*, is one of about a dozen native species of this genus that feed on true firs (*Abies* sp.), Douglas fir (*Pseudotsuga menziesii*), spruces (*Picea* sp.), larches (*Larix* sp.), and pines (*Pinus* sp.) in North America (Harvey 1985). Only two species, the spruce and the jack pine budworms (*C. pinus*), occur in the east. The spruce budworm has the broadest distribution of all the budworms, ranging from the Yukon eastward to Newfoundland. It occurs throughout the range of balsam fir (*A. balsamea*) and of white spruce (*P. glauca*), and can probably be found in plantations outside of the natural ranges of these hosts. It has been recorded defoliating hemlock (*Tsuga canadensis*) in Pennsylvania, and was originally described from specimens collected in Virginia (Clemens 1865), although these southern areas are considered outside of the epidemic range.

While several of the budworms occur in notable, tree damaging outbreaks, the outbreaks of the spruce budworm extend over the greatest area, last the longest, and kill and damage the most trees. The three outbreaks recorded in the 20th Century have extended from Manitoba or Ontario to Nova Scotia and Newfoundland. They have persisted for 10 or more years in any one location (Brown 1970, Kettela 1983, Hardy *et al.* 1986), and have killed substantial volumes of host trees.

Biological background

Budworm has one generation per year with winter spent as unfed, early-instar larvae in silken hibernacula on the host trees. The subsequent, feeding, larval stages develop in spring to take advantage of bud burst and early shoot development; they also feed on developing reproductive buds when present. Feeding is preferentially on current shoots and is completed after 6 or 7 weeks, by late June. Pupation, moth activity, egg deposition, and hatch are completed by mid-August. Details of the life cycle of the spruce budworm are found in many sources (*e.g.* Talerico 1984).

The spring emergence of budworm larvae is best timed to utilize balsam fir and white spruce foliage. These species, the preferred hosts, tend to show severe damage and mortality earliest in an outbreak. Buds of red spruce (*P. rubens*) and black spruce (*P. mariana*) break 10 to 14 days later than those of fir and white spruce, placing them in poorer synchrony with the feeding biology of the budworm; budworms survive somewhat less well on these species. Nevertheless, these hosts may also show severe damage and mortality. Hemlock can be placed with red spruce and black spruce as somewhat less preferred hosts, and

probably would suffer little damage in the absence of the other hosts. Larch (*L. laricina*) and white pine (*P. strobus*) show feeding damage on occasion, but this seems to be restricted to the peak years of budworm outbreaks.

A notable feature of budworm biology is the mobility of populations. Large moth flights have been observed whenever outbreak populations occur. After depositing some eggs, females apparently undertake obligatory flights between subsequent egg masses, and they may drift many miles with the prevailing winds (Greenbank *et al.* 1980). Flights originating in mainland Canada are known to have crossed to Newfoundland (Otvos and Moody 1978). The cartographic histories of budworm outbreaks often show progressive west to east movements of portions of infestations; moth-flights are probably responsible for this. Newly-hatched and spring-emerged small larvae also disperse on the wind, buoyed by silken threads. This leads to substantial mortality of larvae but can also spread infestations downwind for a few miles (Greenbank 1957).

It is not uncommon for outbreaks of two or more insect species to occur simultaneously, and it was recognized late in the 1970's outbreak that the spruce budworm shares such a relationship with the spruce coneworm, *Dioryctria reniculelloides*(Spies and Dimond 1985). Maine Forest Service records showed that population fluctuations of the two species, back to 1949, were parallel; and in a state-wide survey done in 1980, coneworms were shown to represent 15 to 30 percent of the defoliator population densities on spruce at all spruce budworm densities from epidemic to endemic. Scattered reports from other localities and other outbreaks (reviewed by Spies and Dimond 1985) suggest that simultaneous outbreaks of budworm and coneworm are not unusual, and may, in fact, be the rule.

The coneworm is never common on fir; but it may be abundant enough on spruce to cause a significant fraction of the damage attributed to the spruce budworm. Biologically, it may be useful to consider a spruce budworm outbreak as a complex of two defoliator species and their associates in the spruce-fir type.

Population dynamics

The increase in spruce budworm density between endemic levels and epidemic levels is dramatic, with fewer than five larvae per tree characteristic between outbreaks and 20,000 per tree at outbreak peaks. This increase, approaching four orders of magnitude, can occur over a period of 6 or 7 years (Miller 1975). Noticeable defoliation, about 30 percent loss of current needles, occurs with populations numbering about 2000 per tree.

In spite of research on the epidemiology of this insect over the last 60 years, there is still no generally accepted, single hypothesis explaining the initiation and collapse of outbreaks. At this writing, the most recent review of the population dynamics of the budworm (Blais 1985) notes two conflicting hypotheses.

Double equilibrium hypothesis

The older hypothesis associates the development of outbreaks with extensive areas of highly susceptible forest, *i.e.* mature balsam fir, and with favorable weather, *i.e.* warm, dry conditions in May and June, the period of larval development. In theory, the budworm will be held at a low equilibrium by the activities of birds and other natural enemies for long periods. With the chance co-occurrence of highly susceptible forest and 3 or 4 years of favorable spring weather, budworm numbers leap beyond the range that natural enemies can maintain at low equilibrium. Numbers then increase until a new, high equilibrium is reached, dictated by the level of available food for the budworm. This is the double-equilibrium hypothesis first proposed by Morris (1963). Consumption of all or much of the available food by the budworm leads to the beginning of fir tree death in 3 or 4 years and heavy tree mortality after 7 or 8 years. Shortage of food is the initial cause of outbreak collapse, augmented by an increasing impact of natural enemies as budworm numbers decline, until the low equilibrium condition is reestablished. The whole process in a given location occurs over about 10 years.

A key corollary of this hypothesis is that outbreak frequency is not predictable. Obviously, some years will be required for the forest to grow back to a state of maturity where it is highly susceptible. But, this period may vary depending on whether most of the earlier forest was killed or only small portions. The occurrence of highly favorable spring weather is also unpredictable.

Supporting the double-equilibrium hypothesis is the extensive work of Blais (1983) in documenting apparent spruce budworm outbreaks over the last 200 years, using analysis of radial growth in old white spruce in various localities including Maine. He concludes that intervals between outbreaks have varied from 30 to 100 years in different regions of eastern North America. Although not directly related to this present discussion, it is of interest that his studies suggest that outbreaks in the 19th Century were less frequent, less severe, and more localized in area than 20th Century outbreaks. Blais relates this to an increased abundance of balsam fir resulting from logging disturbances, suppression of forest fires, and more recently, prevention of death of fir through application of insecticides.

An important implication of the double-equilibrium hypothesis of budworm population dynamics is that, if large-scale death of trees is the force that initiates collapse of an outbreak, then outbreaks should be prolonged, perhaps indefinitely, if tree death is prevented through protection programs.

Regular oscillatory trend hypothesis

Upon reexamination of the intensive budworm population data from the Green River Project (Morris 1963), with the addition of more recent extensive

data from all of New Brunswick, Royama (1984) has proposed a totally new interpretation of the population dynamics of the spruce budworm. Instead of populations shifting rather abruptly from a low equilibrium to a high one, and the reverse, Royama sees in the data a regular, gradual oscillatory trend in numbers, with the period between peaks and valleys at about 35 years. Modelling by Royama and by Regniere (1984) suggests that an oscillation of this type is probably driven by a density dependent mortality factor (or factors) having a delayed response to changes in budworm numbers. Both have suggested a disease as a likely mechanism, and Regniere's study has simulated a 35-year oscillation using a hypothetical, vertically-transmitted disease (from parent through egg to next generation) as the key mortality agent. At least one such disease, the microsporidian parasite, *Nosema fumiferanae*, is commonly associated with the budworm. Publication of the work of Royama and Regniere has stimulated much interest in this and other diseases, as well as other biotic mortality factors. Yet, at this writing, nothing has been resolved, and even the hypothesis of regular oscillations in budworm dynamics remains controversial. We expect that the question may be resolved by intensive research currently under way in Canada before the next outbreak arrives. But, if that has not happened, the appearance of a new outbreak on schedule in about the year 2005, will be confirming evidence.

An important implication of the regular oscillation hypothesis is that outbreaks should decline after several years whether or not trees have been killed. It is easy to conclude that our experience in the 1970's confirms the oscillation hypothesis since the outbreak has declined dramatically while substantial volumes of fir and spruce remain alive. But a very large portion of that resource that existed in 1970 has disappeared, both to budworm-caused mortality and to harvest. We have data only for Maine.

The 1986 midcycle resurvey of the Maine forest (Anon. 1987) allows comparisons of spruce-fir volumes between 1986 and the earlier 1980 survey (Powell and Dickson 1984). The 1986 survey shows live tree volume losses of 14 percent for spruce and 43 percent for fir between 1980 and 1986. For both spruce and fir, this totals 26% of the resource including all loss of volume: mortality, reduction of growth, and harvest. This is a substantial reduction, but it underestimates the total reduction during this budworm outbreak for two reasons. The heavy harvest of mature spruce-fir in the 1970 decade, especially strong in the large dbh classes, plus budworm-caused mortality in the latter part of the decade, are not included. Schiltz *et al.* (1983) show a substantial negative net growth for fir in the period 1975 to 1980. In addition, we can assume that mortality from budworm and harvesting occurred disproportionately in that portion of the spruce-fir resource that provides the most favorable conditions for budworm survival. From the budworm's point of view, the loss of "good habitat"

has been greater than the loss of trees reported in inventories; much of the resource that is left is in situations where budworm survival tends to be poor, even though foliage complements have improved markedly.

Sippell (1984) and the Green River studies (Morris 1963) suggest that budworm outbreaks include some forested areas which are unsuitable for prolonged survival of infestations. The existence of outbreaks in these types depends on repeated immigration of insects from more favorable regions. The unfavorable areas may be young stands or stands poorly stocked with budworm host trees, where heavy dispersal-loss of small larvae diminishes survival. By the late 1980's in Maine, most of the stands capable of exporting excess moths in large numbers may have been lost to harvest or budworm mortality. While a substantial volume of spruce and fir remains, it is probably in stands where infestations would not persist for long without immigration. Therefore, there is probably nothing in the recent Maine experience that would favor or reject either of the two current hypotheses of budworm dynamics.

Many aspects of the population dynamics of the spruce budworm could be discussed, but they go beyond the purpose of this publication. We will mention them briefly.

Mortality factors affecting spruce budworm are numerous and involve weather, parasitoids, predators, dispersal losses, and disease. The Green River Project monograph (Morris 1963) is probably the most exhaustive discussion; the most recent review is Blais (1985). A major conclusion is that the late larval age interval is the key point where intensity of mortality determines whether populations will increase or decrease. Weather is probably involved in the year-to-year, unpatterned, ups-and-downs in numbers that are superimposed on the overall oscillations (Royama 1984).

Much discussion has concerned whether spruce budworm outbreaks arise from discrete epicenters and spread through moth-flights, or whether there is a synchronous increase of populations across the entire region, with apparent epicenters simply being the points where defoliation is first observed. The double equilibrium hypothesis could accommodate either view; the regular oscillation hypothesis would seem to mandate the latter view. And, it is possible that both processes occur and reinforce each other.

Nevertheless, it is important to resolve this question. It has been suggested (Sippell 1984) that future, large-scale outbreaks might be prevented, delayed, or reduced in intensity by early detection and suppression of epicenters, avoiding or reducing spread from them. This approach has limited value if epicenters are, in fact, simply the first peaks of a general increase in populations across a large region. Finding an answer to this question is an important reason for maintaining budworm population monitoring systems across eastern North America through the endemic period that we seem to be entering.

Several hypotheses have been proposed to explain why warm, dry spring weather encourages increases in budworm numbers. Insects develop faster at warm temperatures; they may avoid some parasitism, predation, and disease when developing quickly in warm weather. Also, cool, wet weather may influence the insects more directly. Sanders and Luciuk (1985), for example, suggest reduced survival of early instar budworms resulting from prolonged precipitation. But, there may also be more subtle effects. Shepherd (1985) points out poor survival of western spruce budworm when spring emergence is poorly synchronized with phenology of the host tree. The degree of synchrony between insect and host is a function of weather. Finally, the chemical status of host tree foliage, in terms of both essential nutrients such as protein and usable carbohydrates and deterrent non-nutrients such as tannins and terpenes, is being recognized as a probable key element in budworm dynamics (Mattson *et al.* 1983). Dry weather, causing water-stress, probably increases the levels of key nutrients in foliage and may reduce the levels of deterrent chemicals. Budworms growing on such foliage are larger and produce more eggs. Similar chemistry may explain the differences in susceptibility between young and mature trees. Foliage of older trees appears more nutritious for herbivores and less well protected with feeding deterrents.

Finally, the observations of Hardy *et al.* (1986) on frequency and persistence of budworm outbreaks in different forest types should be noted. The intuitive notion is that the pure Boreal Forest type should be the most susceptible. But, by mapping frequency of defoliation between 1954 and 1980, it was found that the Transition Forest type, lying between the Boreal Forest and the Northern Hardwood Forest, is much more likely to experience outbreaks. The high susceptibility of Transition Forest, which tends to lie in a strip near the United States-Canadian border, is apparently explained by its combination of sufficient spruce-fir type, and a relatively warm climate. While true Boreal Forest experiences outbreaks, as in the Gaspe Peninsula and in Newfoundland, outbreaks are less frequent there because of the harsher climate.

Budworm-forest models

During the last two decades, there have been attempts to gain insight into budworm population dynamics through computer simulation modeling. The earlier models were developed in collaboration among the Maritimes Forest Research Centre (MFRC), the Institute of Resource Ecology (IRE), and the International Institute of Applied System Analysis, Vienna (IIASA), using data from the Green River Project. The MFRC/IRE model was used as the basis for a task force report on budworm control alternatives in New Brunswick (Baskerville 1976) and for other papers. In this section, we consider only regional budworm-inventory simulators and not stand-level models.

In the late 1970's, Stedinger developed a model similar to the MFRC/IRE model, designed to simulate budworm in the Maine forest (Stedinger 1977, 1984). The Stedinger, or Maine model, combines submodels for forest dynamics, mortality, and budworm dynamics, which interact with each other.

The model describes host behavior within 9300-ha "sites." A fixed percentage of each site is assumed to be covered by spruce-fir, characterized by age distribution and foliage density. The model differentiates between old and new foliage, and foliage density is affected by budworm feeding, tree mortality, and the annual production of new foliage. Budworm mortality, in turn, is based upon the ratio of new to old foliage, as affected by budworm feeding.

The population dynamics submodel simulates budworm survival or reproductive success in each of six distinct life stages. Survival of each stage depends upon functions based on key variables at that stage, including population level, stand characteristics, dispersal losses, defoliation levels, weather, and old-new foliage ratios. The model provides for dispersal of fecund female moths to other sites and for influx by long-range moth flight. The model deals with the effects of spraying by adjusting mortality in the late instars.

Stedinger found that this model simulated the effects of the budworm outbreak on individual sites more accurately than the MFRC/IRE model did. He used the model to simulate three different protection strategies, and found that the best approach was to spray when egg density at the end of the previous summer had reached the pre-outbreak level of 320 eggs/square meter. This strategy was clearly superior to the one then in place in both Maine and New Brunswick, which was to spray when tree conditions indicated that severe mortality was likely without protection. The model predicted that the aggressive spray strategy would have resulted in spraying about 1/3 the area annually as the existing Maine strategy, with 1/6 the annual defoliation. A mass infestation would have been prevented. The New Brunswick Task force study using the MFRC/IRE model also found an aggressive spray strategy to be superior.

Unfortunately, the Stedinger model has a number of weaknesses. It does not differentiate between the effects of spruce and fir on the budworm population, nor does it model the effects of spatial orientation of stands within the 9300-ha sites, or spatial effects between sites. It ignores the preference of dispersing moths for mature and overmature trees, and the effects of humidity and temperature on dispersal. The model treats as random, independent events things which are probably neither, such as weather and mass flights.

Thus, the Stedinger model is not useful in distinguishing between the double-equilibrium and regular oscillation hypotheses. In fact, the model assumes one of the key characteristics of the double-equilibrium hypothesis, the existence of independent epicenters, as one of its initial conditions. Models like this have been very useful in identifying the interrelations among factors in the budworm-

forest system, and in pointing out areas where greater knowledge is useful. However, it appears that scientists are not yet ready to build a global model of budworm behavior on which to base suppression strategies.

The fact that the Stedinger model had little or no influence on Maine policy-making is probably due more to events within Maine at the time of the model's publication, and to the general nature of the model, than to concerns based on a close analysis of the model. In 1977, Maine was engaged in a massive and highly controversial spray program, and the idea of greatly intensifying spraying was probably seen as totally infeasible politically and financially.

A basic problem which prevented both the Stedinger and MFRC/IRE models from gaining acceptance by forest managers is their lack of "transparency" (G. Baskerville, pers. comm.). A common problem with early computer modeling efforts was the tendency to build complex models whose inner workings were difficult to understand. This led to a lack of confidence in the results. Also, the population dynamics models have tended to have more of an entomological than a forestry orientation. Thus, they did not address the situation in a way that managers found relevant. In contrast, the Green Woods and WOSFOP/FORMAN models are much simpler in their logic, and were designed specifically to address particular management problems (see Chapter VI and Appendix D). Because of this, these later models have been widely used.

Historical background

The most recent spruce budworm outbreak (called the 1970's outbreak), was not a unique event and future outbreaks should be anticipated. Three widespread outbreaks in eastern North America in the 20th Century are well documented (Brown 1970, Kettela 1983). We refer to these as the 1910's, 1940's, and 1970's outbreaks, although they were not precisely confined to the decades indicated, and the timing varied somewhat in different regions. For example, outbreak peaks to the west in Quebec were a few years earlier than in New Brunswick to the east. An earlier outbreak, 1870–1880, is also known (Baskerville 1975a) but poorly documented. Several papers by Blais (*e.g.* 1981, 1983) indicate evidence of these and earlier outbreaks back to about 1700 from analysis of radial growth in old white spruce across the region. In addition, Anderson *et al.* (1986) report the finding of abundant head capsules of caterpillars of the same family as the spruce budworm in pond sediments dating back about 10,000 years. It is impossible to identify the species of these head capsules, but it is likely that they represent the spruce budworm. It is generally concluded from this evidence that periodic spruce budworm outbreaks are a natural event, associated with the maturing and regeneration of spruce-fir forests, and that the process has been occurring since early post-glacial times.

Baskerville (1975a) has speculated on the probable ecological role of bud-

worm in the forest in the undisturbed case, before extensive harvesting became dominant. He describes a typical situation for the Green River watershed in the New Brunswick panhandle, where balsam fir dominates the softwood type. Stands are of two age classes, the older having fir about 70–80 years of age, and the younger 20–30 years. A budworm outbreak develops, and in its course kills virtually all the fir in the older stand, leaving some spruce and non-host species such as birch and pine. The stand has so little cover left that it regenerates. At the same time, the younger stand suffers only partial mortality, insufficient to severely reduce stocking. By the time of the next eruption of budworm, the now mature stand suffers heavy mortality. The previous understory has grown to the 20–30 year old condition. The same pattern of mortality is repeated as in the earlier outbreak, but the acres involved are different. This view suggests a symbiotic cyclic relationship between tree and insect. The insect kills overstories but only after the forest has set the stage for regeneration, and the forest provides an endless resource for repeated outbreaks of the insect. In this view, the budworm preserves a stable but oscillatory system that involves large shifts in population numbers but which has persisted with little change for centuries. There probably exist many tree-pest systems of a similar nature. For instance, with bark beetles, young trees possess sufficient defensive systems to resist the pest under normal circumstances. Once the tree has matured and reproduced, its defenses decline and it is killed by the beetles, but continuation of the same forest type has already been assured (Mattson and Addy 1975).

The 1910's outbreak produced heavy mortality of trees in Maine, as well as in parts of Quebec and in New Brunswick (Brown 1970). Maine's loss has been estimated at about 27 million cords (Weed 1977 citing earlier sources) which amounted to about 40 percent of the commercial resource. Harvesting surviving stems further reduced the resource in the next decade (Seymour 1985), regenerating much of Maine's spruce-fir type in a brief period.

The 1940's outbreak reached Maine borders in about 1945 and ebbed and flowed in northern sections until about 1955 (Weed 1977),[1] without causing much tree mortality. The reason is not known; the stands that originated in the 1910's may have been young enough to have low vulnerability. One small area, 20,000 acres around Madawaska Lake, was sprayed in 1954, the first budworm spray project in Maine.

By 1955, the infestation in Maine was restricted to the northeast corner of Aroostook County. It intensified and enlarged somewhat, resulting in several spray projects between 1958 and 1970, but remained confined to the northeast

[1] Some of Weed's infestation maps have been reported as erroneous. For an accurate presentation for a specific year, it is best to consult the annual budworm reports of the MFS.

corner of the state. While the infestations were severe, the limited acreage involved allowed aggressive spray protection, and tree mortality was negligible.

The fact that Maine had some areas of budworm outbreak starting in 1945 and continuing through 1987 has led some to believe that we were dealing with a single budworm episode lasting an unprecedented 40 years. Examination of the cartographic histories (Brown 1970, Kettela 1983, Hardy *et al.* 1986) shows otherwise. While Maine and New Brunswick were spraying budworms in the mid- and late 1960's, this involved the last remnants of the 1940's outbreak. High budworm populations elsewhere in eastern North America existed during this period in only a few, small spots. About 1970, major upsurges once again appeared in Ontario and western Quebec, and by 1975 the entire region from Ontario to Newfoundland was involved in the largest spruce budworm outbreak ever recorded (Blais 1983, Kettela 1983).

Details of the 1970's outbreak in Maine

From the cartographic histories, the 1970's budworm outbreak in Maine appears to have originated by spreading from the remnants of the 1940's outbreak in northeast Aroostook county. However, rising infestations in Quebec undoubtedly contributed to moth flights on the prevailing winds. Maine Forest Service light trap surveys began to record increasing budworm population levels in 1971–1973 (Figure 1). During this time, defoliation was restricted mainly to

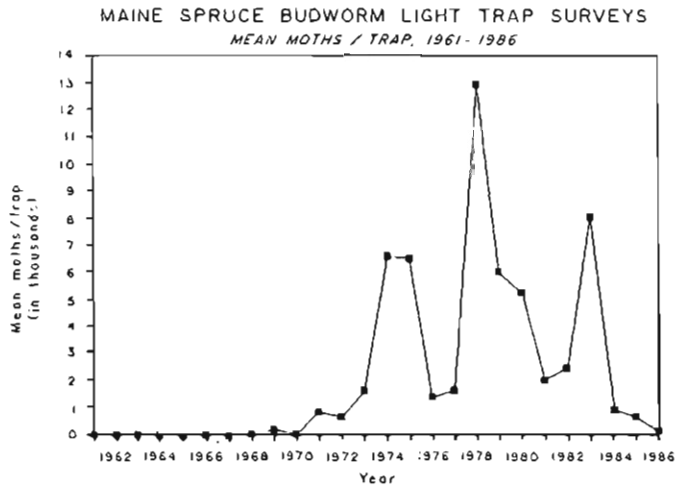


Figure 1. Mean numbers of spruce budworm moths captured in light traps (15–24 traps per year) located throughout Maine, 1961–1986. Data from Maine Forest Service annual spruce budworm reports.

northern regions of the state (Figures 2, 3). In 1974, larval populations ballooned to epidemic levels, and massive moth flights throughout the state ensued. In 1975, infestation levels and defoliation reached outbreak proportions (Figure 4). Budworm populations throughout the next decade remained in the epidemic phase, with regional variations, until their sudden collapse in 1984–1985. These population trends can be summarized by calculating the yearly average LII (second instar larval) counts from the annual spruce budworm reports (Figure 5). Budworm population trends are also revealed by their effect on the resource, as displayed in yearly defoliation maps (Figures 6, 7).

Regional analysis of the budworm outbreak was formalized in 1977, when six survey zones were delineated by the Maine Forest Service's Entomology Division (Figure 8). The regions differed in physiography, forest type, infestation history, and spray history (Table 1).

Table 1. Maine spruce budworm survey regions.

Region	Physiography	Forest Type
Allagash-St. John	Mostly flat with some rolling hills, two major river valleys, hilly in extreme north.	Predominantly contiguous spruce-fir.
Northeast	Several hilly areas with two major river valleys.	Predominantly mixed wood. Much cleared agricultural land. Few large areas of contiguous spruce-fir.
Western Mountains	Very hilly with several mountain ranges.	Susceptible type broken into relatively small sections. Fir in the valleys with spruce and hardwoods in the high areas.
Moosehead	Mostly flat in the north. Very hilly with mountains in the south.	Spruce-fir flats in the north, mixed wood and hardwood in the south.
Penobscot-Mattawamkeag	Predominantly low, flat, wet.	Flat wet areas heavy to softwood, ridges mostly hardwood.
Southeast Coastal	Coastal influence, shallow, rocky soils.	Mixed softwood and scrub hardwood. The softwood is mostly spruce with patches of fir.

From Spruce Budworm in Maine: 1977. Maine Dept. Cons., Ent. Div., Tech. Rep. No. 3.

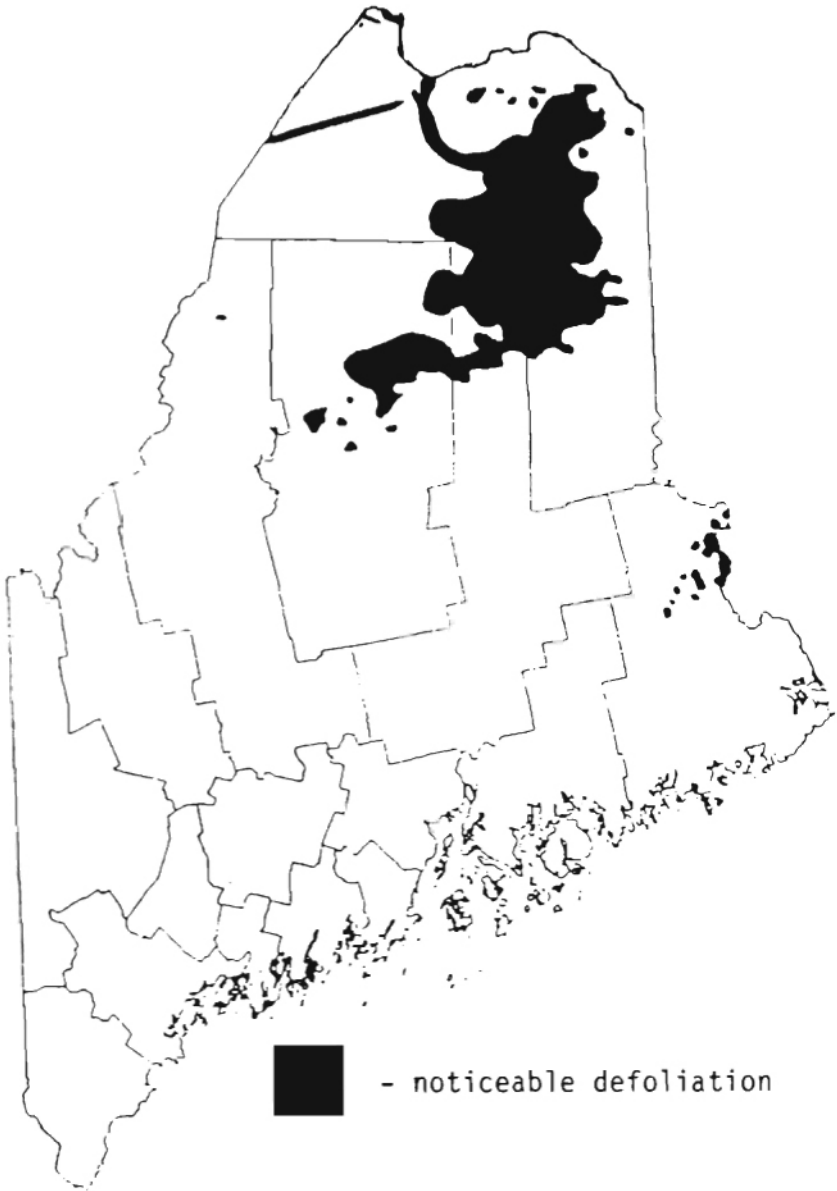


Figure 2. Spruce budworm defoliation in 1972. Redrawn from Maine Forest Service annual spruce budworm reports.

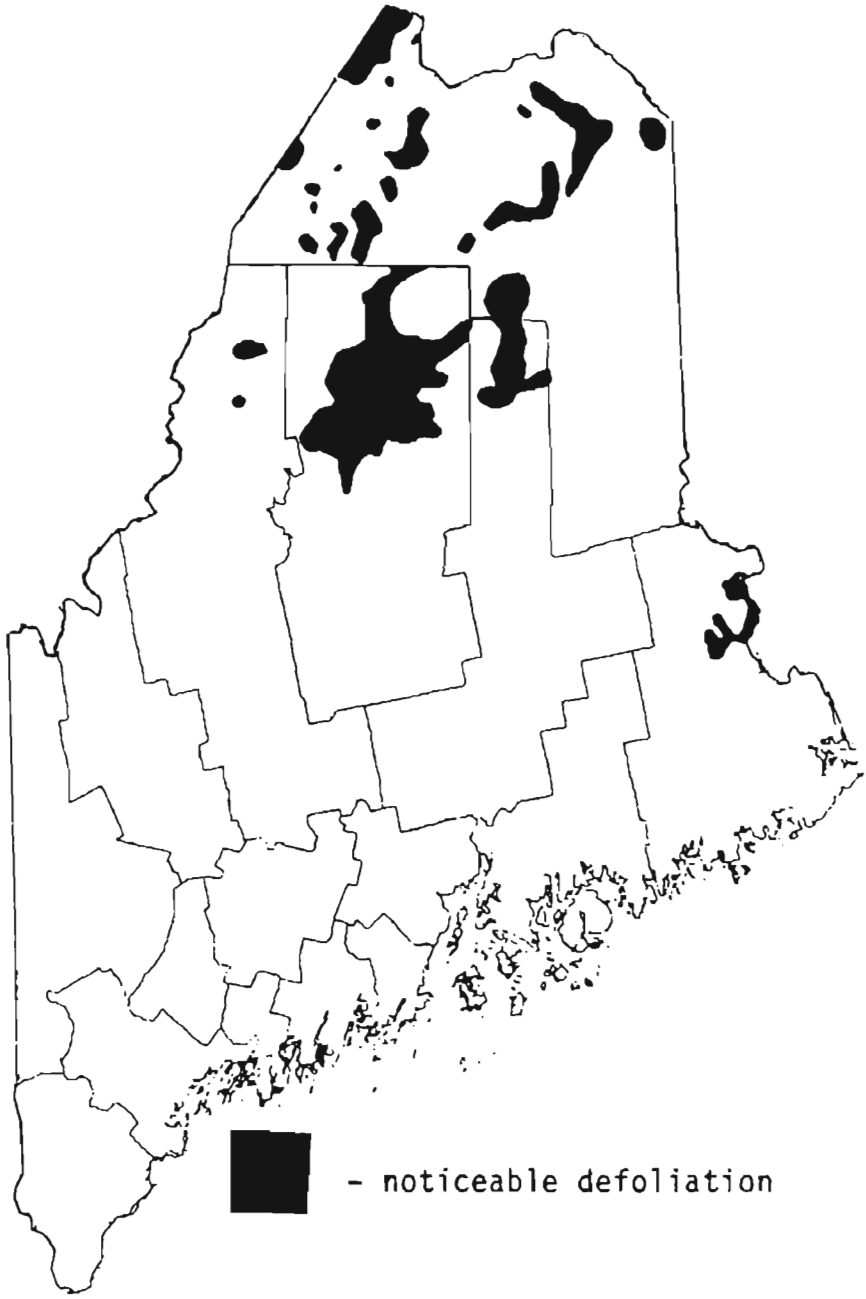


Figure 3. Spruce budworm defoliation in 1973. Redrawn from Maine Forest Service annual spruce budworm reports.

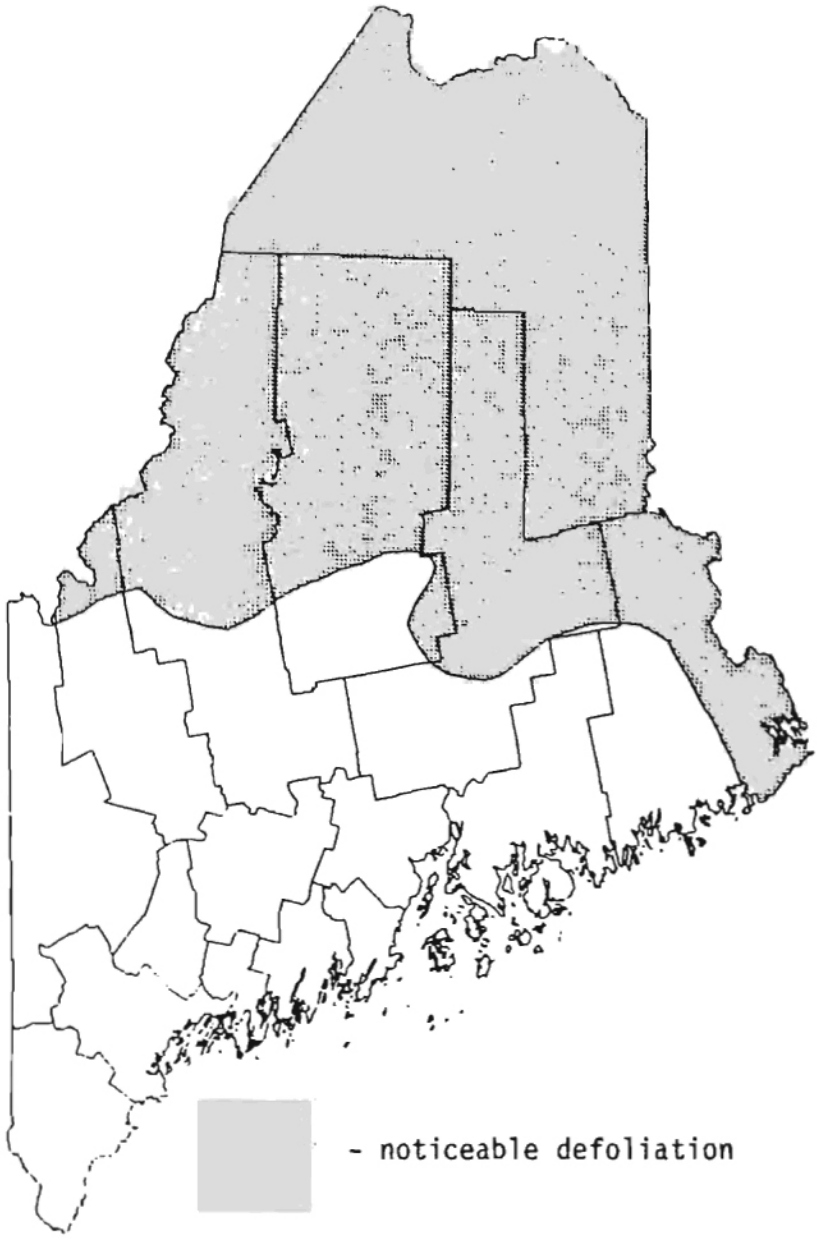


Figure 4. Spruce budworm defoliation in 1975. Redrawn from Maine Forest Service annual spruce budworm reports.

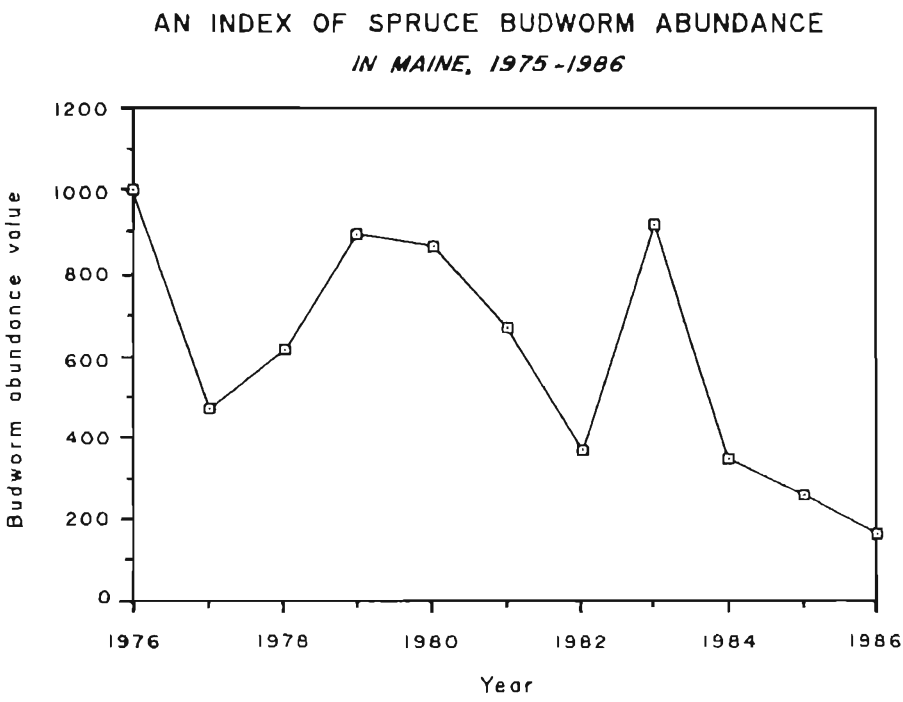


Figure 5. An index of spruce budworm abundance based on egg mass or overwintering larval surveys, state-wide, 1975–1986. Original data from Maine Forest Service annual spruce budworm reports.

Regional budworm abundance values were calculated for each region by combining the weighted averages of LII larval counts for each township in the region (Dimond, unpubl. data). When plotted against time for the six zones, these budworm abundance values provide an impression of regional population trends (Figures 9,10). It is apparent that populations fluctuated widely in all regions, showing troughs in most areas in 1977–1978 and in 1982, and peaks in 1979–1980 and in 1983. The Moosehead and Western Mountain regions showed lower population levels in most years and an earlier decline, missing the 1983 peak characteristic of the other regions. The Southeast Coastal region still shows moderate population levels as of 1987.

The annual hazard ratings prepared by the Entomology Division of the Maine Forest Service help characterize the regional impacts of the outbreak. These ratings were based on combined information from egg mass surveys and tree condition. A typical hazard rating map is shown in Figure 11. When viewed in sequence, these ratings chronicle the outbreak's intensity throughout the state.

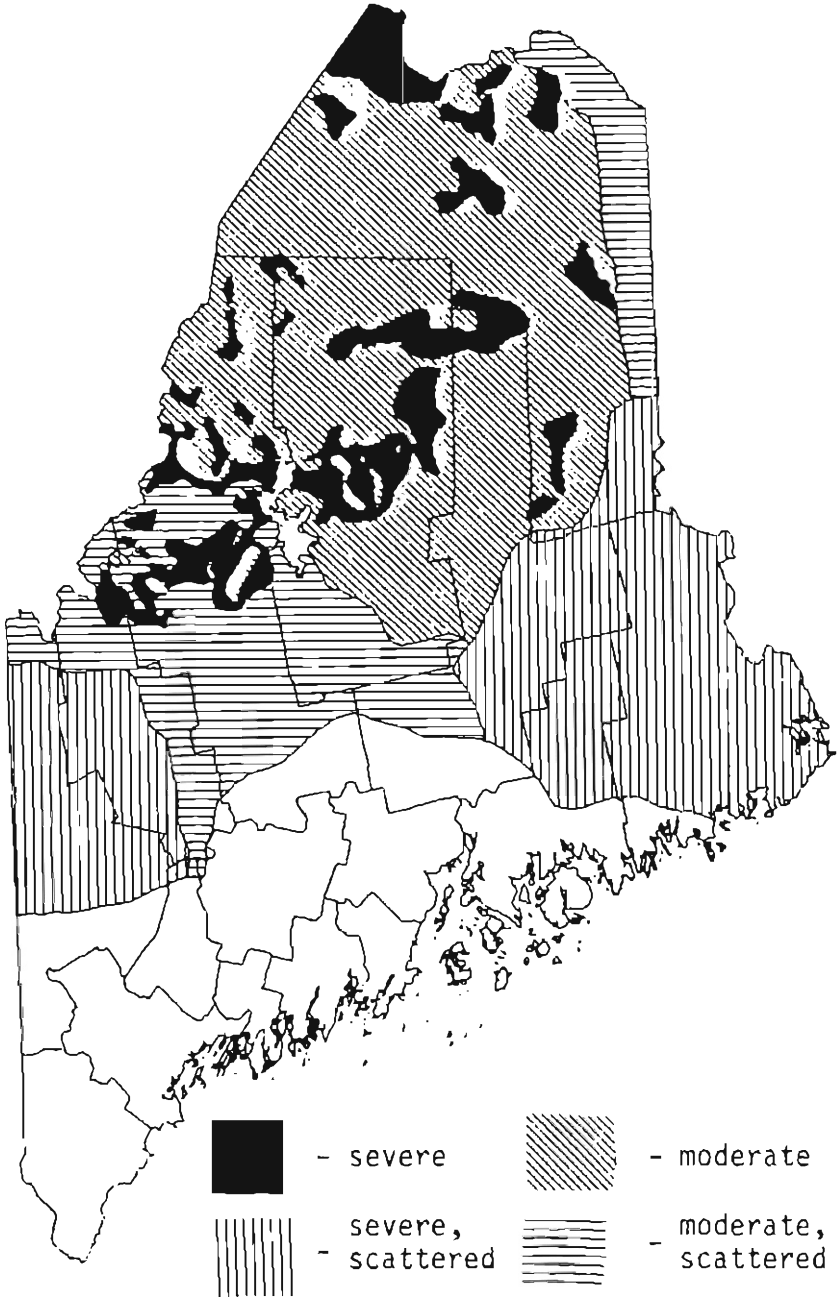


Figure 6. Spruce budworm defoliation in 1980. Redrawn from Maine Forest Service annual spruce budworm reports.

Allagash-St. John

This region, with its large contiguous spruce-fir forests, was the first to sustain severe damage. Defoliation began to occur over much of the region in 1974. Four years later, in 1978, hazard values were near maximum, due to severely damaged tree condition and high egg mass values. By 1980, following three years of protection, hazard ratings were low to high in protected areas. Untreated areas still experienced extreme hazard ratings. Hazard values were lowest in the south end of the zone and highest in the vicinity of Allagash. Hazard in this zone lowered during 1980–1982, but in 1983, heavy defoliation caused a hazard increase in some areas. In 1984, hazard remained high over much of the area. Budworm populations decreased in 1984–1985.

Northeast

The northeastern zone, with large agricultural areas and mixed-wood stands, showed signs of infestation later than the Allagash-St. John region. It did exhibit shifting pockets of infestation from the 1950's onward, but large-scale defoliation did not appear until 1973, at which time most of the zone was classified as being in a high-extreme hazard state. The hazard ratings on treated areas decreased throughout the outbreak. Most treated stands remained in fair or good condition as of 1982. In 1982, heavy defoliation and high predicted populations led to a temporary increase in hazard to extreme in the northern 1/3 of the zone. By 1983, predicted hazard had begun the downward trend that would continue until the outbreak collapsed in 1985.

Penobscot-Mattawamkeag

This region, like the Allagash-St. John zone, contains large areas of spruce-fir flats. Here, however, they are broken up by hardwood-dominated ridges. The Penobscot-Mattawamkeag zone first suffered extreme defoliation in 1975. By 1978, the characteristically high variability of infestation in the region had revealed itself, with some areas showing recovery and others displaying high host mortality rates. In 1982, hazard ratings were high to extreme, except for the Millinocket area, where hazard was only moderate. Hazard ratings fell to moderate for 1984–1985.

Southeast Coastal

Although softwood forests in the southeast coastal zone are dominated by spruce rather than fir, budworm infestation was ranked as "very extreme" beginning in 1975. Feeding by the balsam wooly aphid contributed to the decline of the scattered pockets of fir in the region. By 1980, much of the fir in the southeastern part of this zone was dead. In 1982, the southeast portion of this zone displayed some of the worst tree conditions in the state. By this time, hemlock

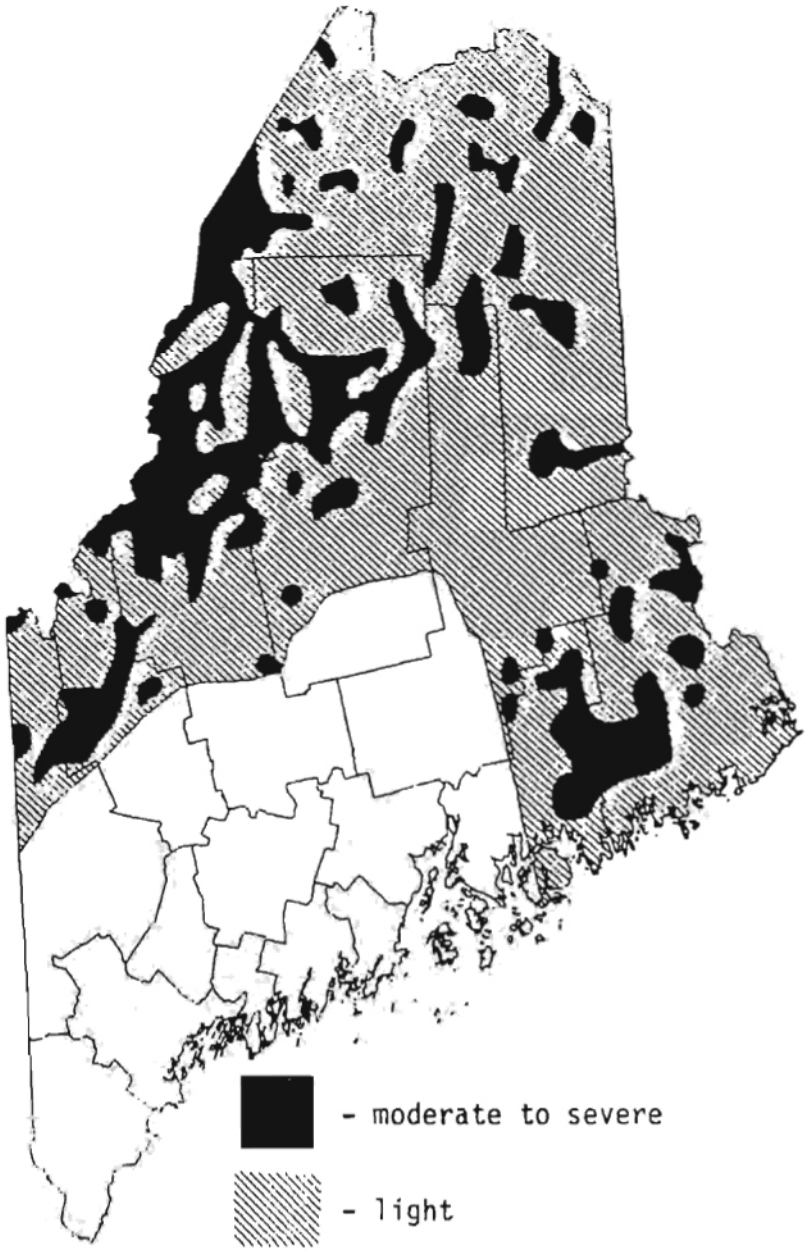


Figure 7. Spruce budworm defoliation in 1984. Redrawn from Maine Forest Service annual spruce budworm reports.

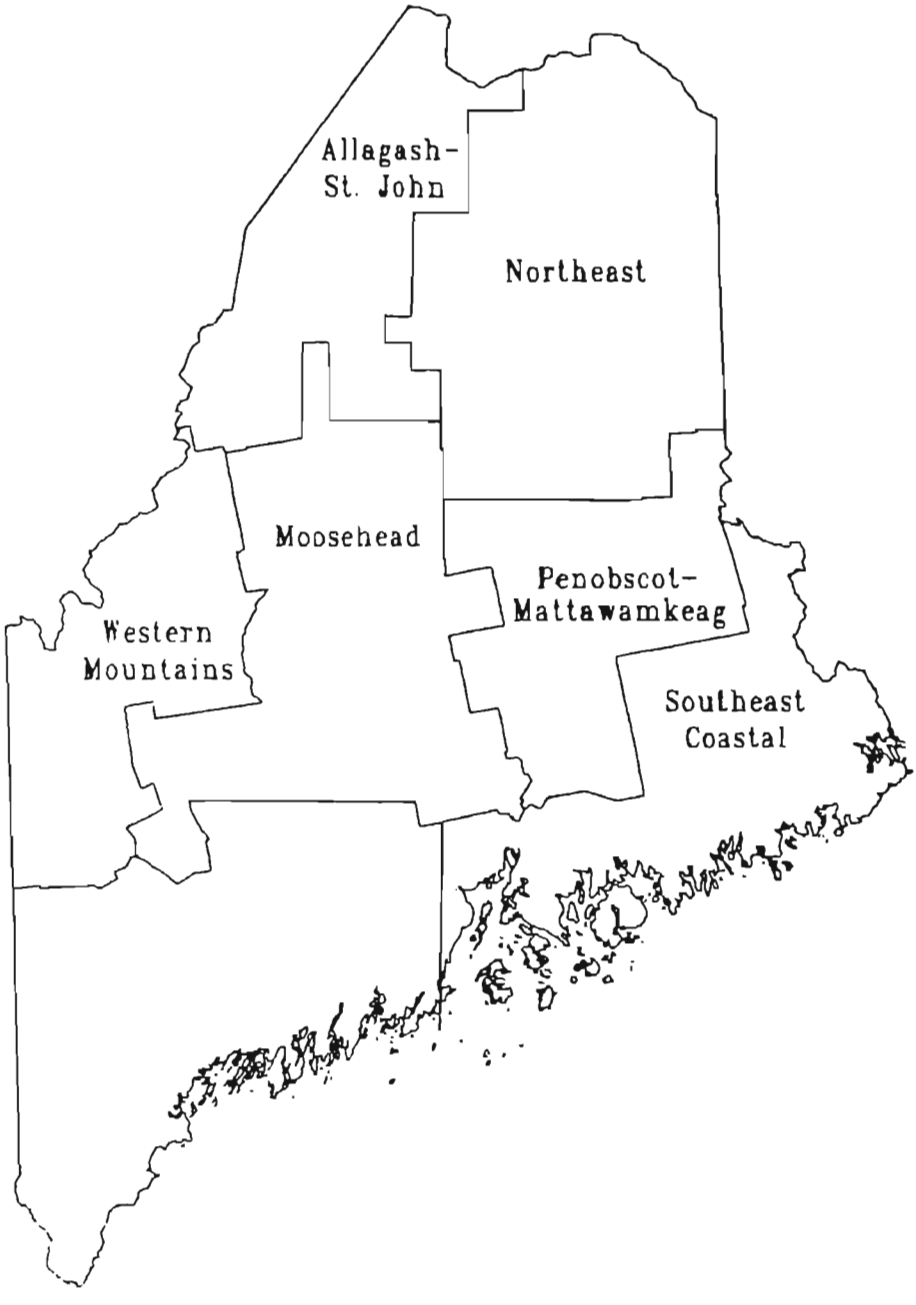


Figure 8. Zones used in spruce budworm surveys in Maine. Redrawn from Maine Forest Service annual spruce budworm reports.

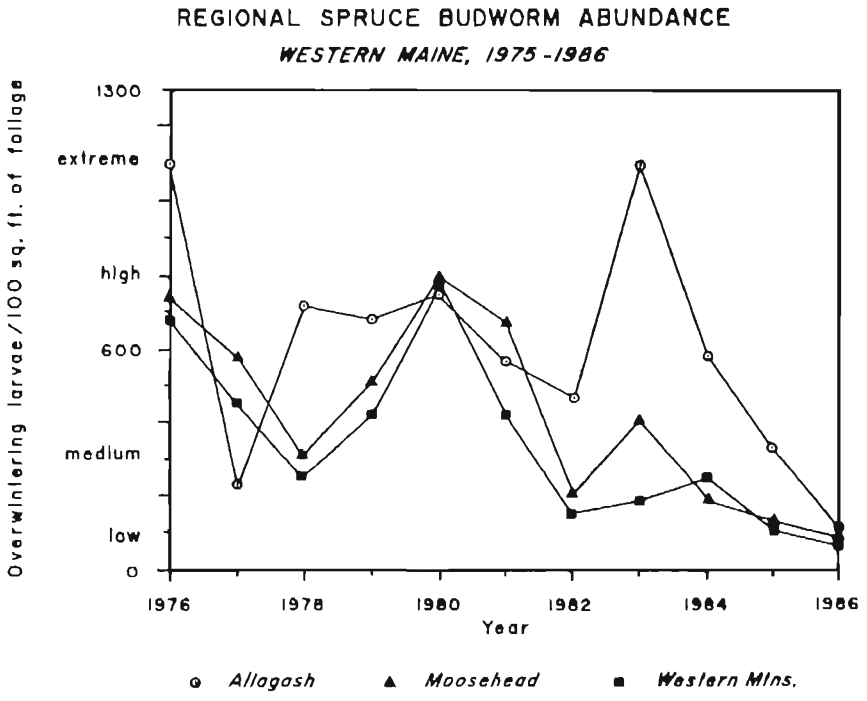


Figure 9. Regional abundance indexes for western Maine survey zones, 1975–1986. Original data from Maine Forest Service annual spruce budworm reports.

and spruce both began to succumb. Most stands were considered to be in critical condition. In 1984, the southeastern and northeastern regions of this zone continued to show high hazard ratings. As of this writing, the southeast coastal zone contains the few remaining patches of infestation in the state.

Moosehead

The northern section of the Moosehead zone is characterized by vulnerable spruce-fir flats, while the southern section consists of mixed and hardwood stands on hilly and mountainous terrain. The northern portions were first heavily defoliated beginning in 1974, the southern in 1975. As of 1979, most of the area was in fair to good condition. Severe host condition was restricted to the areas north of Moosehead Lake and near Lily Bay. By 1981, current defoliation was light, and fair to poor host conditions were due to past damage. The trend towards reduced hazard continued 1982–1985.

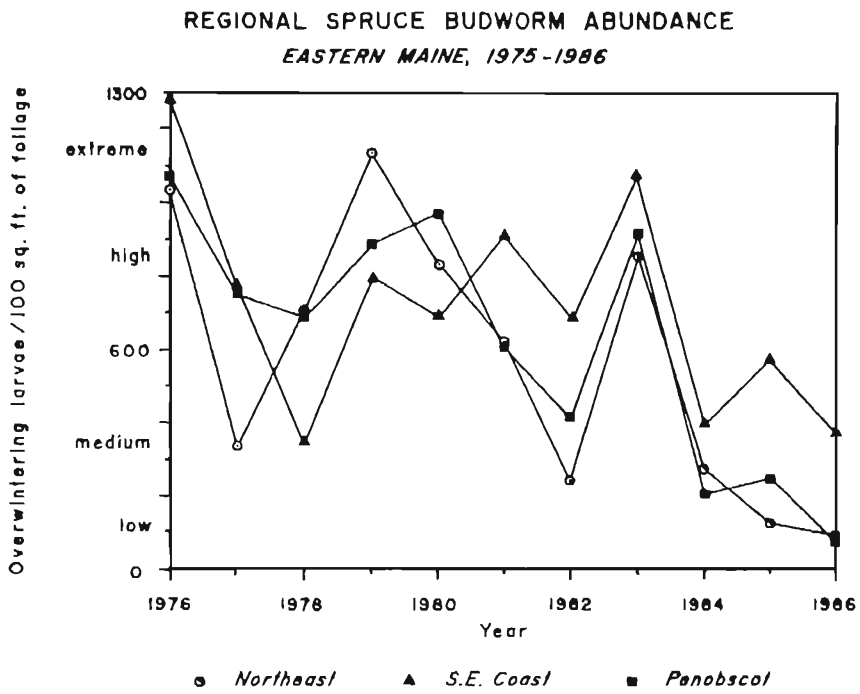


Figure 10. Regional abundance indexes for eastern Maine survey zones, 1975–1986. Original data from Maine Forest Service Service annual spruce budworm reports.

Western Mountains

In this mountainous region, spruce and hardwoods dominate the uplands, with fir often occupying valleys. Extreme infestation commenced in 1975. In 1979, the northern portion of the region was in very poor condition and the southern portion contained patches of severe condition. Heavy fir mortality had occurred by 1981, but most spruce was still alive. At this time, budworm populations began to decrease. Most of the zone received moderate to low hazard rating by 1984–85. Thus, the infestation in the western mountains struck early and passed quickly.

In summary, the outbreak first was felt throughout all regions of the state in 1974–1975. It passed relatively quickly in the Western Mountain and Moosehead regions. The outbreak lingered longest in the Allagash-St. John and Northeast regions and especially the Southeast Coastal region, where spotty defoliation continues. The areas of severe and extensive mortality increased over the years until they covered the state in a patchwork pattern (Figures 12,13,14).

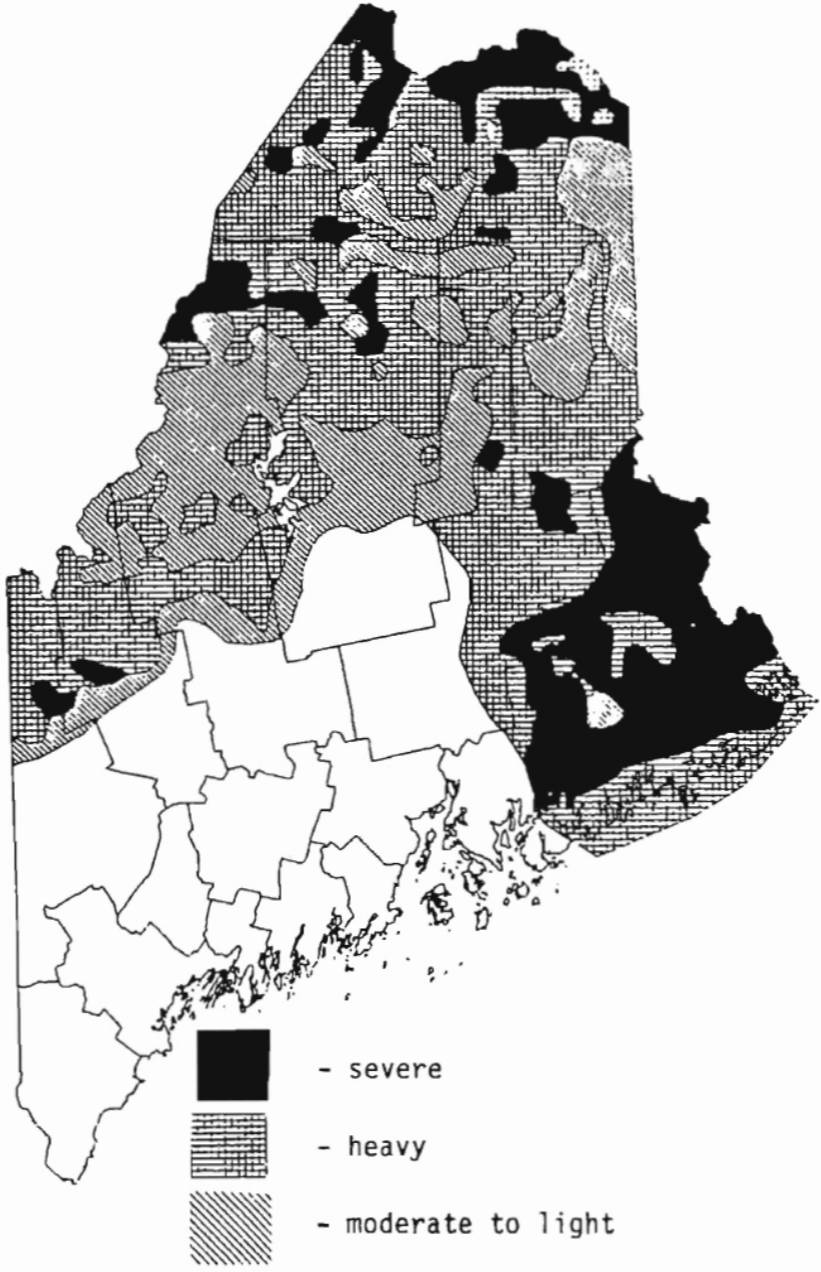


Figure 11. Map of spruce-fir hazard, 1982. Redrawn from Maine Forest Service annual spruce budworm reports.

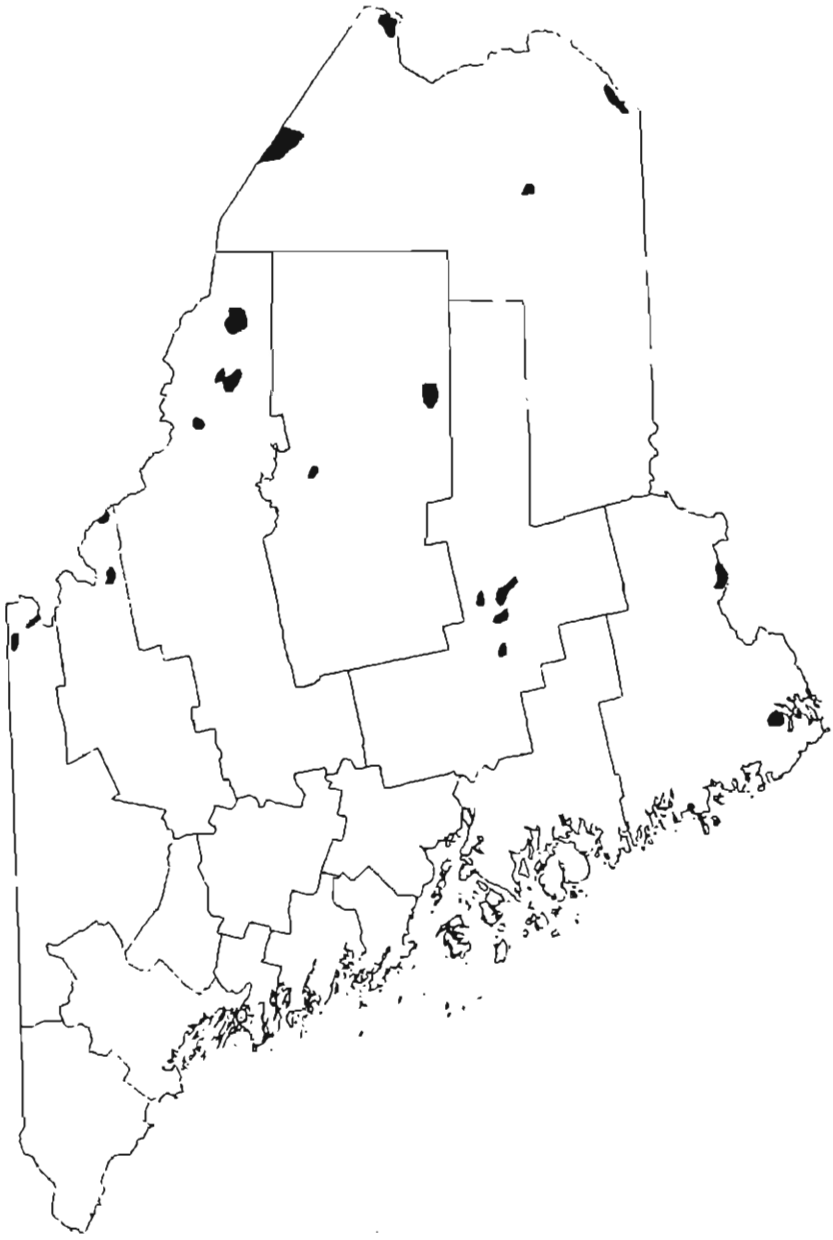


Figure 12. Areas of Maine containing 10 to 12 percent mortality of balsam fir, 1978. Redrawn from Maine Forest Service annual spruce budworm reports.

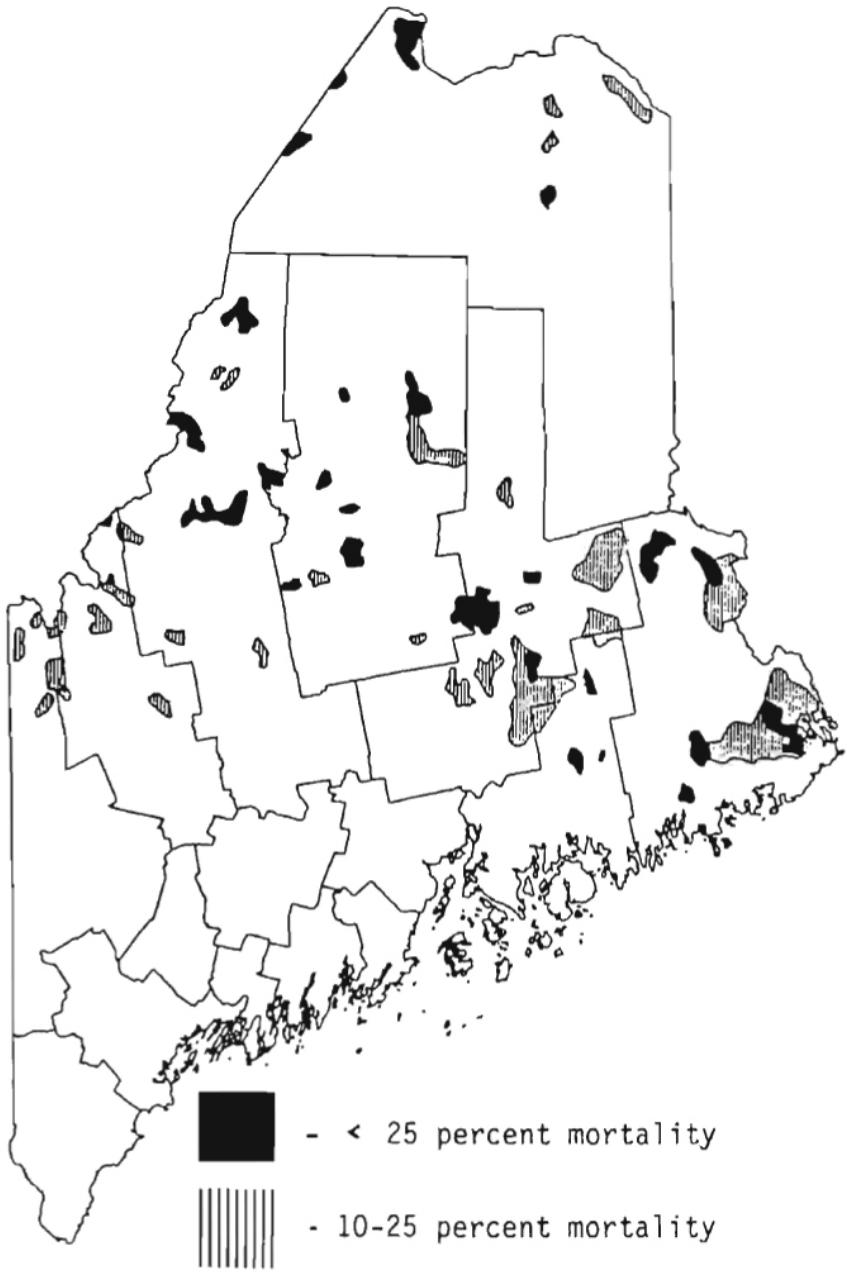


Figure 13. Areas of mortality of balsam fir, in Maine, 1981. Redrawn from Maine Forest Service annual spruce budworm reports.

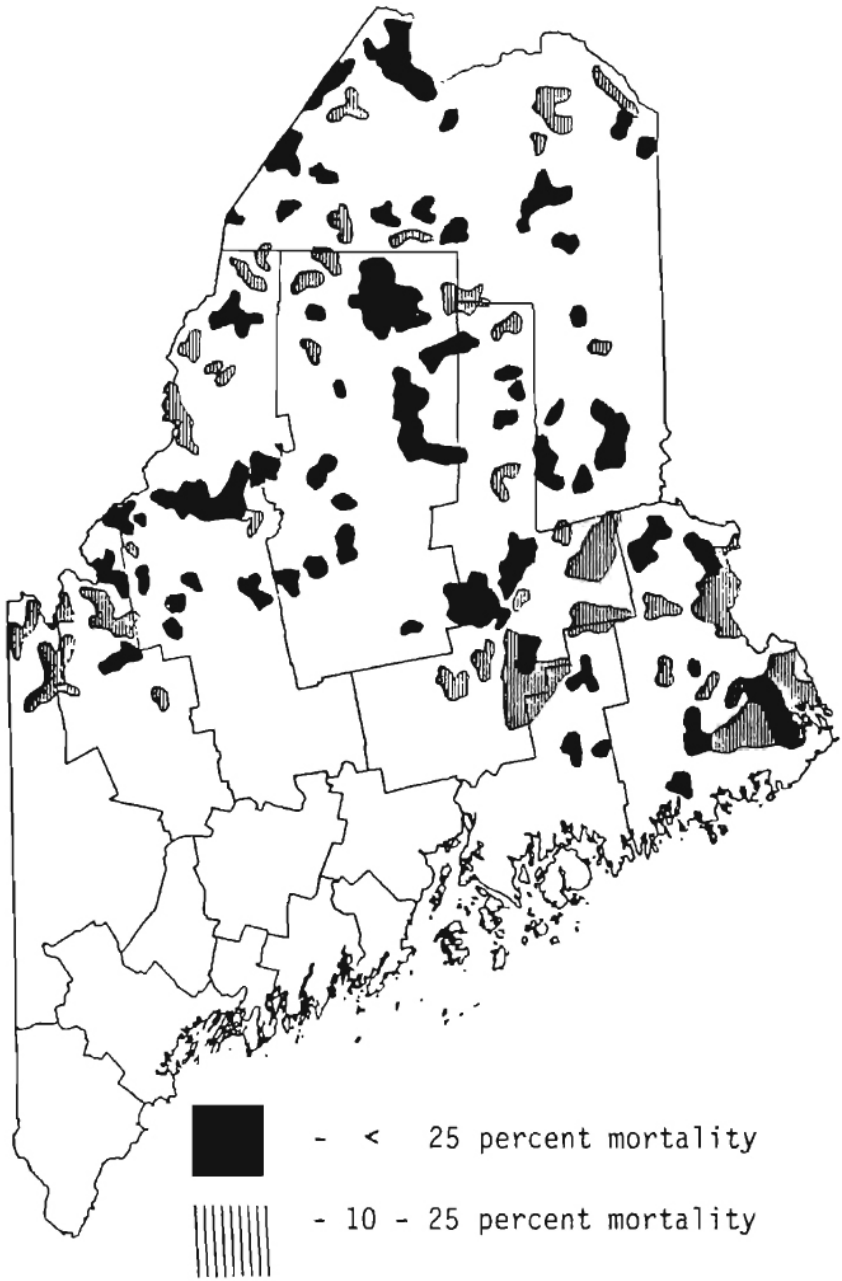


Figure 14. Areas of mortality of balsam fir, in Maine, 1983. Redrawn from Maine Forest Service annual spruce budworm reports.

The reasons for these spatial variations in outbreak intensity and duration are unknown and may simply represent random events. However, we offer the following hypotheses, not because there is much evidence to support them, but as ideas that might be tested in a future outbreak.

1. The Allagash-St. John and Western Mountain regions showed evidence of the outbreak early because they were closest to sources of moth invasion from the west. It is the same principle as with an approaching storm; precipitation begins earliest in western Maine and latest in the east.

2. The infestation declined early in the Western Mountains because, we suggest, budworm infestations will not persist for prolonged periods without moth immigration, at least not in stands of moderate and low susceptibility. The agricultural Eastern Townships of Quebec and scattered budworm infestations in New Hampshire and Vermont exported relatively few moths to the Western Mountain region compared to immigration rates in other regions of the Maine infestation.

3. The western mountain range itself may have provided a partial, physical impediment to moth invasion and further reduced hazard to that region. There is some evidence for this. Mott (pers. comm.) noted that spruce budworm defoliation ceased above a certain altitude on Mt. Katahdin. Osawa *et al.* (1986:49) reported that tree mortality in the western part of Baxter Park was greater than in the eastern part and suggested that the central mountain mass in the Park provided a shield against moth movements from west to east. Greenbank *et al.* (1980) reported that budworm moths do not fly or they drop from the airspace at low temperatures, about 14 degrees C. This is more likely to occur at high elevations, suggesting a reason why mountains may present a partial barrier.

4. For similar reasons, the Southeast Coastal region becomes a convergence zone for moth flights, perhaps explaining the high intensity and longer duration of the outbreak there. Greenbank *et al.* (1980) reported that large moth movements accompany approaching cold fronts, and such air masses move in a northwest to southeast direction in Maine. Moth flights would tend to move, therefore, from elsewhere in Maine towards the southeast coast. But, Greenbank *et al.* also described the common occurrence of night-time sea breezes, created by the cool ocean and warmer land. Moths approaching from the northwest would encounter the local sea breeze over Washington and Hancock Counties, setting up a convergence zone and a sink for moths.

As noted above, hypotheses 1 to 4 are only conjecture, supported by little hard evidence. They also require acceptance of the assumption that immigration is a key element in the dynamics of budworm populations in a given locality. This assumption is not universally accepted among budworm experts.

We have found some weak evidence to support the hypothesis that the West-

ern Mountain region was less susceptible to moth invasions than other regions (Table 2). Using MFS light trap catch data from their annual budworm reports, we assigned numbers of moths caught to the region in which each trap was located and summed these counts for the years 1972 through 1984. We did not use the years before or after this period because of extreme regionalism of the outbreak, with it restricted to the Northeast region before 1972 and to the Southeast-Coastal region after 1984. The total of moths collected in a region was divided by the number of traps operating in the region each year, producing an abundance index in the form of moths per trap-year; for example, if a region had 2 traps operating for 6 years and 3 traps operating for 7 years, the total moths collected over 13 years would be divided by 33 trap-years to produce the index.

The results of this analysis show surprising uniformity of the index for four of the regions, covering all of the central and eastern portions of the outbreak area. On the western edge, however, we have higher numbers in the Allagash-St. John region, possibly because of proximity to Quebec infestations, and quite low numbers for the Western Mountains, perhaps for the reasons we noted earlier. The out-of-region traps are traps located in southwestern Maine, away from the budworm outbreak, and as expected, collected the fewest moths. We caution that these data are weak and suggestive at best; much of the data for the Western Mountain and Southeast-Coastal regions are based on single traps operating in many of the years; the maximum number of traps operating in a region in a given year was six. The single trap operating in the Western Mountain region in a given year might attract few moths because few were there to be attracted or because it was located in a poor place to attract the insects. In defense of the data, however, trap location in the Western Mountains was shifted several times and always caught fewer moths than adjacent regions.

We should also note that data for two traps were omitted. The Blue Hill trap could be assigned to the Southeast-Coastal region. However, in contrast to the rest of the region, the Bar Harbor-Ellsworth-Blue Hill area did not experience

Table 2. An index of abundance of budworm moths in light traps for the period, 1972–1984.

Region	Moth abundance index	Number of trap years
Allagash-St. John	8,616	38
Moosehead	5,460	36
Northeast	6,350	29
Penobscot-Mattawamkeag	6,041	32
Southeast-Coastal	5,059	16
Western Mountains	1,825	23
Out-of-regions	202	42

budworm outbreak in the 1972–1984 period (H. Trial, Jr., pers. comm.), and the trap catches at Blue Hill resembled those of out-of-region traps and are totally different from the Meddybemps trap which was located in the heart of the region. Similarly, of nine traps operated in one or more years in the Northeast region, the Garfield trap averaged moth catches that were 250 times lower than the averages for other traps in the region. There seems to be something about the placement of that trap that reduces its effectiveness (R.G. Dearborn, pers. comm.), and we eliminated its counts from consideration.

CHAPTER II

THE MAINE FOREST

This chapter describes the forest itself, as it stood in 1971, and how its structure and dynamics were shaped by the budworm outbreak.

Pre-outbreak inventory

Maine's spruce-fir forest region roughly corresponds with the boundaries of the state's eight northern and eastern counties including 83% of Maine's total timberland. These counties, which are 91% forested, contain over 14 million acres of commercial timberland. In these counties spruce-fir is the dominant forest type, covering more than 50% of the timberland area; and balsam fir and red spruce are the principal species (Table 3). The dominance of spruce and fir is even more apparent when inventory volumes are compared (Table 4). In 1971, balsam fir and red spruce net growing stock volumes were roughly equal (4.9 and 4.5 billion cubic feet, respectively). There were much smaller amounts of white and black spruce. Spruce and fir in the eight counties together constituted 54% of the growing stock volume in that region, and 48% of the state's total timber volume.

Table 3. Land area by county and land use classes, 8 northernmost counties in Maine, 1982.

	in 1000's of acres					
County	Timber-land	Productive Reserved	Unpro-ductive	Total Forest	Non-Forest	Total Land
Aroostook	3768.4	10.3	32.5	3811.2	490.4	4301.6
Franklin	1014.2	4.3	16.4	1034.9	52.6	1087.5
Hancock	776.3	29.7	32.1	838.1	145.7	983.8
Oxford	1190.6	4.9	5.8	1201.3	112.7	1314.0
Penobscot	1872.7	1.4	67.3	1941.4	253.6	2195.0
Piscataquis	2238.1	192.7	32.6	2463.4	87.8	2551.2
Somerset	2334.5	0.2	11.0	2345.7	169.8	2515.5
Washington	1454.2	12.6	47.7	1514.5	140.4	1654.9
Totals: 8 northern counties	14,149.0	256.1	245.4	15,151.4	1453.0	16,603.5
Statewide	17,060.2	272.0	273.1	17,607.4	2229.4	19,836.8

From Powell and Dickson 1984, Table 151.

Table 4. Area of timberland by county and forest type group, 8 northernmost counties in Maine, 1971.

	1000's of acres		
County	Spruce/fir	Northern hardwoods	All groups
Aroostook	2237.6	1032.7	3768.4
Franklin	389.6	458.0	1014.2
Hancock	403.0	186.0	776.3
Oxford	234.1	506.5	1190.6
Penobscot	805.1	504.9	1872.7
Piscataquis	1357.9	658.6	2238.1
Somerset	1255.9	747.1	2334.5
Washington	804.7	318.5	1454.2
Totals: 8 northern counties	7487.9	4412.3	14,649.0
Statewide	7770.5	5000.9	17,060.2

From Powell and Dickson 1984, Table 153.

Red spruce and fir volumes were roughly equal, but the two species did not occur in equal proportions throughout the region. In Aroostook County and the western mountain counties of Franklin and Oxford, fir dominated spruce in the inventory by a margin of approximately 3 to 2. Conversely, in Hancock and Washington Counties the forest was quite different, with red spruce nearly twice as abundant as fir in Washington County, and nearly three times as plentiful as fir in Hancock County (Table 5).

The spruce-fir inventory in the eight county region included 15.4 billion board feet of sawtimber. This constituted 50% of the sawtimber volume in the region, and 40% of all of Maine's sawtimber. Total volumes of red spruce and fir growing stock were roughly equal. But there were 8.9 billion board feet of red spruce sawtimber, compared with only 5.1 billion board feet of fir, reflecting spruce's ability to survive longer and grow to a larger size (Table 6).

Ownership patterns

In Maine, forest industry owns the greatest percentage of timberland, and the public the smallest percentage of any state in the country. Of this industrial land, 98% is in the eight northern counties. Only 4% of the timberland is publicly owned. The remaining 42% is in private, non-industrial ownership, much of it held in large trusts, and managed essentially like the industrial lands (Table 7). The diverse pattern of ownerships has contributed in some measure to a diversity of management goals and practices across the host forest.

Table 5. Net volume of growing stock trees by species and county, 8 northernmost counties in Maine, 1971.

	In millions of cubic feet						
County	Fir	White Spruce	Red Spruce	Black Spruce	Total Soft-wood	Total Hard-wood	All Species
Aroostook	1821.5	274.9	1271.3	41.0	3965.4	1357.0	5322.4
Franklin	324.7	50.5	187.2	0.2	635.5	571.4	1206.9
Hancock	90.0	26.9	261.8	5.7	579.7	199.1	778.8
Oxford	207.2	21.4	162.2	0.0	705.0	619.6	1324.6
Penobscot	434.6	38.3	464.8	30.5	1544.6	690.0	2234.6
Piscataquis	843.9	91.0	1030.6	46.7	2501.2	947.4	3448.6
Somerset	938.3	107.7	682.5	10.5	2020.0	1038.4	3058.4
Washington	252.0	19.0	484.6	29.8	1121.8	452.4	1574.2
Totals: 8 northern counties	4912.2	629.7	4545.5	164.4	13,073.2	5875.3	18,948.5
Statewide	5050.2	652.4	4684.6	188.6	14,556.3	6810.6	21,366.9

From Powell and Dickson 1984, Table 162.

Table 6. Net volume of sawtimber trees by species and county, 8 northernmost counties in Maine, 1971.

	In millions of board feet						
County	Fir	White Spruce	Red Spruce	Black Spruce	Total Soft-wood	Total Hard-wood	All Species
Aroostook	2328.3	562.0	3048.3	26.7	7138.1	3064.4	10,202.5
Franklin	333.2	107.7	293.3	0.0	931.6	976.4	1,908.0
Hancock	32.4	53.5	564.7	6.1	1046.7	241.1	1,287.8
Oxford	279.8	35.0	299.9	0.0	1516.3	1124.5	2,640.8
Penobscot	380.0	60.0	927.8	12.3	2607.6	1302.6	3,910.2
Piscataquis	734.1	197.6	1824.2	34.8	4011.8	2149.5	6,161.3
Somerset	898.2	260.1	1052.0	8.8	2827.8	2061.4	4,889.2
Washington	132.7	37.9	886.6	14.5	1768.4	598.7	2,367.1
Totals: 8 northern counties	5118.7	1313.8	8893.8	103.2	21,846.3	11,518.6	30,999.8
Statewide	5215.3	1370.6	9141.8	114.8	25,703.4	12,840.0	38,543.0

From Powell and Dickson 1984, Table 166.

Table 7. Area of timberland by ownership class and geographical unit, 8 northernmost counties in Maine, 1982.

	In 1000's of acres					
County	Public	Forest Industry	Farm	Misc. Private	Total Private	Total
Aroostook	164.3	1955.6	273.4	1375.1	3604.1	3768.4
Hancock	41.5	337.0	64.6	332.2	734.8	776.3
Penobsot	113.8	761.1	132.8	865.0	1758.9	1872.7
Piscataquis	9.6	1433.1	20.0	693.4	2146.5	2238.1
Somerset	57.6	1647.9	105.5	523.5	2276.9	2334.5
Washington	45.8	858.1	94.2	456.1	1408.4	1454.2
Western Maine*	137.9	881.1	145.0	1040.8	2066.9	2204.8
Totals: 8 northernmost counties	570.5	7873.9	835.5	5287.1	13,996.5	14,649.0
Statewide	690.1	8016.9	1306.5	7046.7	16,370.1	17,060.2

* Western Maine = Franklin and Oxford Counties. From Powell and Dickson 1984.

Forest history and structure

The structure of the spruce-fir forest in 1971 was in large part determined by the outcome of a previous budworm outbreak, in 1910–20. While this fact is generally accepted today, its significance for budworm control and forest management was not well understood in the early 1970's. According to one reconstruction, the severe outbreak of 1910–20 left a forest with two broad age classes. These were the remnants of an older forest that had survived earlier sawlog cutting and the budworm outbreak, and a new, young age class that was released when the budworm killed the overstory (Seymour 1985). The resulting stands were understocked and two-storied, with widely scattered surviving merchantable trees, which grew slowly.

Cutting during the 1920's and 1930's removed the outbreak survivors, creating new young stands. These were similar to those composed of advanced regeneration established before 1910, which had been completely released when the budworm killed all of the overstory. The result of the budworm outbreak and subsequent harvesting, together with low wood demand before 1975, was a forest with a severely unbalanced age structure. The Sewall wood supply analysis (Sewall Co. 1983) assigned 54% of the softwood and mixedwood acreage in the 1970 forest to age classes 50–70.

By the 1950's, harvesting shifted to younger stands that had survived the 1910–20 outbreak in sapling stage. During this period, both the US Forest Serv-

ice and large private landowners began establishing systems of continuous forest inventory (CFI), using permanent plots to measure changes in the spruce-fir resource. Data from these inventory efforts began to show unprecedented growth rates, due to ingrowth as the budworm-origin age class began to reach merchantable size. Studies reported annual growth rates from 30–60 cubic feet/acre, several times those predicted by earlier studies.

These high growth rates continued through the 1960's. As the unexpectedly high growth led to a significant increase in the spruce-fir inventory, the general belief developed that the resource was underutilized, and major sawmill and pulpmill expansions were undertaken. "The possibility that this was only a temporary, non-sustainable phenomenon, due to a seriously imbalanced age structure with much of the forest in the rapidly growing 40- to 60-year age classes, apparently was not considered seriously" (Seymour 1985:203).

Cut: volume and products

Between 1971 and 1981, Maine Forest Service data show that the softwood pulpwood harvest increased by 10%, from 169.6 to 186.9 million cubic feet, while the harvest of other products (nearly entirely sawlogs), increased 27% during the same period, from 96.9 to 123.5 million cubic feet. Overall, the softwood harvest increased 16% during the period. These figures understate the sawlog harvest, since a large proportion of spruce and fir sawlogs harvested in northern and western Maine is exported to Quebec sawmills, which have not always accurately reported log purchases to the Maine Forest Service. Also, fully detailed data since 1981 are not available.

In 1981, spruce and fir sawlogs from the eight county region constituted 74% of the softwood sawlogs cut in the region, and 64% of the softwood sawlogs cut in the state (most of the remainder being white pine). When the hardwood sawlog harvest is added in, the spruce-fir sawlogs from the eight counties amounted to 64% of all sawlogs harvested in the region, and 59% of Maine's total sawlog harvest (Table 8). The principal use of spruce-fir sawlogs, in both Maine and Quebec, is in the manufacture of construction lumber.

Projected growth and demand

Forecasts of future inventories made during the 1970's were based on extrapolations of then current periodic growth rates, which led to a very optimistic view of the forest's future. For instance, in their report on the first US Forest Service resurvey of Maine, Fergusen and Kingsley (1972) predicted that Maine's softwood inventory would actually increase from 14.7 to 18.7 billion cubic feet from 1970–2000, even in the face of a 2.5-fold expansion in the harvest by 2000.

These forecasts influenced landowners' and millowners' decisions about

Table 8. Sawlog production by county and species, 8 northernmost counties in Maine, 1981.

	In millions of board feet				
County	Fir	Spruce	Total Softwood	Total Hardwood	All Species
Aroostook	90.2	155.5	256.5	17.6	274.1
Hancock	2.0	17.3	35.9	0.4	36.3
Penobscot	5.5	21.7	58.5	2.1	60.0
Piscataquis	12.4	49.6	69.1	7.7	76.8
Somerset	4.1	30.4	47.0	2.0	49.0
Washington	3.1	39.3	66.9	0.3	67.2
Western Maine*	23.7	9.7	93.9	19.0	112.9
Totals: 8 northernmost counties	141.0	323.5	627.8	49.1	679.9
Statewide	143.1	329.0	730.9	62.9	793.8

* Western Maine = Franklin and Oxford. From Nevel, Lammert, and Widman 1985.

harvest levels and capacity expansion, especially in sawmills. They also affected decisions about forest protection in the early years of the budworm outbreak. Unfortunately, the reality with regard to future spruce-fir inventories was far less hopeful. The fact that a lopsided age class structure would profoundly affect future harvest potential began to be appreciated by researchers and land managers in the late 1970's.

In 1983, the Sewall Company, under contract with the Maine Department of Conservation, used the Green Woods forest simulation model (Seymour *et al.* 1985) to analyze future spruce-fir wood supplies in Maine's eight northern counties (Sewall Co. 1983). The Green Woods model (described in more detail later in Chapter VI of this report) grows the forest being modeled in one-year age classes. Thus, it forced attention to be focused on the age class distribution that had been ignored previously.

The Sewall report presented 11 simulations of the results of different levels of harvesting and protection on the forest. The simulation which projected the current harvest level (approximately 2.9 million cords/year), showed that the harvest could not be sustained until the year 2020 (the end of the simulation). Even without a budworm outbreak, total inventory volume steadily declined. While this inventory decline is not necessarily a bad thing, the simulation results were in sharp contrast to earlier predictions. The report's methods and con-

clusions were largely substantiated in an independent review by Gordon Baskerville (1983).

The projections showed that, given the budworm outbreak, there was no feasible level of protection that would allow current harvest levels to continue until the year 2020 without a shortfall. "Clearly, the unbalanced age structure and a widespread, severe budworm outbreak have set in motion an inexorable process of inventory decline and structural change in the resource" (Seymour 1985:210). This view of the age class structure is also supported by Smith (1981:82).

Our picture of the age class structure of Maine's spruce-fir forest has been improved, as indicated above, and it is still changing. Our measured data on stand age is less extensive than might be desired, and age class estimates have, therefore, been rough approximations. There remains a school of thought that feels that the age class imbalance is not as extreme as we have depicted in this report (for an analysis emphasizing changes in tree size, see Powell, 1985). Complicating the matter further, Seymour (1987) has introduced the concept of "effective age" to account for periods of regeneration lag, early suppression, and overstocking. Undoubtedly, the accepted view on the age structure of the forest and its significance will continue to evolve in the future.

The age class structure of the forest is different from the age class structure of individual stands. Many spruce-fir stands in Maine display a wide diameter distribution of stems. In many cases, however, these often represent a single age class displaying divergent diameter and height growth due to overstocking. There are also many spruce-fir and mixed wood stands with multiple age classes but there are few stands displaying a true all-aged condition. While fir in particular tends to be present in many understories, it tends to be released by discrete events such as overstory harvest or budworm-caused mortality, thereby leading to stands (or age classes in multi-storied stands) that are effectively even-aged.

The 1986 midcycle resurvey (Anon. 1987) of the spruce-fir resource conducted by the Department of Conservation found that spruce-fir removals from 1980–86 averaged nearly 5 million cords/year, more than 70% greater than the 2.9 million cords/year figure used in the Sewall projection (Anon. 1987). Some of this discrepancy may be explained by the underreporting of log exports to Canada. If this much higher harvest figure represents a long-term trend, the spruce-fir resource may be under even greater pressure than the Sewall report indicated. On the other hand, the harvest level has already declined as the brief burst of salvage activity subsides. The long-run implications of demand and supply for Maine timber were reviewed in a recent report commissioned by the Maine DOC (RISI 1987). A more recent analysis, using a different model, projects more optimistic conclusions but shows that the harvest level of the late

1970's cannot be sustained beyond the year 2000 without intensified management (Seymour and Lemin 1987, Seymour 1987).

In summary, the spruce-fir forest of northern and eastern Maine represents the state's principal timber resource, and supports the majority of Maine's forest product industries. In the 1970's, at the beginning of the budworm outbreak, the prevailing opinion was that there was an abundance of spruce and fir. Forest survey data (Table 9) show that the inventory peaked in the 1970's. In fact, even without budworm, the harvest was already approaching, or even exceeding, the level which could be sustained in the long term. Thus, the budworm infestation developed in a forest in which there was no long-term surplus of spruce and fir.

Table 9. Spruce-fir growing stock volume in Maine (billion cu. ft.)

	1959	1971	1982	1986
Fir				
Growing stock	3.6	5.0	4.0	—
All live trees	—	—	4.4	2.5
Spruce				
Growing stock	4.0	5.5	5.8	—
All live trees	—	—	6.4	5.5
Total				
Growing stock	7.6	10.5	9.8	—
All live trees	—	—	10.8	8.0

Note: The 1959–82 and 82–86 comparisons overlap in 1982 to account for different geographic coverage and tree definitions used.
Source: Powell, 1985, p. 63, and Maine Forest Service, 1987, p. 15.

CHAPTER III

IMPACTS OF THE OUTBREAK ON SPRUCE-FIR STANDS

This chapter reviews literature and field experience concerning the impact of the budworm outbreak on spruce-fir stands in Maine. Impacts on the resource as a whole are reviewed in Chapter VII.

Mortality patterns in Maine

Mortality due to spruce budworm defoliation varies widely, both within and between stands (Tables 10, 11), and is therefore difficult to predict for any given stand (MacLean 1980). Note, however, that of the Maine studies listed (Table 11), only Osawa *et al.* (1986) was undertaken at the end of the outbreak. The remaining four studies were made 6 to 8 years into the outbreak and do not represent the final impact. It may be significant that, in describing losses on Great Northern Paper Co. lands following the 1910's outbreak, Hazelton (1976) reported losses very similar to those reported by Osawa *et al.* for Baxter Park in the recent outbreak. But some generalizations can be made about conditions which are correlated with high susceptibility and vulnerability. Susceptibility, or the probability that a forest area will be attacked by budworm, is influenced

Table 10. Components of change in volume of all trees alive in the 1980 U.S. Forest Service Survey.*

	SPRUCE		FIR	
	Mil ft^3	Percent	Mil ft^3	Percent
1980 live growth	6439.2	100	4399.8	100
Ingrowth	+ 372.2	+ 5.8	+ 196.1	+ 4.5
Accretion	+ 550.0	+ 8.5	+ 333.5	+ 7.6
Mortality	– 402.6	– 6.3	–1478.6	– 33.6
Net growth	+ 520.6	+ 8.1	– 949.0	– 21.6
Removals	–1476.3	–22.9	–1011.0	– 23.0
Net change	– 956.7	–14.9	–1960.9	– 44.6
		(–14)		(– 43)
1986 live growth**	5482.5	–8.5	2438.9	– 55.4
	(5532.3)		(2525.1)	

*The average time between surveys is 5.4 years.

**The change components were based on a subsample of the survey. The first value is obtained by adding the change components to the 1980 live growth volume. Values in parentheses are estimates based on the survey as a whole.

From the 1986 Midcycle Resurvey of the spruce-fir forest in Maine, Tables 1 & 7.

Table 11. Average budworm-caused mortality in softwood stands as a percentage of pre-outbreak basal area during the 1970's outbreak in Maine.

Citation	Years defoliated	Region	% Fir mortality	% Spruce mortality
Brann *et al.* 1985	8	Maine	14.6[a]	1.9[a]
Devine and Conner 1980	6	Moosehorn	48.5	7.5
Osawa *et al.* 1986	13	Baxter	85-96	25-45
Seymour 1980	6	Baxter	16.9-24.5[b]	3.3-4.1[b]
Seymour 1980	6	Baxter	22.7-63.8[c]	3.2- 25.5[c]

[a] Includes both protected and unprotected stands; all other values in this table refer to unprotected stands.
[b] Ranges represent increasing percentage of fir in softwood stands.
[c] Ranges represent decreasing crown position in spruce-fir stands.

by stand composition, age, intensity of the outbreak, and geographic location. Vulnerability is the probability that an infestation will result in damage and is partially dependent upon susceptibility (Mott 1963). Other factors such as individual tree vigor, presence of other insects and of diseases, tree species, and duration of the outbreak also affect vulnerability. Since vulnerability is the more inclusive term, it will be used in this paper to indicate "susceptibility and vulnerability" unless specifically indicated otherwise.

Fir vs. spruce vulnerability

The relative vulnerability of fir and red spruce was first quantified by Craighead (1924) for the 1910–1920 outbreak. He studied spruce-fir flats in southern Quebec and New Brunswick, in what was known as the "Acadian" region. This forest type, which also extends into Maine, was a northern hardwoods association mixed with conifers, of which red spruce was most characteristic. Craighead found that spruce mortality was consistently lower than fir mortality. On plots where fir mortality was greater than 90%, spruce mortality was only 29–65%. Fir mortality was distributed throughout all diameter classes, while red spruce mortality was concentrated in small diameter classes.

Seymour (1980) stated that in Baxter Park, "fir mortality was 3–8 times greater than spruce in all years and under all conditions. After three years of mortality in 1979, fir tree mortality had reached over 50% in all softwood types, while red spruce mortality remained under 10%" (Table 12). In the same region

Table 12. Annual mortality of balsam fir and red spruce due to spruce budworm defoliation according to stand type in Baxter State Park.

Stand type	Balsam Fir Mortality			Red Spruce Mortality		
	1977	1978	1979	1977	1978	1979
	Percentage of 1976 basal area					
>70% fir	11.9 a	18.2 a	24.5 a	1.4	3.4	4.1 a
>85% spruce	13.2 a	16.8 a	20.7 a	2.8	2.6	2.8 a
mixed spruce-fir	10.5 a	14.8 a	16.9 a	1.5	1.5	3.3 a
sprayed control	*	7.0 b	10.3 bc	*	1.2	1.1 b
>35% non-host	4.2 b	4.5 bc	8.3 bc	2.2	1.2	1.0 b
young fir (< 25 yrs old)	0.3 b	1.5 c	5.4 c	none	none	0.04 b

* Control plots established in 1978. Area sprayed in 1973, 1975, 1976, and 1979.
Within years, means followed by the same letter do not differ at the 0.05 level.
From Seymour 1980.

four years later, Osawa *et al.* (1986) found that the average volume lost to mortality of spruce was 27% and in fir was 77%.

These studies might be seen as a special case in Maine, since they are restricted to unsprayed areas. However, the Cooperative Forestry Research Unit reports on the Growth Impact Study, which covers all of northern Maine, echo these findings. In 1976, near the beginning of the outbreak, balsam fir accounted for about 47% of the total mortality in the spruce-fir type. By 1980, 78% of the total mortality volume was fir (Schiltz *et al.* 1983, Solomon 1988). During the year 1981–1982, 14.6% of fir basal area was lost to budworm mortality in softwood stands, but only 1.9% of spruce basal area (the great majority of which is red spruce) (Table 13; Brann *et al.* 1985).

Two hypotheses have been advanced to explain the lower vulnerability of spruce. The first, labeled the phenology hypothesis (Osawa *et al.* 1986) holds that fir is more vulnerable because development of budworm larvae is better synchronized with fir shoot growth than with red and black spruce shoot growth. Balsam fir bud break coincides with the emergence of budworm larvae from hibernation, while the buds of spruce open later. The other hypothesis grants relative invulnerability to spruce because old foliage of fir is more readily consumed than that of spruce (Seymour 1980). Also, spruce trees bear more buds than fir.

Despite studies showing spruce to be far less vulnerable than fir, landowners perceive the situation differently. Ten out of fourteen respondents to our survey felt that while spruce is initially less affected than fir, the two are equally vulnerable, given enough time. The time lag could explain the incompatibility of these perceptions with the studies conducted in the 1970's, but not with those con-

Table 13. Mortality due to the spruce budworm in northern Maine during 1981-1982.

	Balsam Fir		Red Spruce	
	sq ft/ acre	% of 1981 total BA	sq ft/ acre	% of 1981 total BA
SOFTWOOD STANDS				
1982 growing stock [a]	22		45	
1981 growing stock [b]	26.02		45.58	
1981-1982 cut [c]	1.25	4.8	0.93	2.0
1981-1982 mortality	4.41	17.0	1.21	2.6
mortality due to budworm [d]	3.79	14.6	0.87	1.9
MIXED WOOD STANDS				
1982 growing stock	21		20	
1981 growing stock	22.99		19.72	
1981-1982 cut	0	0	0	0
1981-1982 mortality	2.36	10.3	0.43	2.2
mortality due to budworm	1.63	7.1	0.25	1.3

Figures taken from the following sources in Brann *et al.* 1985:
[a] 1982 growing stock taken from Table 1.
[b] 1981 growing stock calculated by subtracting net growth (Table 2) from 1981 growing stock value.
[c] Cut and mortality values are from Table 3.
[d] Mortality due to the spruce budworm is from Table 4.

ducted in 1982 (Brann *et al.* 1985) and 1983 (Osawa *et al.* 1986). Perhaps the landowners' opinions stem, in part, from an earlier view that spruce would be absolutely invulnerable to attack.

Also, there is a difference between the fact that spruce is less vulnerable than fir and the belief that unprotected spruce will not suffer heavy damage in a severe budworm outbreak. Many landowners found that, although spruce stood up better than fir to budworm attack, unprotected spruce stands still suffered economically unacceptable losses. Some spruce stands suffered nearly 100% mortality.

Spruce vulnerability: white vs. red vs. black

White spruce is generally regarded as the next most vulnerable species after balsam fir, followed by red and black spruce. Quantifications of white spruce vulnerability and mortality in Maine, where it is patchily distributed, are almost non-existent in literature.

Several life-history traits of white spruce make it an acceptable second choice for budworm (Greenbank 1963). Its buds open about 4 days after balsam fir in New Brunswick, while red and black spruce buds open 10–14 days later. White spruce offers ideal oviposition sites in stands filled with defoliated fir, since moths prefer closely spaced needles of new shoots. It also produces more and larger shoots than does balsam fir, allowing it to support a high budworm population with less mortality than fir.

Red spruce is considered to be the next most vulnerable host, followed by black spruce, which is relatively invulnerable. Although the phenology of the two species is similar, their foliage quality is different. Red spruce foliage from previous years can support budworm larvae until bud break, whereas the old foliage of black spruce does not supply adequate nutrients (Greenbank 1963).

For the current outbreak, most interviewees agreed with the susceptibility ranking white>red>black. Some felt, however, that white spruce was more resilient than red, resulting in a lower vulnerability. Almost everyone agreed that black spruce was the least vulnerable, but some people mentioned that black spruce on upland sites may not exhibit the same vulnerability as it has on poorly-drained sites.

Osawa (1986) examined the vulnerability of hybrid swarms of red and black spruce in relation to drainage class. "Reddish" (>50% red characteristics) spruce showed about 70% average mortality for all drainage classes. "Blackish" (>50% black characteristics) spruce mortality was higher on dry sites; an average of 24% died on hydric sites, while 49% died on mesic sites. It is not clear whether phenology, foliage quality, or some factor affecting tree vigor is responsible for the greater mortality of black spruce on upland sites.

Osawa's research demonstrates the fact that red spruce and black spruce in Maine are not distinct and well-defined species. Red and black spruce actually exist as a continuum, with red spruce at one end, black spruce at the other, and hybrids which are more or less "reddish" and "blackish" in the middle. It is not clear how much of the observed variability in red spruce vulnerability in Maine can be attributed to this genetic variability.

Damage to black spruce, and in some cases red spruce, appears to have been reported more commonly in maritime climates such as Nova Scotia, Newfoundland, and southeastern Maine (Dimond, pers. comm.). Maritime weather conditions may provide closer synchrony between budworm spring emergence and bud break on spruce.

Species composition: proportion of fir/spruce

Seymour (1980) found that average mortality of fir and red spruce was not significantly affected by the relative proportions of the two species (Table 12).

Due to the higher vulnerability of fir, however, total basal area loss increased with increasing proportions of fir in softwood stands.

Species composition: mixed wood stands

Seymour (1980) found that mortality of both fir and red spruce was much lower in mixed wood than in softwood stands. Fir mortality in mixed wood stands was only one-third that in mature conifer types. During 1978 and 1979 in the mixed wood types, only 8% of the codominant firs and 30% of the overtopped and intermediate crown classes died, compared to 32% of the co-dominants and 60% of the lower crown classes in the softwood types. Spruce showed a similar pattern, with mortality for all crown classes lower in the mixed wood type.

Osawa *et al.* (1986) found that, for Baxter Park as a whole, both fir and spruce mortality decreased with increasing proportions of non-host species. As the proportion of non-host species increased from less than 5% to greater than 35%, the percent mortality of spruce dropped from 32% to 16% and that of fir from 93% to 52%. In four out of the six individual towns, however, the proportion of non-host species was not related to mortality levels.

Various theories have been advanced to explain the lower vulnerability of fir in mixed stands. It seems that all stands may be equally susceptible and that only vulnerability differs (Seymour 1980:59). Seymour (1980) reviews some of the current theories: 1) parasitism of budworm eggs by *Trichogramma minutum* increases due to increased availability of alternate hosts (Kemp and Simmons 1978). 2) Dispersal losses of budworm larvae are higher in mixed-wood stands (Kemp and Simmons 1979). 3) Budworm favors exposed crowns as oviposition sites. Fewer spruce and fir have emergent crowns in mixed wood sites; many are at least partially overtopped by hardwoods. 4) Hardwood shade reduces cambial respiration of defoliated firs, saving energy.

In spite of the theoretical basis and experimental evidence for lower vulnerability of spruce and fir in mixed-wood stands, about half of the land managers that we interviewed did not perceive much difference in vulnerability in mixed-wood stands. Most emphasize that at lower outbreak levels or near the boundary of the infestation, host species within mixed-wood stands may be less vulnerable. But they believed that when budworm populations within a stand remained at extreme levels for a long enough time, the vulnerability of host species in mixed wood stands approached that of softwood stands.

Stand age

During the 1910–1920 outbreak in the spruce-fir flats of the Acadian region, stands under 60 years of age were relatively invulnerable, with mortality restricted to smaller diameter classes (Craighead 1924). In stands 60–100 years

old, average fir mortality was greater than 60% and was distributed throughout all diameter classes. Seymour (1980) found that mortality was not related to age in stands between 60–90 years, but was much lower in 25-year old stands. During the last year of the study, however, mortality in the young fir stand increased 400% (Table 13), so perhaps the lower vulnerability of young fir disappears after prolonged infestation. Young red spruce, in contrast, was apparently invulnerable to budworm attack throughout the duration of the study.

Interview respondents were evenly divided into three views about the influence of age on stand vulnerability: older stands are more vulnerable, stands of all ages are equally vulnerable, or older stands are more vulnerable only at peak infestations. This gradient of opinions parallels the respondents' beliefs regarding species composition and stand vulnerability; the classical theories regarding initial stand conditions hold up until peak infestations, at which point all stands seem equally vulnerable.

Stand density

Several authors have suggested that vulnerability increases with stand density (Craighead 1925, Morris and Bishop 1951, Witter *et al.* 1984). Lower vulnerability in open stands may be due to increased vigor (Craighead 1925), increased dispersal loss of larvae (Mott 1963), or a combination of the two. At outbreak levels, dispersal loss probably has a negligible effect, but increased tree vigor resulting from optimum stocking might still decrease vulnerability. Unfortunately none of the studies to date has separated the effects of age and density. Since older stands are often overstocked, the resultant lack of vigor may be as important as age in determining vulnerability. One of the land managers interviewed lent support to this idea by citing severe budworm damage on thick, 25–30 year old stands that originated from clear-cuts in the 1950's.

The interviewees were divided about the influence of stand density on vulnerability. Almost half thought that density made no difference, an equal number thought that open stands are less vulnerable, and several felt that open stands were more vulnerable. A majority agreed that thinnings undertaken during the course of an outbreak did nothing to reduce vulnerability, and might even increase it. Thus, they believed that thinning needed to be accompanied by protection to minimize loss. In general, interviewees felt that stand density was a less significant influence on vulnerability than many other factors.

Site quality

Stands on poorly-drained or extremely dry sites are considered more vulnerable to budworm damage (Witter *et al.* 1984). Beyond this, little has been established about the influence of site factors on stand vulnerability, although re-

search on this subject has been initiated recently (Schmitt *et al.* 1983, Witter *et al.* 1984).

Vigorously growing trees are reputed to be less vulnerable to budworm defoliation (Craighead 1925), which could imply that stands on better sites, where growth is generally vigorous, would tend to be less vulnerable. A relationship between site quality and vulnerability has not been established, however. Seymour (1980:56) suggests that site quality tends to be confounded with species composition, since mixed wood stands tend to occupy the better sites. Mixed wood firs have a root system up to 25% larger than similar-sized trees on softwood sites. This is important, according to the energy-budget hypothesis, which says that trees with lower levels of stored energy may be more vulnerable (Osawa *et al.* 1986). Smaller root systems could also explain why vulnerability increases on poorly-drained sites.

Stands on extremely dry sites are also vulnerable, perhaps due to the effect of water status on foliar nutrient level (White 1976, Osawa *et al.* 1986). According to this theory, trees experiencing (water) stress will produce "quality" rather than "quantity" foliage, that is, they will allocate more nutrients, especially nitrogen, to the needles that they do produce (Montgomery 1985). Higher nitrogen content facilitates budworm growth and development. The observation that dry sites are especially vulnerable is supported by a growing body of evidence relating drought to insect outbreaks (Mattson and Haack 1987).

The foliar nutrition theory, if true, has sobering implications. Capital-intensive activities such as planting on good sites and applying fertilizer on poorer sites, may lead to increased vulnerability because higher foliar nitrogen content will lead to increased vulnerability (Schmitt *et al.* 1983).

Topography

Topography could influence the course of budworm outbreaks due to differences in micro-climate, site effects on tree vigor, or wind patterns associated with topographical features. Impressions of those interviewed were not strong in this area, and it is difficult to separate the effects of site quality and topography. Some felt that high elevation sites (>700 m) were less affected, while others mentioned that stands on poorly drained sites may have been more vulnerable. Mott (pers. comm.) believes that physiography and geography act together to influence host vulnerability. He observes that spruce is more vulnerable on lowland sites on the coast and on upland sites in Baxter State Park. Entomologists noted early in the outbreak that heavy defoliation tended to appear first along stream courses (D. Stark, pers. comm.).

Osawa *et al.* (1986) found that spruce mortality was consistently higher at high elevations than at lower ones (Table 14). Above 600 meters, spruce mortality was 41%, while below 600 meters, it was 22%. Fir mortality did not show

Table 14. Fir and spruce mortality following a 13-year uncontrolled spruce budworm outbreak in Baxter State Park in relation to stand composition and elevation..

	% fir mortality	% spruce mortality	combined mortality	N
Proportion of non-hosts by basal area				
less than 5%	93 a	32 a	48 a	101
5-35 %	85 b	25 b	51 a	203
greater than 35%	52 c	16 c	36 b	98
significance level	***	***	***	
Proportion of fir by basal area				
greater than 50%	94	36 a	71 a	13
30-50 %	93	45 ab	62 a	16
10-30 %	92	38 ab	47 b	43
less than 10%	96	23 b	27 c	
significance level	n.s.	**	***	
Elevation				
below 600 m	82	22 b	44 b	347
600-870 m	78	41 a	64 a	55
significance level	n.s.	***	***	

Significance levels: *** is $p < 0.0001$, ** is $p < 0.01$, and n.s. is not significant.
The same letter indicates that the means are not significantly different at the 5% level.

this change. This effect may be an interaction with spruce mortality as seen on other high-elevation sites in New England where budworm is absent, the cause of which may be air pollution or other environmental stress.

Mortality patterns in other regions

Some mortality patterns appear similar across the entire area from the Lake States to the Maritimes. One of the most constant is the relationship of mortality to the duration of the outbreak. In a review of nearly 20 studies, encompassing 100 plots throughout the eastern budworm infestation zone, mortality in mature fir stands consistently began about 4–5 years after the onset of severe defoliation (MacLean 1980). Mortality ended, on the average, about 12 years after the onset of the outbreak, with an average of 70–100% mortality in mature fir stands. In general, immature stands took longer to show mortality losses,

averaging 7–8 years after the onset of severe defoliation, and total mortality in immature stands was lower, only about 30–70% (MacLean 1980). This agrees with studies and landowner perceptions in Maine. One study found an exception to this pattern, however. In the Ottawa watershed in Quebec, mortality in 20–50 year old stands was almost as high as in mature stands (Blais 1981).

The lower vulnerability of spruce was another consistent pattern. Studies in Quebec (Blais 1981), New Brunswick (Clowater and Andrews 1981), and Nova Scotia (Wellings and Bailey 1982) agree with findings in Maine that fir is far more vulnerable than spruce. Within spruce species, the perception that the vulnerability decreases in the order white>red>black is not substantiated by a study in New Brunswick, where all four types of spruce (white, red, black, and red/black hybrid) were found to be equally vulnerable (MacLean *et al.* 1984).

Protection history is also related to mortality patterns region-wide. In the 50's outbreak in Minnesota, Batzer (1973) found that 12 years after the onset of the outbreak, the volume of the unsprayed stands averaged 1/3 that of the sprayed stands. Most of this mortality occurred after the collapse of the outbreak, a result not unfamiliar to Maine, where the 1982 forest inventory showed minor losses compared with the 1986 mid-cycle survey (see Chapter 7).

Protection history and mortality

According to the land managers interviewed, protection history is an important variable in determining the mortality rate in infested areas. Several stated that the difference is so clear that one can see distinct borders between protected and unprotected areas from the air. Others emphasized that spraying, at worst, bought time in which to salvage.

While qualitative judgments agree that protection makes a major difference in forestalling mortality, quantitative studies are few. Normally, spraying is applied to badly damaged stands and withheld from stands in better condition, making direct comparisons difficult. Fleming *et al.* (1984), in one of the few studies of spraying in Maine, suggest that spraying may not always confer the benefits that landowners might hope. Each year from 1975–1980, they examined the benefits conferred by spraying. The maximum reduction in average defoliation was only 20%, while the maximum reduction in average egg mass density was 50%. This study does not separate aggressively protected stands from those sprayed only once. An unpublished MFS study comparing aggressive treatments to unsprayed stands will show a much more favorable outcome from spraying (H. Trial, Jr. pers. comm.). The Cooperative Growth Impact Study (Solomon 1988 in prog.) provides one basis for such a comparison, but the final report was not available at this writing.

Baxter State Park and the Moosehorn National Wildlife Refuge, due to their no-spray policies, provided controls for "natural experiments" on the effect of

spraying. In the Moosehorn study, no tree or top mortality was attributed to budworm in the sprayed area following three summers of severe defoliation. Within the unsprayed area, average fir top and tree mortality was 43% and 13% respectively (Table 15). By the spring of 1981, fir top and tree mortality had increased to 56% and 48.5%. Spruce began to show top mortality (8.5%) and tree mortal-

Table 15. Percent tree and top mortality due to spruce budworm in the Moosehorn National Wildlife Refuge and a neighboring protected forest.

	1977 Moosehorn (unprotected)	1977 Control (protected)	1979 Moosehorn (unprotected)
FIR			
% top kill			
suppressed	43 *	0	75.0
intermediate	45	0	73.0
co-dominant	40	0	62.0
dominant	25	0	54.0
average	43	0	56.0
% tree kill			
suppressed	18	0	62.0
intermediate	18	0	55.0
co-dominant	10	0	52.0
dominant	5	0	49.0
average	13	0	48.5
SPRUCE			
% top kill			
suppressed	—	—	0.0
intermediate	—	—	9.0
co-dominant	—	—	0.0
dominant	—	—	7.0
average	—	—	8.5
% tree kill			
suppressed	—	—	0.0
intermediate	—	—	10.0
co-dominant	—	—	3.0
dominant	—	—	4.0
average	—	—	7.5

From Figures 13, 15 and 16 in Devine *et al.* 1978 and Figures 10,12, and 13 in Devine and Conner 1980.

* All values except for the averages are estimated from the published line graphs.

Table 16. Balsam fir and red spruce mortality in the Baxter State Park region for sprayed and unprotected stands by crown class and stand type. Mortality values express the percentage of trees alive in 1977 that died in 1978-1979.

Stand type	BALSAM FIR			RED SPRUCE		
	Over-topped	Inter-mediate	Codom-inants	Over-topped	Inter-mediate	Codom-inants
>70% fir						
sprayed	59.4	39.4	11.3	3.7*	5.3*	0.0*
unsprayed	77.9	68.5	41.7	18.6	20.5	9.7
spruce-fir						
sprayed	38.7	38.1	13.7	11.3	0.9	0.0
unsprayed	63.8	56.5	22.7	25.5	9.9	3.2
>85% spruce						
sprayed	68.0	38.6	3.8	23.7*	2.1	0.0
unsprayed	52.2	58.2	7.9	22.8	7.0	2.8
>35% non-host						
sprayed	15.1	11.8	3.4*	11.1	3.8*	0.0*
unsprayed	26.4	22.2	7.9	5.6	3.1	0.6

From Seymour 1980, Table 8.

* Rates not significantly different at the 0.05 level. The lack of significance in the spruce mortality rates in the fir stand type is probably due to the small sample sizes for these comparisons.

ity (7.5%), mostly in the 2–4"dbh and intermediate crown class. The sprayed areas were not treated after 1977, so a long-term comparison was not possible.

In and near Baxter State Park, Seymour (1980) found that fir mortality was lower in sprayed than in unsprayed stands for every combination of crown class and stand type (Table 16). On the average, between 31% and 43% of the fir basal area was lost to mortality on the unsprayed plots during 1978–1979, while just over 17% was lost on the sprayed plots. Red spruce mortality in softwood types was also lower in protected stands (Table 17). Spruce in protected stands lost 2.3% of its original basal area to mortality in protected stands and 4.8% to 7.5% in unprotected stands. Solomon (1985b) noted that moderately aggressive spraying could also preserve growth.

One private landowner provided us with the company's own analysis of the impact of spraying. Northern Maine, excluding this company's ownership, provides an example of partial spray protection with a heavy reliance on salvage harvests. Inventory data before, or early in the outbreak and inventory data after or late in the outbreak are used to make the comparisons.

By 1986, 81% of this company's 1981 spruce and fir inventory still remained. By contrast, on all other ownerships in northern and central Maine, just 65% of the 1981 spruce and fir inventory remained. Both situations are significantly affected by harvesting. Mid-cycle survey results indicate that harvesting took place at a much greater rate in the northern part of the state as a whole than on this company's lands. This was undoubtedly primarily in reaction to heavy damage and mortality from the spruce budworm, in spite of some efforts at protection. Probably no other landowner in the state stuck with the protection program as consistently and aggressively as did this company.

The estimate of unprotected inventory can be compared with the actual inventory reported in 1986. This information indicates a gain due to protection of 36%. Other, less quantifiable benefits have certainly occurred and will occur in the future, including:

- greater success in directing harvest operations into the areas with the worst mortality while "holding" others;
- fewer dead stubs to pose a safety hazard to employees working in the woods;
- better tree health or vigor which will permit resumption of higher growth rates than from live, but unprotected trees; and, finally,
- higher total volume growth in the future because there are more live trees surviving.

A more recent study in Baxter Park corroborated earlier evidence that spraying improved fir survival (Osawa 1986). Twelve years after the onset of the infestation, unprotected softwood stands lost over 90% of their original fir basal area, while protected softwood stands lost 56%–65%. The benefit of spraying spruce was less clear in this study; only in stands dominated by fir was spruce survival significantly higher under a protection regime (Table 17).

The inconsistent success of chemical protection on spruce is echoed in land-manager perceptions. Although spruce is less vulnerable, it has a reputation for being difficult to protect, due to several factors (Keenan and Moritato 1985). First, spruce defoliation is harder to detect than fir defoliation because spruce retains its older foliage longer. Since damage to spruce takes the form of bud-mining rather than the inefficient foliage destruction that occurs on fir, the vivid reddening of crowns is not seen on spruce. This delay in recognizing spruce defoliation tends to lead to a delay in initiating protection. In mixed softwood stands, spray application is often timed to correspond with fir bud break, rather than with spruce. In fact, one land manager interviewed stated he would prefer pure stands of spruce or fir to mixed spruce-fir stands during a budworm outbreak, due to the difficulty of timing spray applications to protect both species. Finally, the more tightly packed needles of spruce may protect the budworm larvae from spray deposition. But experts in the field of spray technology think that we have now learned to protect spruce, by recognizing incipient damage

Table 17. Mean percentage mortality by basal area in unsprayed stands in Baxter State Park and sprayed stands in a neighboring control area.

Stand Type	Treatment	Mean Percentage Mortality by Basal Area		
		Fir	Spruce	Spruce & Fir Combined
Fir stands (> 20% of sw b.a.is fir)	Sprayed	56.7	16.3	39.3
	Unsprayed	91.2	29.9	61.6
		*	**	*
Spruce stands (< 20% of sw b.a.is fir)	Sprayed	64.9	31.1	31.8
	Unsprayed	97.4	24.9	30.7
		*	NS	NS
All softwood stands (< 35% hardwood)	Sprayed	59.3	20.6	37.0
	Unsprayed	93.1	28.5	53.0
		*	NS	*

From Osawa 1986, Table 1.
* significant at $p < 0.001$
** significant at $p < 0.01$
NS not significant the 0.05 level

and by timing applications properly (H. Trial, pers. comm.). It is likely that recovery of foliage complement and vigor will take longer for spruce than for fir.

Growth reduction

Volume loss due to slowed growth may not be as spectacular as loss due to mortality, but it is of nearly equal concern, especially in young stands. In general, surviving balsam fir exhibits 50-75% annual reduction in growth during the outbreak period (MacLean 1985). Growth reduction due to defoliation increases over the course of the outbreak, primarily because the new foliage makes the greatest contribution to photosynthesis. Severe defoliation can cause 15–20% and 25–56% annual growth loss reduction in the first and second years respectively (MacLean 1985). Ultimately, severe defoliation can lead to 75–90% annual growth loss. Spruce growth reduction has been poorly studied but appears to be lower than that of fir. In studies from earlier outbreaks, red spruce showed an average of 50–60% (Craighead 1924), white spruce 36% and black spruce 18% (Blais 1964) annual growth reduction.

Growth reduction is highest near the base of the live crown and lowest in the lower bole (Solomon 1985a). Studies which report that growth reduction lags 2–5 years after the onset of defoliation are inaccurate, because they are usually

based on radial measurements at breast height rather than whole stem analysis. Stem analysis is also more accurate because it includes losses due to top kill. Often 50% or more of trees surviving budworm attacks have dead tops. This can result in a loss of 0.5–4 meters in total tree height, in addition to causing stem deformities and an entryway for decay organisms.

Stem analysis was used to study growth loss in 44 plots in 35–65 year old spruce and fir stands undergoing different defoliation regimes in northern Maine and New Hampshire. The 5-year report showed that stands suffering mild defoliation (<20% of current foliage) suffered negligible growth loss. Severe defoliation (90–100% of current foliage) resulted in 60% annual growth loss, or 34% cumulative loss. The cumulative 5-year growth loss was equal to 215 ft^3/acre of wood production (Kleinschmidt *et al.* 1980).

The seven-year CFRU report on the cooperative growth impact plot study found that trees that were less than 50% defoliated every year showed a 10–15% cumulative reduction in volume growth (Solomon 1984). Severe defoliation of greater than 80% per year resulted in cumulative growth losses of 45 to 50%.

The Moosehorn study found that lower bole growth reduction in fir occurred after only 2 years of severe defoliation. In 1977, radial growth of fir in the Moosehorn was 0.5 mm/year, half of the growth in the sprayed area (Devine *et al.* 1978). By 1980, radial growth of fir was only 0.3 mm/year (Devine & Conner 1980). Spruce growth also showed a gradual but statistically insignificant decline, to about 0.97 mm/year in 1980. But later studies in the Moosehorn showed similar growth reductions as reported elsewhere—35 to 45% (H. Trial, Jr., pers. comm.).

Unlike the situation in the Moosehorn Refuge, where spruce growth was hardly affected, in Baxter State Park basal area growth of red spruce was reduced to between 41% and 54% of the pre-outbreak rate (Seymour 1980). Spruces in mixed wood stands lost growth at the same rate as in other forest types, in contrast to mortality, which occurred at a lower rate in mixed wood sites. In stands with a high proportion of spruce, growth loss of more vigorous trees was proportionately higher than that of less vigorous ones.

Growth loss was once attributed to carbohydrate starvation, but newer theories suggest that it is due primarily to hormonal changes (Seymour 1980). The growth hormone IAA is produced primarily in buds and elongating shoots, which are destroyed by budworm defoliation. Stored photosynthate could still be used for respiration, so vigorous trees would live longer, although with much reduced growth. Like mortality, growth loss continues after defoliation has ceased, until rootlet and foliage components are rebuilt.

Most of the forest managers interviewed for this report felt that preventing significant growth loss in spruce and fir was either technically infeasible, prohibitively costly, or both. Their protection strategy was to keep as much of the

resource alive as possible, without placing much hope in maintaining growth. Two of the respondents, however, said that they targeted young stands on good sites in an effort to prevent growth loss.

Damage to regeneration

The classical view of budworm-forest dynamics holds that spruce budworm outbreaks produce ideal conditions for fir regeneration by removing mature overstories, allowing young fir to become established (Baskerville 1975a). Budworm's "silvicultural" activities in the 1910's outbreak were revealed by the dense, fir-dominated stands that developed in the following decades. But budworm infestations may also seriously damage regeneration. This damage to regeneration by budworm can take three forms: damage to the advance regeneration, cessation of cone and seed crops, and modification of site factors affecting seedling establishment.

Budworm feeding on advance regeneration varies widely from stand to stand. Interview respondents were evenly divided over whether or not regeneration was vulnerable. In 1983 in Baxter State Park, fir and spruce regeneration densities were proportional to the density of advance regeneration established before the outbreak (Osawa 1986), implying that budworm defoliation on advance regeneration is density-independent.

A more serious effect on regeneration may be the absence of cone crops during and following outbreaks. The male strobili of fir are one of budworm's preferred foods (Blais 1952) and developing cones are also fed upon by the budworm. The high percentage of top kill among surviving trees reduces future cone production since female cones are produced in the upper part of the crown. In the studies undertaken in Baxter Park, nearly all fir seedlings existing at the end of the outbreak had been established before its onset (Osawa 1986). In the sprayed area, two-year old fir seedlings were found, indicating that spraying may reduce cone losses to budworm.

Reports of spruce cone crop production during outbreaks are mixed. Red and black spruce normally have episodic reproduction, producing large cone crops every 5–6 years. During the outbreak, cone production was conspicuously absent on red spruce (J. Dimond, pers. comm.). In general, spruce cone production seems to be reduced, although exceptions have been reported: black spruce produced a large seed crop in 1982 in the Sourdnahunk region (Mott, interview) and spruce seedlings in Baxter Park (Osawa 1986) had been produced during as well as before the outbreak. As well as directly affecting seed production, budworm outbreaks also alter site and seedbed conditions. In Baxter Park, percent cover of raspberries was correlated with pre-outbreak basal area of balsam fir, and thus with the post-outbreak dead fir patches (Osawa 1986). In Ontario and Quebec, another study showed a 20–65% decrease in balsam fir seedlings

over a 5-year period (Ghent *et al.* 1957). Nearly 90% of this loss was attributed to coverage by dead fir stems and competition from shrubs.

Management techniques designed to lessen budworm impact can also affect regeneration patterns. Two of those interviewed stated that partial removal of infested overstory, such as a shelterwood cut, left the regeneration and understory extremely vulnerable. If infested overstories were removed by harvest or mortality, budworm populations would collapse, allowing uninfested regeneration to establish, in the absence of larval dispersal from nearby stands.

In spite of these adverse effects on regeneration, preliminary data from the Forest Service's 1986 mid-cycle survey indicate that about 85% of the area where the overstory was killed or removed is stocked with regeneration. It appears that more advance regeneration was present than was apparent to observers during the outbreak. However, the data do not allow conclusions to be drawn about such questions as proportions of spruce and fir and amount of herbaceous competition (Seymour, pers. comm.). Thus, more study is needed before the future development of these new stands can be predicted.

CHAPTER IV

RESPONSES TO THE OUTBREAK: SURVEY AND DETECTION

Evolution of population survey techniques

Largely in response to the budworm outbreak, the Maine Forest Service developed one of the strongest forest insect survey programs in the northeast. During the outbreak, surveys and assessments of insect and tree conditions were used extensively in Maine for:

1. detecting outbreaks early;
2. monitoring population levels and health status through an outbreak and predicting populations for the following year;
3. monitoring current-year defoliation levels in stands and the cumulative effect of several years' damage on the viability of stands;
4. combining information on population levels and on tree condition to design protection programs;
5. designing spray blocks and timing applications;
6. assessing the budworm impacts on the forest resource; and,
7. determining spray efficacy.

As experience was gained during the course of the budworm outbreak, survey techniques evolved and improved significantly. Several reviews of these techniques (Sanders 1980, Dorais and Kettela 1982, Allen *et al.* 1984, Witter *et al.* 1984) were produced. Successful efforts were made to standardize survey and assessment methods throughout the Canadian provinces and the states involved, facilitating exchange of information (Dorais and Kettela 1982).

Early detection efforts in Maine prior to the 1940's outbreak consisted primarily of a regular forest insect survey, designed to monitor numbers of foliage-inhabiting species on the trees being sampled. The method used was tree-beating, wherein the lower foliage of a tree was beaten with a pole over a sheet spread on the ground (Sanders 1980). Dislodged insects were collected from the sheet and sent to the Maine Forest Service Entomology Laboratory in Augusta for identification and counting. At that time, most fire wardens, as well as the insect rangers, made repeated collections, accumulating 1000 or more each summer. The system does reflect insect abundance (Spies and Dimond 1985), but it has low resolution and only major population shifts are detectable. The other detection procedure was a series of light traps distributed over the state. In anticipation of the 1940's outbreak, the number of these was increased to about 25 (Weed 1977).

With the development of the 1940's outbreak in northern Maine, sampling systems appropriate for dense populations were adopted. The dominant procedure was to prune branches from the mid- or upper crowns of trees, usually fir

unless spruce was of special concern. The branches were placed in plastic bags with location labels, and transported to a "counting mill," a field laboratory where workers counted the insects. When collecting larvae, pole pruners were equipped with a cloth or screen basket below the pruning head to catch any larvae dislodged by the pruning. This pruning method of sampling budworm numbers remained dominant through the 1970's outbreak.

Pruning and counting were used to estimate densities of all stages of the insect that remained on the tree: eggs, larvae, and pupae. The egg mass survey, undertaken in August and September, was the most intensive survey used throughout most of the 1970's outbreak. Its importance was that it predicted budworm infestation levels for the next season, providing critical data for planning protection programs. As many as 1300 of these egg mass samples were taken per year during the 1970's outbreak; this was an intensity of 1 to 3 collections per township throughout the infested area and its periphery (see Figure 15).

Samples of larvae and pupae were taken for more specialized purposes. These included checking on the accuracy of the egg mass prediction of the preceding season, providing prespray and post spray populations estimates to monitor success of protection programs, updating the egg mass prediction to guide last-minute adjustments in the protection program, monitoring spring development of the insects for the proper spray timing, and for surveys of parasitoids (Tilles and Woodley 1984) or diseases. Most sampling involved branch tips of specified length, starting as a 15 inch branch but changing to an 18 inch (45 cm) branch to conform with Canadian methods. Numbers of sample branches and trees sampled at a site varied depending on the stage of insect sampled and the specific purpose of the survey. The reviews cited above should be consulted for details of the sampling process.

A major change in population surveys occurred in the 1970's when Miller and Kettela devised a method of estimating populations of overwintering budworm larvae (Miller *et al.* 1971, Miller and Kettela 1972). Branch samples are soaked in warm caustic soda, which dissolves the silken hibernacula, and floats the larvae into the liquid medium. The insects are then extracted into a small volume of hexane. The latter is filtered, leaving the larvae and some debris on a filter paper, where they are counted under a microscope. By the 1980's, this method had largely replaced the egg mass survey for predicting populations for the following year. This "soaking-out," or "L II" (for instar two larvae) survey can be done at any time through the winter, but is usually done in fall and early winter to allow lead time for the next season. It is probably a more accurate predictor of spring populations than the egg mass survey, since it samples the same stage of the insect that is of concern the following spring. But its major advantage is in its economy, as the number of personnel needed to process the branches

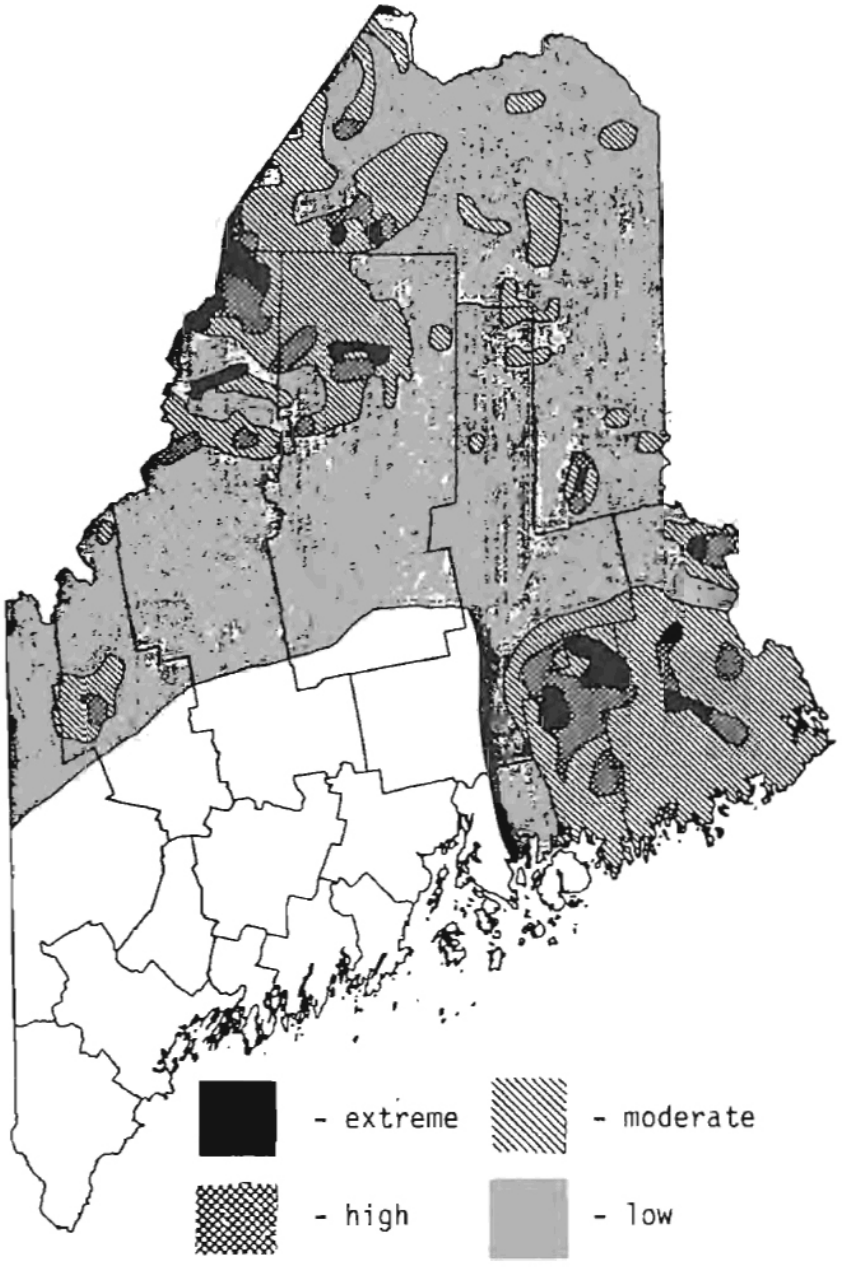


Figure 15. Predicted spruce budworm population levels for 1985. Redrawn from Maine Forest Service annual spruce budworm reports.

and make counts is much less than required for the egg mass survey (Allen *et al.* 1984).

Monitoring tree condition

In gathering data about the status of the budworm outbreak, monitoring the condition of trees was as important as determining insect numbers. Spray decisions were generally based both on insect densities and on the likelihood that the trees could survive the level of defoliation anticipated for the next season. One type of damage survey was done at the same time and site as the egg mass or L II survey. Visual estimates of percent current defoliation, of defoliation in the two preceding years, and of general tree vigor were recorded and given numerical rankings. Once the egg masses or overwintering larvae from the site were counted, they were given similar numerical rankings. The rankings for both tree condition and insect densities were summed to produce a hazard value, upon which spray decisions were based. Examples of the Maine hazard rating system and of hazard maps from Maine's annual budworm reports are presented in Figures 16 and 17.

The efficacy of any year's spray program was assessed by both the degree of defoliation and the effects on the budworm population. A successful protection program should not only reduce insect numbers but also must do it early enough in the budworm feeding period to significantly reduce defoliation.

In a large budworm outbreak, the only practical means of mapping defoliation is through aerial survey. In the 1940's, a systematic process was devised to accomplish this (Heller *et al.* 1952). Straight, east-west lines at intervals of six miles were flown across the state, using landmarks as guides. Two observers, one at each side of the aircraft, continuously recorded the level of defoliation (light, medium, heavy), as shown by the degree of browning of crowns, on an operations recorder. This method allowed very accurate mapping of defoliation. (See example, Figure 18.) Aerial surveys of this type were abandoned in the 1960's; it was difficult to find observers who could tolerate the hours of uninterrupted staring at the trees from a moving aircraft. Systematic aerial surveying was replaced with simple sketch mapping of areas known from ground observations to have been severely damaged. Most data used to prepare a defoliation map came from the 1000 to 1500 ground estimates of defoliation made when collecting egg mass or L II samples.

Occasionally, more detailed information on defoliation was desired, usually in connection with a trial of a new protection product or method. These trials required more intensive evaluations to compare the efficacy of the experimental procedure to the operational methods in reducing budworm populations and in protecting trees from defoliation.

MAINE FOREST SERVICE HAZARD RATING SYSTEM USED IN 1984

CURRENT DEFOLIATION

Category	Values	Hazard Values
Trace	0-05	0
Light	6-20	1
Moderate	21-50	2
Heavy	51-80	4
Severe	81 +	6

PREVIOUS DEFOLIATION
(1983% PLUS 1982%)

Trace	0- 09	0
Light	10- 49	3
Moderate	50-129	6
Heavy-Severe	130 +	9
Dead Tops		+3

EGG MASS 7 OVERWINTERING LARVAL DEPOSIT
BASED ON NO./100 SQ. FT. OF FOLIAGE

	Egg Mass	L-II	
Light	1- 99	1- 175	1
Moderate	100-239	176- 500	2
High	240-399	501-1100	3
Extreme	400 +	1101 +	4

TREE VIGOR

Good	0
Fair	1
Poor	2
Very Poor (No Chance of Recovery)	3

HAZARD

Hazard Rating	Range of Total Values
Low	0-06
Moderate	7-15
High	16-22
Extreme	23-25

Figure 16.

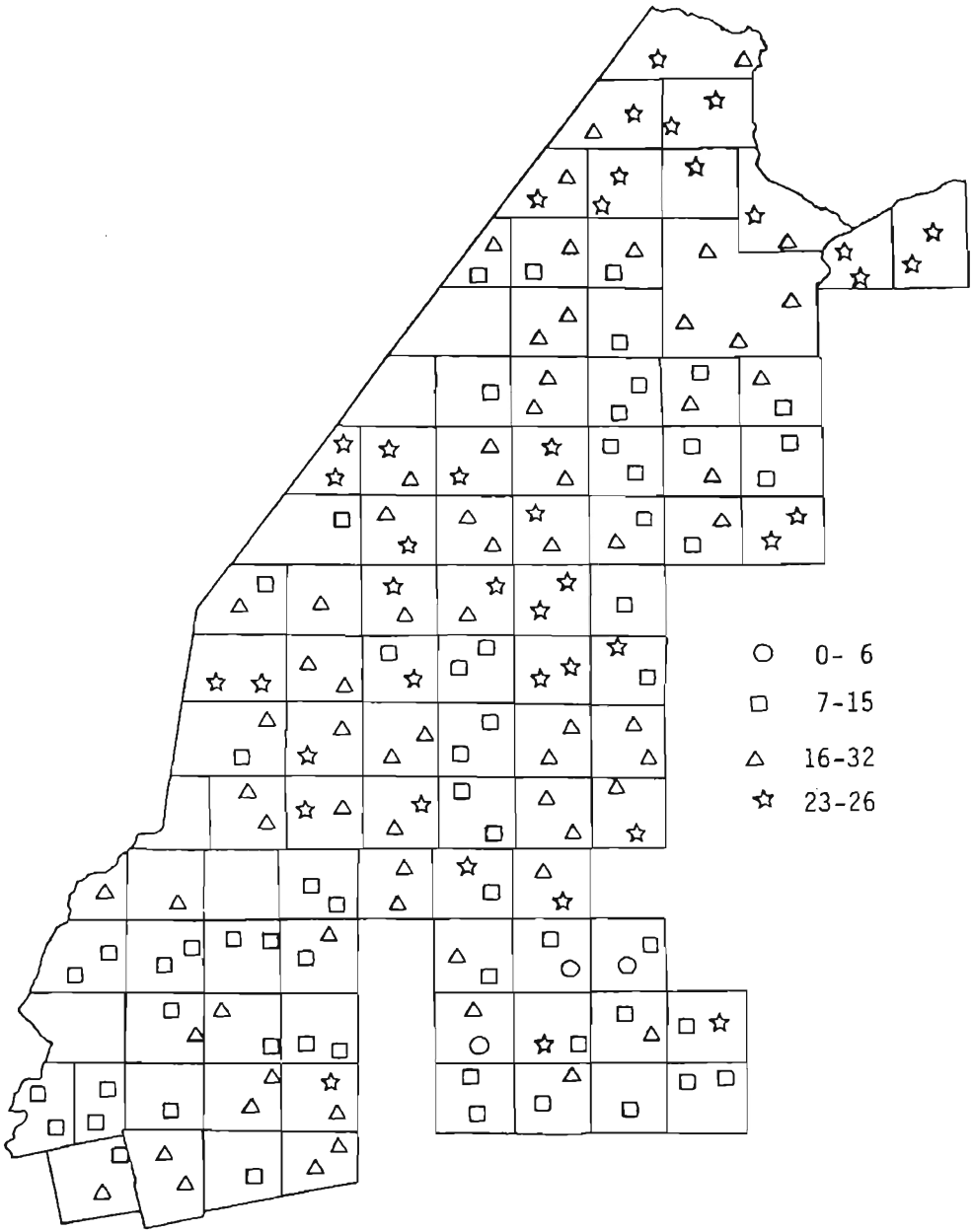


Figure 17. Hazard ratings map for 1981 for the Allagash-St. John zone. Redrawn from Maine Forest Service annual spruce budworm reports.

On a large scale, spruce budworm damage can be mapped by remote sensing using a variety of photographic and non-photographic techniques (Witter *et al.* 1984). Current defoliation can be classified by the degree of browning of crowns, using simple color photography. Infrared photography is better for detecting the cumulative effects of several years of damage; healthy trees appear red and unhealthy trees appear gray. Private landowners were the major users of remote sensing in Maine during the 1970's outbreak, primarily to help schedule salvage and presalvage activities.

During the late 1970's, the Maine Forest Service obtained Color-IR photos of those portions of the spruce-fir zone where small landowners predominate. These photos were very useful in assessing damage at a more local level and in a vigorous extension effort that was undertaken to make small owners aware of the problem. The photos were also valuable in the general service forestry program.

Attempts were made to adapt satellite imagery to detecting spruce budworm outbreaks and damage. While some progress was reported (Witter *et al.* 1984), use of such imagery did not become operational in the recent outbreak.

Pheromones and light traps: tracking moths

A new technology that is expected to be widely used in the next several years is sex-pheromone traps to monitor moth numbers (Allen *et al.* 1984, Sanders 1985). As budworm numbers decline to endemic levels, most survey techniques become unsuitable. For example, in June of 1987, a collecting crew was sent to the Rangeley region of western Maine to locate some budworm larvae for disease diagnosis. Two hundred branches from fir and spruce were brought back to a field laboratory and searched; no budworms were found. Similarly, in the L II survey made by the Maine Forest Service during the winter of 1986–87, most samples from northern and western Maine were counted as zeros. This simply means that budworm numbers in most of Maine have fallen below the limits of resolution of sampling procedures developed for epidemic numbers.

Pheromone traps may provide a means of monitoring budworm numbers at these low populations. Non-saturating pheromone traps and appropriate pheromone emitters have been developed that allow traps to be collected and moths counted only once at the end of the moth flight period. Dozens of traps can be deployed around the state at low cost. The present expectation is that these traps will be an important budworm detection device for local populations (as opposed to moth flights) during the endemic period. However, in the most recent survey, summer of 1987, large regions of Maine produced zero catches in pheromone traps. This suggests the possibility that budworm populations may decline below the level of resolution of even these devices, at least as presently used.

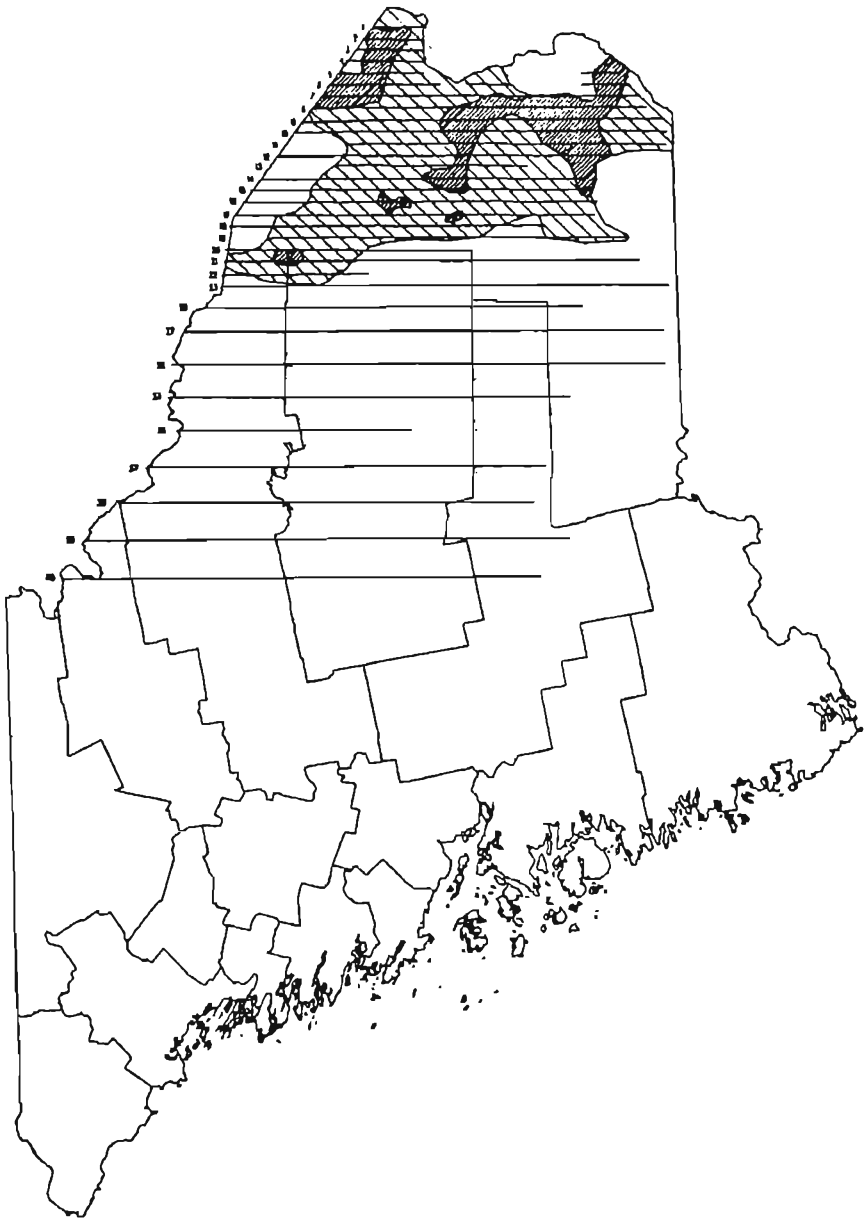


Figure 18. Map from aerial survey of defoliation in 1950, showing continuous and scattered feeding. Horizontal lines numbered on the left are flight lines. Redrawn from Maine Forest Service annual spruce budworm reports.

Light traps, which share with pheromone traps the ability to sample low numbers of spruce budworms, have been operated in Maine forests since the 1940's, and have captured some budworm moths in every year. Simmons (1980) suggests from a selective examination of the Maine light trap data that an increasing trend in population could be seen in the late 1960's, 4 to 7 years before noticeable and extensive defoliation appeared in the 1970's. It might be argued that pheromone traps can replace the grid of 20–30 light traps that have been operated by the MFS for decades; light traps require more labor to operate and to evaluate the captures. However, light traps have some advantages over pheromone traps that should justify retaining them. Light traps capture many species of moths, and pests other than the budworm can be followed. In addition, moths in light traps are segregated by day of capture while pheromone trap catches are totals for a season. In light traps, very high catches of moths over one or a few days, compared to the usual catch for those traps, are evidence of moth flights invading the area. This information is not available from pheromone traps as presently operated.

Annual cycle of work

In summarizing, we might describe survey and detection efforts in a typical year in the early 1980's. The period from September through March was devoted to the L II survey of overwintering larvae. A listing of the winter survey staff from the 1984 annual budworm report is shown in Figure 19. While this group made field collections and processed all collections in the laboratory, additional collections furnished by landowners were processed for a fee. Winter was also devoted to data analysis, meeting with landowners to plan protection programs for the next year, and report writing. The summer staff was larger (Figure 20) and began activities in April. The period until spraying would begin, about June 1, was spent in locating sampling areas, stands from which prespray and postspray collections of larvae and pupae would be taken to evaluate success of the protection program, identifying spray blocks upon which special assessments of new spray technologies would be demonstrated, sampling insect and tree bud development 2 or 3 times per week at a dozen or so locations throughout the budworm protection zone so that spray applications would be timed properly, taking and analyzing prespray samples, and deleting or adding spray acreage based on prespray insect numbers.

After spraying, one postspray sample was taken from each operational spray block, but additional samples were often taken in blocks of special interest where new technologies were being demonstrated. In June, when larval feeding was completed, defoliation surveys were made, both from the ground and with sketch mapping from the air. In mid-July, pheromone traps were deployed, with retrieval and counting in August. Light traps were also operating over the same

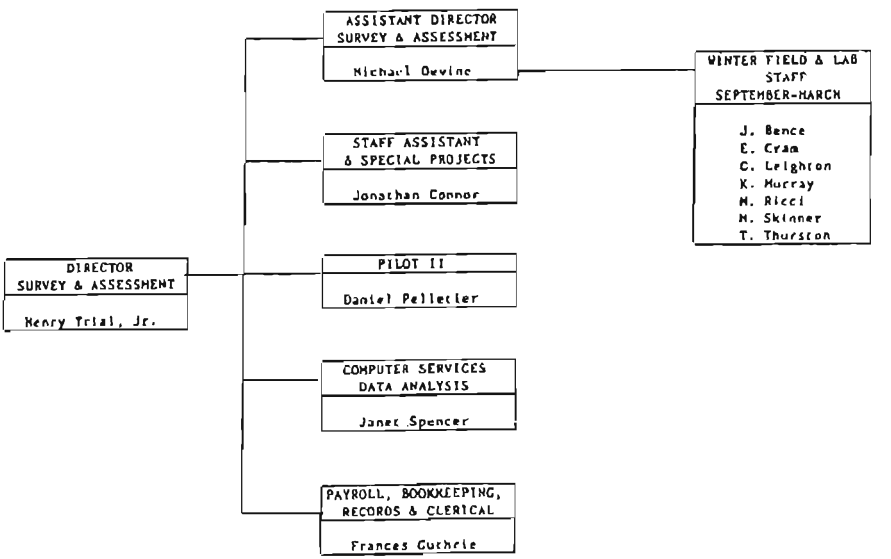


Figure 19. Maine Forest Service spruce budworm survey and assessment unit, winter organization. From Maine Forest Service annual spruce budworm reports.

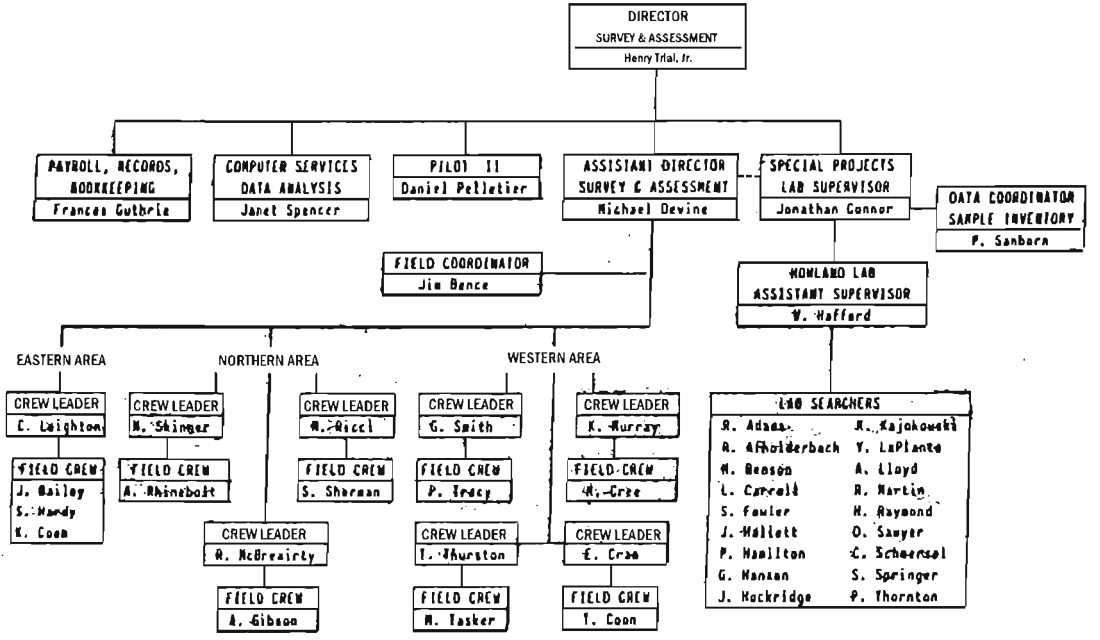


Figure 20. Maine Forest Service spruce budworm survey and assessment unit, summer organization. From Maine Forest Service annual spruce budworm reports.

period. In some years, special surveys of the abundance of parasitoids of the budworm were conducted. The annual budworm reports for the years of the early 1980's (Trial *et al.* 1984, Trial *et al.* 1983, etc.) are particularly good sources for the status of surveys at the end of the 1970's outbreak.

Evaluation

In this study, interviewees were asked the question, "Did state and landowner survey and detection efforts adequately forewarn of the outbreak and adequately monitor its progress?" The consensus was that the state monitoring system evolved into an efficient and adequate system. However, most respondents indicated that coverage was general and information often inadequate to assess conditions on a small scale of resolution. Most large landowners dedicated professional staff to augment the state information with data from their own sample plots, cruises, and aerial surveys. Perhaps this outcome is inevitable; it is unlikely that the state could ever provide all of the information needed to anticipate all of the specific questions of landowners. The aerial survey of the state was singled out as "cursory" by one forest manager whose organization did an annual, two-week, helicopter survey of its own.

While surveys evolved, in the words of one respondent, to "one of the best systems in North America," there was general agreement that early warning was lacking, either because the state lacked the information or failed to communicate it to landowners. This seems clearly to have been the case. In Figure 1 earlier, we show an index of budworm abundance for the years 1975 through 1987 using data provided by the annual Maine Forest Service spruce budworm reports. The graph does not cover the period of the early 1970's because reports for those years provide little quantitative information. The reports clearly indicate an increasing trend in the budworm problem, but the rapid increase in budworm numbers and area infested was not foreseen.

The Maine Forest Service lacked a specifically designated budworm control staff until the mid-70's. Budworm control and survey operations of the 50's, 60's, and early 70's were managed by using virtually the entire staff of the Entomology Division and temporarily borrowing personnel from the Fire Control and Forest Management Divisions. Through 1970, with budworm infestations and control programs limited to the northeast corner of the state, the problem was manageable. As the extent, severity, and complexity of the problem increased dramatically between 1970 and 1975, without a concomitant expansion of staff, the quality of the program suffered, and other pests received less and less attention.

CHAPTER V

RESPONSES TO THE OUTBREAK: SPRAY PROTECTION HISTORY, POLICY, AND RESEARCH

Evolution of state policy and protection program administration

Budworm infestations and protection programs were relatively small throughout the 1950's and 60's. As long as spray projects were small, used familiar methods and insecticides, and took place every few years, they could be managed by the Entomology Division without creating a specialized, formal organizational structure. This section provides a general overview of major policy developments. More detail is found in Pistell and Harshberger (1979), Anon (1979), and Lund *et al.* (1979).

Before 1976, spray programs were funded on a year-to-year basis and no ongoing policy was established. The approach to funding was borrowed from existing experience with the fire control program. Under this approach, landowners had to participate in the funding and in the control program that the state determined to be needed (Rumpf *et al.* 1981). The projects were designed primarily by state entomology personnel. They were funded by a mix of about 1/3 each state-landowner-federal funds. The landowner share was raised by a flat per acre levy on acres owned within the protection region. In some years mixed wood and even hardwood was taxed.

By 1975–76, the clear need for annual large spray projects coupled with new legal and substantive requirements made a more formally organized, long-term approach necessary. The 1976 Spruce Budworm Suppression Act provided for a six-year protection program, established the position of Forest Insect Manager (FIM) within the Maine Forest Service to manage the effort, a research program, and a program of silvicultural withdrawals from spraying. The Act created a spruce budworm tax within a defined Protection District to finance the budworm protection program. All survey and detection continued to be managed by the Entomology Division.

During the next several years, the year-round staff for budworm grew in response to the need to administer research and environmental monitoring, to train airport managers and monitors, to carry out the survey and detection and mapping functions, and to better inform the public about spray operations.

Extensive coordination continued with Canadian spray authorities and with the federal CANUSA budworm research program which was in operation from about 1978 to 1984. Close cooperation was maintained with the Entomology Division's survey unit, with federal USDA Forest Service technical staff, the University, and with landowner technical staff. An annual cycle of meetings and reports kept all parties informed on developments and needs.

The funding process was an important determinant of the administrative cycle. As long as federal funding was available, the National Environmental Policy Act (NEPA) had to be complied with. This meant preparing an annual Environmental Impact Statement; after 1980 a five year plan (1981–85), with annual supplement, was required. The NEPA process was an important method of informing the public and other federal agencies of the state's plans, but it was cumbersome and led to completing the federal funding process, in several years, after the spraying had actually begun (Irland 1983). It was not successful in prompting searching interagency review by either federal or state agencies.

By the mid-70's, the issue of public cost-sharing was coming to a head. State and federal funds provided a high of 2/3 of project costs in 1975. With the high costs of the projects, the state legislature and the federal government became less willing to participate on the previous basis, and began cutting back their contributions. This began a process which resulted by the early 80's in spraying itself being funded entirely by the participating landowners.

By 1978, Maine Department of Conservation officials were looking ahead to the form which the spray program should take in the 1980's. They recommended that the program be spun off to a group of private owners, that state and federal funding for spraying be eliminated, and that reliance on spraying be reduced after 1981. In 1979, the Legislature directed the Department to develop policy recommendations along precisely these lines. The Department impaneled a broadly representative group to advise on policy recommendations, resulting in a report suggesting far-reaching changes in late 1979 (Anon. 1979). This report became the basis for the 1980 Budworm Management Act. Though a major report to the MFS suggested that a private spray entity was feasible (Lund *et al.* 1979), the Legislature did not adopt that approach.

Under the new Act, landowner participation in the spray program became voluntary. The state funded administration, research, and general functions, while landowners were to carry the costs of spraying. Landowners were to decide to participate in the general spray program for a period of time, and would pay a modest per acre tax ("shared tax") on the basis of their acres participating. They would then pay a higher tax each year for each acre sprayed. For example, in 1985, the shared tax was $.208/A.; the spray tax was $7.462/A., and the total spray cost was $8.47/ A.

As a result of rising treatment costs per acre and the reductions in public cost sharing, spray taxes on the landowners rose dramatically. In 1976, the spray tax was below $1.00 for softwood. The tax rose to almost $9.00 in 1982, but then fell to $7.67 /A. by 1985, as a result of lower insecticide costs and concerted efforts to improve efficiency.

From 1976 to 1980, then, the degree to which owners could choose or decline to participate increased. In addition, the involvement of participating land-

owners in designating spray blocks greatly increased. As a result of this, and of the rising per acre costs, acreage participating dropped. In 1976, when the Act was passed, about 8 million acres of softwood and mixed wood in the Protection District participated and were taxed. By 1981, before the new law took effect, this had fallen to 4.6 million acres because of several extensive silvicultural withdrawals under the 1976 Act. By 1985, acreage participating was only 1.6 million.

One interviewee, a forest manager for International Paper, indicated that the high costs of the spray program after 1980 were one reason why IP chose to operate its own spray program, rather than participate in the state program (Williams 1985). However, most respondents felt that the change in the program from state designation to landowner designation of spray blocks was a great improvement, although one indicated that the new policy was not good for small landowners.

By the mid 80's, spray projects were diminishing in size. But the need to operate many different airstrips and to engage in intensive monitoring of spraying maintained a need for a large staff and personal services budget. In addition, MFS block planning became much more a process of coordinating with participating landowners who were actively involved in selecting treatment blocks. No more was the annual project planned almost exclusively by state employees and then just reviewed by landowner staff. The MFS staff contracted and the formal organization with a FIM was eliminated when the year 1986 passed without a state spray project.

Insecticides used

Table 18 lists all the state-sponsored operational spray projects ever conducted by the MFS, which extended from 1954 through 1985. Not listed are non-MFS programs, *e.g.* private spray programs of International Paper Co., small aerial private programs of some Christmas tree growers, spray programs of the Indian Nations (which involved federal but not state assistance), and small experimental spray applications undertaken by researchers.

Certain trends are evident:

1. Because of its low cost and effectiveness, DDT was the sole insecticide used until the Forest Commissioner banned its use for budworm spraying after 1967. A national ban on the insecticide was established in 1970.

2. Thereafter, fenitrothion and mexacarbate (Zectran) were used exclusively until 1975. Spray authorities in Maine were never content with the results of fenitrothion, feeling that the registered dosages applied were marginal in efficacy. In 1975, mexacarbate was withdrawn from the market; it had few registered uses other than the budworm, and this was a period of escalating costs for products derived from petroleum. With only one registered option and that op-

Table 18. List of all MFS-directed spray projects against the spruce budworm undertaken in Maine through 1987.

Year	Insecticides used (% of acreage)	Total acres (in 1000's)
1954	DDT (100%)	21
1958	DDT (100%)	302
1960	DDT (100%)	217
1961	DDT (100%)	53
1963	DDT (100%)	479
1964	DDT (100%)	58
1967	DDT (100%)	92
1970	fenitrothion (100%) [1]	210
1972	mexacarbate (100%) [2]	500
1973	mexacarbate (100%)	450
1974	mexacarbate (100%)	430
1975	fenitrothion (67%), carbaryl (22%)[3], mexacarbate (11%)	2,233
1976	carbaryl (98%), trichlorfon (2%) [4]	3,500
1977	carbaryl (88%), trichlorfon (6%), acephate (6%) [5]	921
1978	carbaryl (85%), acephate (9%), trichlorfon (5%), *Bt* (1%) [6]	1,138
1979	carbaryl (91%), acephate (4%), trichlorfon (3%), *Bt* (2%)	2,791
1980	carbaryl (84%), *Bt* (16%)	1,213
1981	carbaryl (87%), *Bt* (10%), acephate (3%)	1,172
1982	carbaryl (83%), *Bt* (11%), acephate (6%)	820
1983	aminocarb (74%)[7], *Bt* (14%), carbaryl (11%), acephate (1%)	846
1984	mexacarbate (62%), *Bt* (33%), aminocarb (5%)	668
1985	*Bt* (80%), mexacarbate (20%)	411
1986-87	no operational spraying	

1. fenitrothion = Accothion, 1987; Sumithion later
2. mexacarbate = Zectran (Dow Chemical early years, Union Carbide later years)
3. carbaryl = Sevin-4-Oil
4. trichlorfon = Dylox 4
5. acephate = Orthene Forest Spray
6. *Bt* = *Bacillus thuringiensis*, several formulations of Dipel and Thuricide
7. aminocarb = Matacil

tion an unpopular one, a crisis situation existed. The crisis resulted in enlarged programs of field and pilot testing of other insecticides.

3. Carbaryl (Sevin) was the first of the new insecticides registered and became the principal insecticide used from 1976 to 1982. Results with carbaryl were reliable, with wide margins for error. However, smaller amounts of trichlorfon (Dylox) and acephate (Orthene), both newly registered, were used near honeybees and near water where their environmental impact was less than carbaryl.

4. All of these chemical insecticides were replaced by 1984 by aminocarb (Matacil) and mexacarbate (Zectran), reintroduced by a new manufacturer. These chemicals had significant cost advantages over the materials they replaced and provided reliable results.

5. The biological insecticide, *Bacillus thuringiensis* (*Bt*), was first tried operationally in 1978, following several years of field testing. Its use remained token for five years because of the high cost and marginal reliability of early formulations and application technology. By 1984, cost and reliability of *Bt* approached that of chemicals, and its use increased dramatically.

The large use of *Bt* in 1985, 80% of the project, is probably indicative of future spray programs had they occurred. *Bt*'s possible disadvantages in cost and efficacy, compared to chemical insecticides, were balanced by its greater public acceptance, reduced potential for liability, reduced need for unsprayed buffers, and greatly reduced hazard in transport, handling and application. Interviewees were nearly evenly divided over how they weighed these different factors. Five preferred *Bt* to chemicals citing its narrow spectrum of toxicity, and the lack of a requirement for buffer zones. On the other hand, six respondents preferred chemicals because of their perceived lower cost, easier timing of application, and greater reliability.

The ultimate acceptance of *Bt* as a major insecticide can be ascribed to two causes. Because of public hostility to chemical insecticides, there was strong motivation for the state, the USDA Forest Service, and landowners to persist in trials of *Bt* even after several years of erratic results. Such persistent efforts would not have been made with chemicals. In addition, the producers of *Bt* made large improvements in their technology (Dimond and Morris 1984) in just 3 or 4 years, greatly reducing costs (Irland and Rumpf 1987). Nearly all the interviewees agreed that *Bt* had been improved significantly during the last few years of the outbreak. The first *Bt* products used were 16 B concentrates, meaning that each gallon of formulation contained 16 billion International Units (BIU) of active ingredient. Since the operational dosage was 8 BIU per acre, this required at least one half gallon of spray per acre. Also, formulations were believed to require some dilution with water. Operational spray emission rates with *Bt* were around 1 gallon per acre, at a time when chemicals were applied at about 1 quart

per acre. Use of *Bt* was 2 to 4 times more expensive than use of chemicals, and most of this difference derived from application costs.

Bt formulations quickly evolved from 16 B, to 32 B, to 48 B, to 64 B concentrates, and a 96 B formulation was tested experimentally. More concentrated formulations allowed an increase of operational dosage to 12 BIU per acre, in place of 8 BIU, while keeping spray emission rates low. It was found that if rotary atomizer nozzles were used to finely divide the spray cloud, *Bt* concentrates did not require dilution but could be applied "neat" (Dimond 1982), providing several advantages. Mixing costs were virtually eliminated, and spray droplets containing very concentrated *Bt* seemed more effective. An insect eating a droplet of *Bt* will cease feeding. If the droplet is concentrated, the insect likely will die; if the droplet is dilute, the insect may survive and resume feeding once the *Bt* deposit has degraded. In the last operational use of *Bt*, 1985, most used was a 64 B concentrate, undiluted, at 24 fl. oz. per acre spray emission rate.

The shift to low volume applications of neat *Bt* prompted Canadian researchers to test more concentrated, lower volume applications of chemical insecticides than had been conventional practice. These were apparently successful, but with the budworm outbreak declining, Maine did not have occasion to try them. It is uncertain whether these ultra-low volume tactics could have been effective against healthy, rapidly growing populations early in an outbreak.

Spray block design and application techniques

During the 1972–1985 period, significant changes occurred in the approach taken to spray block design and to aerial application techniques. Changing size of spray projects, demands for more accurate application, and new developments in the use of smaller aircraft all interacted to radically change the techniques.

Application tactics and timing

Early in the outbreak, protection of balsam fir, the most vulnerable host species, was the principal concern of landowners and the state. One application of spray, timed at the peak of larval instar IV, was often adequate to protect fir. Earlier instars are protected from spray deposit by their habit of feeding as needle and bud miners. Later instars are easily killed, but delayed spray application leads to more defoliation.

Spray applications timed to protect fir frequently failed to provide good protection for red spruce, the buds of which break later than fir. As a result, spruce condition had deteriorated greatly by about 1979–80, even in stands where fir had been protected (Trial 1984). Canadian experience suggested that split applications provided better protection of spruce. These usually were about half

the normal dosage of insecticide applied on two occasions, several days apart. The best timings were just before larvae started mining buds of spruce and just after spruce shoots started to elongate. This approach was an improvement and was providing reliable protection of spruce at the termination of the outbreak. Most interviewees believed that spruce was more difficult to protect than fir. Seven stated that split applications were more effective than single applications on both spruce and fir, while six felt that single applications were adequate on fir, but not on spruce. In some cases poor protection of spruce appeared to be a result of high survival of coneworms rather than budworms (Spies and Dimond 1985). This indicates the need for further research on spruce coneworm control, in order to improve spruce protection techniques. The last experimental spraying done in the outbreak involved split applications of *Bt* to protect spruce. This was successful (Trial and Dimond 1987) but requires confirmation on an operational scale (see also Keenan and Moritato 1985).

The evolving use of *Bt* produced a change in spray equipment on aircraft. It was noted earlier that low volume applications of "neat" *Bt* seemed to require rotary atomizer nozzles for reliable success, rather than the booms and flat fan nozzles that had been standard from the beginning of spraying. In the last two spray projects, all spray aircraft used rotary atomizers whether spraying *Bt* or chemicals.

Concurrent with the efforts to reduce emitted spray volumes for *Bt*, considerable progress was made in reducing spray volumes for chemicals as well, also using rotary atomizers.

Changing aircraft types

The standard spray aircraft of the 1950's was the Stearman biplane, a converted military trainer. The Stearman's low capacity (150 gal.) and slow speed were no difficulty as long as spray blocks were small and close to airports. However, with 200 Stearmans employed in the 1957 New Brunswick spray program alone (Miller and Kettela 1975), a search began for larger spray aircraft. Within a few years, most Stearmans had been replaced with war-surplus Grumman TBM torpedo planes. These aircraft, designed for heavy loads, carried 500 gallons of spray and could efficiently reach more remote spray areas. For years, planes of this type were the backbone of Maine spray operations as well. The huge spray operations of the mid seventies prompted their supplementation with a mix of planes including twin-engined PV-2s and four-engined C-54s that were tanked and offered for work by aggressive aircraft contractors. For small blocks near airports, TBMs and helicopters were used.

In the 1978 project, a pair of agricultural spray planes was used in an effort to shorten flight times to blocks and see if application could be improved by flying lower and slower. The excellent results achieved led to increasing acreages

being sprayed by small planes from an increased number of airports. The airplanes were based close to spray blocks to take advantage of short spray periods in ways the large aircraft could not match. Increased use of small aircraft reduced the aircraft constraints on block design, permitting smaller spray blocks. In 1985, the entire project was sprayed with a mix of agricultural spray planes. This was the first project sprayed entirely with aircraft designed for spraying in contrast to refitted obsolete military aircraft. The use of small planes was facilitated by the development and improvement of remote airstrips and the convenient location of the blocks in that year. In a way, then, aircraft types in the program had come full circle back to the approach of the 1950's. In 1981–83, private spray operations employed small planes as well.

Airport needs shifted over the period. In some remote areas where precise application was required, helicopters were used in the late 1970's, operated from gravel pits and other improvised bases. This enabled them to spray from within their blocks, a critical consideration in view of their low capacity and low speed. But their limited capacity, high costs, and short operating range limited the use of helicopters. The managerial demands of operating with small agricultural spray aircraft were strenuous, requiring several small airstrips to be established and often moved during a single project, and requiring the use of less experienced staff. But the advantages justified these difficulties (Rumpf *et al.* 1985).

The increasing use of *Bt* in the spray program had important implications for the choice of aircraft. Since the initial formulations were water based, *Bt* demanded careful application at lower flying altitudes in order to reach the canopy without evaporating. As *Bt* became the principal insecticide used in the spray project, this consideration began to dominate aircraft choices. At the same time, however, *Bt* use relaxed the need to define spray buffers adjacent to waterways, thereby simplifying block planning and aircraft guidance.

Spray aircraft guidance

Spray aircraft flying at tree-top level require guidance to correctly spray a block, the borders of which may simply be pencil lines drawn on a map. There are frequently no visual boundaries of the block that can be seen from an aircraft at any height; but at higher altitudes, an observer can locate the approximate boundaries by relating a map to the visual landmarks in his panorama of lakes, streams, ridges, and roads.

The original guidance systems for budworm spraying were devised by Forest Protection Ltd. of New Brunswick in the early 1950's. A spray team of three TBMs was accompanied by two guideplanes, which were high-winged, light aircraft of the Cessna 180 type. The spray team, flying in echelon, would orient

on the first guideplane and follow it on the first swath of the block. By mid-block, the spray team would be directly below the guideplane, allowing the guideplane a good perspective for radioing booms on and off at start and end of the block as well as for water and other exclusions. The first guideplane was too slow to lead the team on the next pass, but the second guide plane would be in position to lead the team after the turn. Blocks were frequently designed to be 8 miles in length so that with a pass up the block, a turn, and a return pass down the block, TBMs would be empty and return to base.

In the mid-1970's interest developed in the Loran-C electronic guidance system, which was used initially in the multi-engined spray planes, where a co-pilot could assist in navigation. Later, Loran units were used in guideplanes leading teams of small agricultural aircraft. In these formations, a single guideplane was adequate since their speed matched the spray planes. In the final years of spraying the spray team and guideplane, furnished by the spray contractor, were accompanied by a second light aircraft carrying spray monitors furnished by the state. Monitoring was done to assure that spraying was done only in proper weather conditions, that spray block boundaries were recognized and respected, and that no-spray buffers and exclusions were adhered to. Spray contracts provided for penalties for violating the guidelines.

Spray block design

In the mid-seventies, spray block design was primarily based on timber type and infestation conditions and aircraft capabilities. North-south orientations were used to minimize eyestrain for pilots in morning and evening spray periods and to take advantage of prevailing westerly breezes to obtain good swath overlap. Blocks ranged in size from tiny ones for small helicopters (Bell G-5) to 30-mile long ones for Constellations. The length of the long blocks used with the large, high speed aircraft was limited by the fact that insect development could be significantly different from one end of the block to the other.

The spray projects of the mid-seventies were the first multi-million acres projects in Maine. Also, spraying moved for the first time into the more remote regions beyond the Allagash to the Canadian border. This created a new need for large aircraft capable of covering the long distances to blocks and treating large areas quickly. During the projects from 1972–76, the Maine Forest Service developed experience with the operational, loading, and guidance problems of using large aircraft for these remote blocks. Previous Canadian experience was drawn upon heavily. The peak was the 1976 project which treated 3.5 million acres over much of the spruce-fir region.

In the more remote areas of the state, block design was initially constrained by the principal airport locations. Under the conditions of the time, it was simply impossible to spray regions beyond the Allagash with other than C-54 and Con-

stellation four-engine aircraft. This meant that much of the region was treated in large, long blocks suited to large aircraft.

As aircraft types changed, the ability to treat smaller, more targeted blocks improved. MFS and the landowners were motivated to target spray treatment more precisely by two considerations:

—Rising cost of spray and application. The rising total costs of spraying were due to a host of factors. In addition to rising costs, federal and state assistance declined, leading to much stronger interest in cost control. The costs of spraying nontype acres, or areas that were about to be cut, were obviously more important when insecticide cost per acre reached $5.00 than it had been when insecticide cost only 50 cents.

—Increased pressure by federal and state regulators and by citizen groups to minimize or eliminate the drift of spray from treatment blocks to human habitations and into water. This meant the prescription of no-spray buffers along streams and near settlements, which had the effect of fragmenting the blocks further. Because buffers differed by insecticide, the buffer policy became quite complex (Oliveri 1986). One interviewee felt the buffers were "out of hand" by the end of the spray program.

These developments to some extent reduced the cost advantage of using large spray planes, and they motivated a search for application systems relying on smaller aircraft that flew slower and closer to the canopy so that waterway protection and drift concerns could be addressed. The spray maps from 1979 and 1984 illustrate the changes (Figures 21 & 22).

Thirteen interviewees stated that targeting spray applications was better than the earlier practice of huge spray blocks, although several added that spray blocks should not be too small (*e.g.* less than 50–100 acres). However, six interviewees, a significant minority, felt large blocks (greater than 1,000 acres) were preferable, saying that there was less chance of misapplication or reinfestation from unsprayed stands, or that spraying large blocks was more efficient.

Pesticides and environmental regulations

Pesticide regulations were an ongoing concern of the budworm spray program. In a few instances, regulations actually affected the choice of insecticides for use. While a detailed history of pesticide regulation is outside the scope of this project, a few of the major points are worth comment. During the 1970's budworm outbreak, American society witnessed an escalation in public, media, and scientific concern about the effects on health and the environment of small doses of insecticides, food additives, and radiation. These concerns naturally affected the budworm spray program.

The loss of DDT as a key insecticide initiated the era of modern budworm control. After DDT, an intensive search began for alternative insecticides and

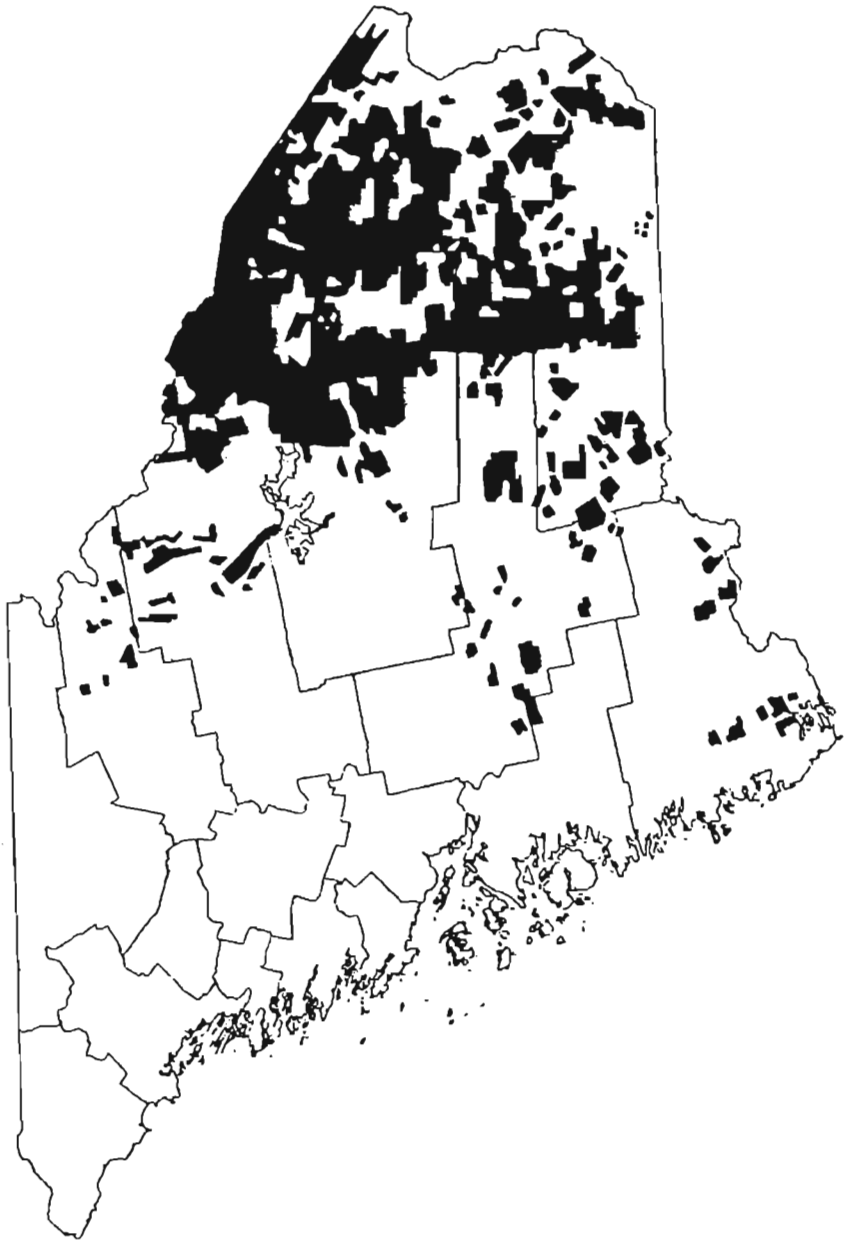


Figure 21. Proposed spray blocks for the 1979 spruce budworm protection program. Redrawn from Maine Forest Service annual spruce budworm reports.

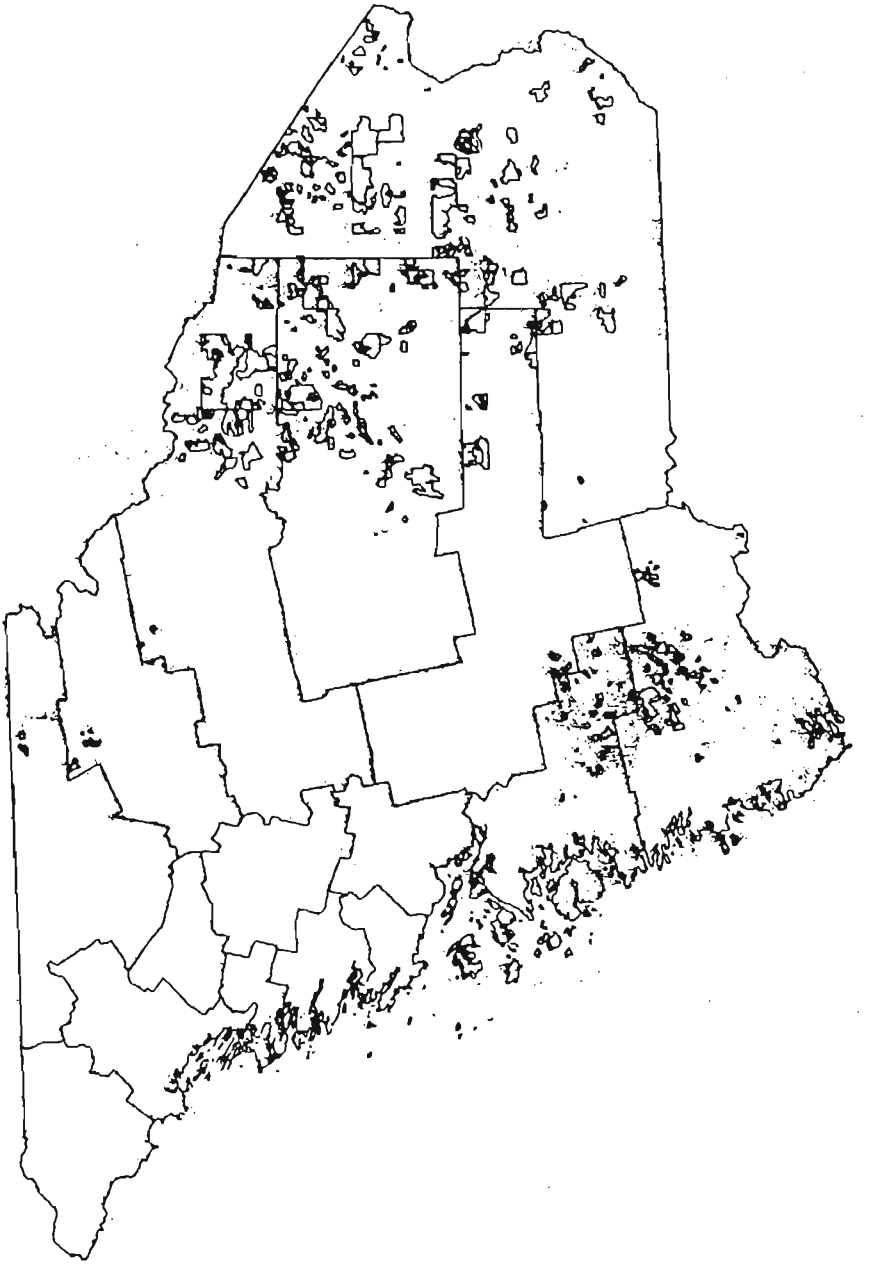


Figure 22. Proposed spray blocks for the 1984 spruce budworm protection program. Redrawn from Maine Forest Service annual spruce budworm reports.

for ways to deal with the increase in insecticide costs. Several different insecticides became available for use by 1976, just in time for the largest spray projects, while efforts continued to pilot test still more insecticides. Of greatest interest to program managers were aminocarb (Matacil) and mexacarbate (Zectran), which offered excellent efficacy and low cost.

These efforts required cooperation with the manufacturers and with the US Forest Service in field testing. They also required state support in obtaining special local need and similar registrations to permit testing the compounds and using them under EPA regulations before they had been formally registered. The slow pace of registration actions at EPA under the federal pesticide laws often created serious problems for pesticide users including the MFS. An especially strong effort was invested in *Bt*, which resulted in the availability by the mid-80's of *Bt* as a cost-effective and efficacious insecticide.

After the 1977 spray project, environmental agency scrutiny of budworm spray projects increased. This led to stiffer buffer requirements, to a requirement for MFS employees to monitor from the air the application of virtually every load, and to more intensive field inspections by EPA officials. In several years, EPA actually hired an aircraft with video equipment—the "Big Eye in the Sky"—to record spray application from above and assess compliance with no-spray areas. Several large projects of drift monitoring and personnel exposure testing were undertaken by the EPA and the state.

In the winter of 1979, the Legislature reformed the state's own pesticide regulation scheme, creating a new Pesticides Control Board, consisting of citizens instead of state officials. This Board then acquired state permitting authority over the MFS program, which had previously been lacking.

For a pesticide to be legally used in the US, it must have a "label" which is an administrative permit from the EPA governing the dosage rates, timing, target insects and host plants, states in which use is permitted, and environmental conditions. In at least one instance, a pesticide was registered, but only at what MFS managers considered a sublethal dosage. This low dosage was prescribed because of concerns for the material's impact on birds. For several years, confusion over unclear wording on pesticide labels frustrated spray managers, attorneys, and regulators. EPA's enforcement division was unwilling to provide clear guidance as to the meaning of the specific label provisions, leaving state spray managers, attorneys, and regulators uncertain as to how to proceed in several cases.

Responses to outbreak—research

Research on the spruce budworm has been reviewed in several sources for both Maine and for the larger, subcontinental region involved with budworm

outbreaks. We will therefore cover the topic of research in a general way. The reviews cited below can be consulted for specifics.

There was very little research during the 1910s outbreak since the technology of managing insect outbreaks was in its infancy. Several studies followed the outbreak in which damage to forests was described and quantified, leading to suggestions for silvicultural treatments to reduce stand vulnerability in the future. A recent review of these studies can be found in Osawa *et al.* (1986). With knowledge of the damage caused by that outbreak, significant research efforts were begun with the approach of the 1940s outbreak. A large research program was inaugurated at the Canadian Forestry Service Research Centers, which continues to this day. In Maine, the initial efforts were largely federal. The Penobscot Experimental Forest in Bradley was established by the US Forest Service in 1950, one of whose goals was demonstrating silvicultural practices for reducing vulnerability to budworm. US Forest Service entomologists, based at the Forest Insect and Disease Laboratory in Hamden, CT, spent a decade or more of summers in northern Maine in the 50s and 60s developing population sampling and damage survey techniques. This work was in cooperation with the Maine Forest Service, leading to several joint publications (*e.g.* Heller *et al.* 1952). Research undertaken by Maine institutions in that era involved environmental hazards of aerial spraying of DDT (*e.g.* Gorham 1961, Warner and Fenderson 1962, Dimond *et al.* 1970), and, as the reputation of DDT deteriorated, testing of alternative insecticidal treatments.

With the ban on use of DDT after 1967 and the explosive development of the 1970's outbreak, testing of alternative sprays became a major enterprise involving the MFS, the University of Maine, and the US Forest Service, often in cooperative ventures. A review of these tests through 1978 (Morrison and Dimond 1978) lists 16 different chemical insecticides, plus several *Bt* products. The number of tests was greater since several insecticides were tested more than once, at different dosages, or in different formulations. Insecticide testing with aerial trials continued through 1986, with most emphasis on *Bt* in the latter years; and laboratory and ground field trials, using laboratory-reared budworms, are still continuing.

The 1970's budworm outbreak resulted in the addition of research professionals to the technological base located in Maine. The US Forest Service silvicultural research unit at Orono added a budworm silviculturist, D.G. Mott, and entomologists, D.T. Jennings and D.G. Grimble. The Cooperative Forest Research Unit (CFRU) of the College of Forest Resources, University of Maine, was organized at this time using pledged funding from Maine forest industries. One of three original professional positions was that of an entomologist, M. W. Houseweart, much of whose original effort was devoted to the budworm problem. Using "soft money," the University of Maine Entomology Department em-

ployed G.A. Simmons and J. Granett in postdoctoral positions for brief periods on budworm research. And enhanced research funding, described below, involved many others in the budworm research enterprise. The CFRU played a lead role in carrying out the cooperative mortality assessment funded by the industry, the state and the US Forest Service (a final report on that project is in preparation) (Solomon 1988).

Two other major sources of research support developed in response to the 1970s outbreak. The MFS supported selected applied research projects in some of the years before 1976. This research support became formalized by the 1976 Spruce Budworm Suppression Act which mandated a state research program. Thereafter, approximately one million dollars were spent by the MFS on research proposals having a high likelihood of producing useful products, until the program was terminated in 1987. Burke and Hulsey (1979) review this and other budworm research undertaken in Maine through 1978. In the late 1970's the decision was reached that the MFS provide no further financial support to the development of chemical insecticides. It was believed that the insecticide industry should finance such tests, which they proceeded to do, providing an additional large input of research support. After 1978, the MFS issued annual reports on the research funding, listing projects financed and progress achieved. These reports can be consulted for projects funded in the 1980's. Additional funds from spray taxes were devoted to monitoring environmental impacts of the aerial spray programs. Again, the MFS issued annual reports on the monitoring studies, which can be consulted for details. Trial (1986) has prepared an annotated bibliography of environmental monitoring programs during the period throughout the eastern US and Canada.

The second major source of research support was the CANUSA Program, an international program involving US and Canadian federal dollars and scientists from both nations. A philosophy in the 1970's was that federal forest pest research dollars should be concentrated on specific pest problems in hopes of achieving major progress. These programs were known as "big bug programs," and the first three, running concurrently, involved the gypsy moth, southern pine beetle, and the Douglas fir tussock moth. As these programs wound down, funding was available for accelerated research on spruce budworms, eastern and western, and the CANUSA program began in 1979, running six years. The accelerated funding in the US brought many new scientists and graduate students into spruce budworm research. Canada, having a well-established budworm research effort, did not provide accelerated funding of research, but did carry out strong coordination and cooperation with the US effort. The accomplishments of the program are best represented by three major publications, a budworm management handbook for eastern North America (Schmitt *et al.* 1983), proceedings of a major symposium on advances in spruce budworm research (Sand-

ers *et al.* 1985), and a bibliography of all spruce budworm research literature involving more than 3300 citations with abstracts (Jennings *et al.* 1979, 1981, 1982, 1983).

The largest single project funded in Maine by the CANUSA program became known as the Green Woods Project, and its goal was to demonstrate that the emerging concepts of targeted spray application and harvest would reduce spray inputs and costs with little sacrifice of forest resource values. Townships devoted to these demonstrations were T14R16 and T15R15 near St. Pamphile, Quebec, the block of six townships south of Baker Lake, and T6R10 in Baxter Park. Project efforts led to a 50% reduction in acres sprayed in the best case and significant savings in all cases (Dimond *et al.* 1984, 1985). The project developed the Green Woods Model (Sewall Co. 1983), discussed elsewhere, which was a critical tool in reaching a decision on how much resource to protect.

With the decline of the outbreak in 1984–1986, significant reductions occurred in all budworm-related activities, including research. The entomology position in the Cooperative Forest Research Unit was eliminated; the two entomologist positions of the US Forest Service unit administering the Penobscot Experimental Forest are expected to be moved elsewhere in 1988; the MFS research support program is terminated; and the CANUSA program no longer exists. With the ebb of the budworm infestation, reductions in research support are understandable as more immediate problems are addressed. However, maintaining a minimal spruce budworm research capacity in Maine is necessary, both to develop new information on the insect in its endemic phase and to maintain liaisons with Canadian and other workers. Without this, Maine will be poorly prepared for the next outbreak.

CHAPTER VI

RESPONSES TO THE OUTBREAK: SILVICULTURE AND SALVAGE

Much has been written about the possibility of using silvicultural techniques to ameliorate spruce budworm outbreaks (*e.g.* McLintock 1947, Westveld 1946, Blum and MacLean 1985, Dimond *et al.* 1984, 1985). At the beginning of the 1970's budworm outbreak, these "classical" views on silviculture and budworm were extended by some forest managers and others to include the belief that it was possible, through silvicultural techniques, to create "budworm-proof" stands. This belief was also incorporated in the silvicultural withdrawal policy of the 1976 Budworm Act, which was based on the idea that stands under the right type of silvicultural management would not need to be sprayed. That idea worked out poorly in later experience.

Judged in terms of whether silviculture in fact eliminated the need to spray stands, the results of silvicultural management during the 1970's outbreak were disappointing. Landowners' ability to carry out all but the most extensive silvicultural activities before the 1970's outbreak was severely restricted by low stumpage prices and lack of markets. Further, prescriptions developed from observations taken during relatively moderate outbreaks did not hold up during the peak budworm population levels of the 1970's. Red spruce showed itself to be quite vulnerable when high budworm populations persisted for a long enough time. As significant spruce mortality began developing around the state, and as the overall scope of the outbreak overwhelmed landowner's ability to harvest and market all the timber that was being damaged, the management emphasis shifted from reducing fir content in stands to pre-salvage, salvage, and a concern for protecting spruce. For a thorough synthesis of literature, see Blum and MacLean (1985).

By the end of the budworm outbreak, forest managers had greatly increased their capacity to manage for budworm (or for any other purpose), through the development of a much more extensive road system, better inventory data, and computer modeling. With these tools, it is now possible to include silviculture in an integrated management program that is much more sophisticated than that which could have been carried out at the beginning of the 1970's outbreak.

Classical prescriptions

The classical prescriptions for reducing the vulnerability of the forest to budworm are directed towards reducing the proportion of fir, growing younger, more vigorous stands, and avoiding large contiguous areas of overstocked, biologically overmature fir. The techniques for achieving these goals include dis-

criminating against fir in both even-aged and uneven-aged management systems, and insuring non-fir regeneration either through obtaining natural regeneration or by planting. This is primarily a stand-level view of the forest, based on the assumption that initial stand conditions do make a difference in vulnerability. But experience during the 1970's outbreak has shown that the impact of initial stand conditions is not always clear, that silvicultural activities conducted during an outbreak are generally ineffective or have a negative effect in reducing vulnerability, and that even when silviculture is carried out before the outbreak the results can be mixed.

Baskerville has pointed out that the impact of the budworm within and between stands is variable (interview). Some of the reasons for this variability are discussed in Chapter III. In addition to the observed species composition and stand vigor, vulnerability may be influenced by site and soil conditions, red-black spruce hybridization, topography, climate, and moth migrations. The combination of all these factors tends to obscure the real contribution to vulnerability which research shows that species composition and stand vigor make.

This observation is borne out by the interview responses. With regard to fir-red spruce stands, many respondents were not sure that, given a long enough outbreak, initial conditions made a great deal of difference to stand vulnerability. It was clear that, contrary to the beliefs underlying the silvicultural withdrawal program, in many, if not all, cases the respondents felt that spruce stands would also need protection.

Uneven-aged (selection) management

Some authors have advocated the selection harvesting method for creating a budworm-resistant forest. Since disturbance favors fir regeneration, selection management could in theory help shift species composition towards spruce by minimizing the extent of harvesting disturbance. Baskerville (1975b), on the other hand, feels that selection management actually increases stand vulnerability by indefinitely maintaining stands with mature, deep-crowned trees possessing abundant sun-foliage and flowering—ideal conditions for budworm development.

This discussion as it applies to Maine is largely academic, since there are actually very few uneven-aged stands in the state. The great majority of spruce-fir and mixedwood stands in Maine at the beginning of the 1970's budworm outbreak were essentially even-aged. These stands had their origins in the 1920's outbreak and subsequent harvesting.

The cutting practices that were termed "selection harvesting" in these stands during the 1950's and 1960's were actually partial cuts in even-aged stands, usually based on diameter limits. This harvesting left stands with a single age class, or with an overstory and regeneration, depending on the portion of the stand that

was removed. These "selection" cuts were at worst a euphemism for high-grading, and at best a form of thinning or shelterwood cut that attempted to discriminate against fir through the use of a lower diameter limit. In any case, there was not enough experience in Maine with true uneven-aged management of spruce-fir to gain any new knowledge about budworm behavior in such stands.

Still, experience in the Bradley Experimental Forest (Frank 1985) and on several large private properties shows that periodic light cuts can substantially reduce fir representation in overstories, even when the all-aged stands are not being created. Such multi-storied stands offer a way to maintain vigor in canopy trees, maintain full forest cover, and minimize brush competition with regeneration. Such management is especially attractive on smaller holdings.

Even-aged management—pre-commercial thinning

Pre-commercial thinning, in theory, permits a landowner to both reduce the fir component of a stand and increase the vigor of the residual stand. Both of these measures should reduce vulnerability to budworm. In the past few years, pre-commercial thinning has become an increasingly common practice in Maine (Table 19). However, the principal motivation for most of this activity is not budworm vulnerability, but concern over the future supply of spruce and fir. The object of the thinning is to increase production, shorten rotation lengths, and ameliorate the anticipated spruce-fir shortfall. While this type of thinning represents a substantial investment which must be carried for many years until commercial harvesting is possible, it can yield acceptable returns if stumpage prices are high enough (Anon. 1983).

While pre-commercial thinning has theoretical advantages in reducing stand vulnerability, there is little experience in Maine to draw from since few stands received this kind of treatment before the beginning of the budworm outbreak. It is clear, though, from the interview responses, that pre-commercial thinning during an outbreak does not immediately reduce vulnerability. In fact, the thinning may increase vulnerability by increasing the proportion of host species, and exposing more of the trees' crowns. It seems clear that, during an outbreak, landowners should be prepared to protect previously thinned stands.

Even-aged management—commercial thinning

Although the practice was not prevalent, there was a significant acreage of spruce-fir stands that had undergone commercial thinning prior to and during the budworm outbreak. Eleven interviewees stated that they had undertaken some form of partial cutting in spruce-fir and mixedwood stands. Where this cutting took place before the budworm outbreak, and where it had the effect of significantly reducing the proportion of fir in the forest, it appeared to be beneficial. In this context, six interviewees reported that fir-only cuts were successful

Table 19. Estimated acreages of various components of Integrated Pest Management for 1982 and 1983 among Maine landowners/land managers involved in budworm suppression activities.

Component	Estimated acreage 1982	Estimated acreage 1983
Harvesting:		
Partial cutting	105,400	73,335
Clearcutting	74,300	87,138
Cable yarding system	600	100
Precommercial thinning and release:		
Chainsaw and brushsaw	3,500	5,050
Herbicide application	11,000	23,700
Planting:		
Site preparation	4,250	4,450
Planting	4,275	17,300
Targeted mortality:	20,000	——
Insecticide application:		
Chemical insecticides	864,000	765,000
Bt	96,000	135,000

From USDA Forest Service 1982 and 1983.

in reducing vulnerability, citing as evidence areas in northern, eastern, central and western Maine.

Fir-only cuts and other forms of thinning were not effective in every stand, nor should they be expected to be so. For a partial cut to be successful, the stand must have a sufficient amount of spruce and/or non-host species in it to form a well-stocked residual stand after most of the fir is removed. The fir must be of merchantable size, the stand should be young enough to respond to thinning, and the residual stand should be reasonably windfirm. By the time of the 1970's outbreak, many, if not most of Maine's softwood stands did not meet these criteria. The typical stand by that time was excessively dense, growing on a wet site with shallow roots, and had a large component of overmature fir. Many landowners learned from experience that, under these conditions, any sort of commercially feasible partial cutting would probably lead to heavy wind damage (Falk 1980). These stands had simply been left too long for partial cutting to be effective once the budworm outbreak began. By the late 1970's, partial cutting was no longer a viable option in most spruce-fir stands.

While fir-only cutting before the outbreak did seem to reduce vulnerability and mortality, it did not necessarily eliminate the need to spray the stands. However, several respondents stated that the fir only cuts reduced the amount

of spraying that was needed, since red spruce can sustain an infestation longer before beginning to show mortality.

Even-aged management—shelterwood harvests

Shelterwood cuts are an effective way to regenerate spruce and fir, while to some extent controlling raspberries and other competing vegetation. Some researchers have recommended the use of shelterwoods to control the species composition of the regeneration (Frank interview). The theory is that by leaving a spruce overstory, spruce regeneration will be favored over fir. However, one interview respondent noted that his company had been unable to find any relationship between the proportion of spruce in the overstory and the amount of spruce in the regeneration. The same respondent noted the difficulty of applying herbicide to control competing vegetation when an overstory was present.

The limitations of windfirmness and stand composition that affect fir-only cuts apply to an even greater degree to shelterwoods. In fact, in practice there is no clear distinction between the two forms of harvesting, since most fir only cuts remove enough of the stand to act as a shelterwood. Like commercial thinning, shelterwood harvesting is probably only effective when carried out between outbreaks. This is especially true since little or no seed production occurs during an infestation, and larger advanced regeneration will be severely damaged by budworms dropping out of the overstory.

Stand conversion

One obvious way to reduce a stand's vulnerability to budworm is to convert it to less vulnerable species. In the past, planting has not been practiced to any great extent in Maine. But in recent years, planting has greatly increased. Like pre-commercial thinning, this planting is motivated more by a desire to increase productivity on good sites than to reduce budworm vulnerability. As pointed out in Chapter III, black spruce growing on good sites may be more vulnerable to budworm than it is on poorly-drained sites. But, it is probably still less vulnerable than the other budworm hosts.

Shift to salvage and focus on spruce

As the 1970's outbreak progressed, the magnitude of damage that was occurring overwhelmed most landowners' attempts to reduce vulnerability through silvicultural means. Also, by the early 1980's, the degree of red spruce's vulnerability became apparent. These two factors led to a changed harvesting and protection strategy on the part of most landowners. Harvesting shifted to salvage and pre-salvage operations to use timber before it was lost. Since balsam fir decomposes rapidly, losing its usefulness as a fiber source about 1–3 years after

it dies, pre-salvage predominated. At the same time, there was much more emphasis on leaving and protecting spruce stands, to insure a supply of timber after the end of the outbreak.

Salvage and pre-salvage operations were conducted by every land manager interviewed. At first, forest managers typically "chased" the budworm, trying to capture mortality on a year-by-year basis. Over time, the companies found it more effective to adopt long-term plans. Stand hazard rating systems were used to construct salvage schedules, with the most vulnerable stands on accessible, good-quality sites receiving high priority. This approach resulted in reduced protection costs for some companies, which would stop spraying stands that were scheduled for harvesting within the next 1–2 years.

Most of the land managers interviewed said that lack of access to stands that needed to be salvaged was a serious problem at the beginning of the outbreak. By the time the outbreak collapsed, nearly all of these landowners had constructed enough roads to gain access to most of the threatened stands. The road-building and camp-moving operations which the pre-salvage and salvage operations required were a significant hidden cost of the outbreak for these landowners.

For non-industrial landowners, lack of markets was also a serious problem. They needed to market increased volumes of timber in order to capture the budworm-caused mortality. However, the industrial landowners were also trying to use their own salvage wood, and thus reduced significantly the proportion of wood they were buying.

Integrated management and the Green Woods model

In order for landowners to minimize the volume of timber lost to mortality by pre-salvage, to minimize protection costs, and to preserve the maximum amount of spruce to grow on a longer rotation, they had to integrate protection and harvesting operations to a much greater degree than ever before. This, in turn, required better inventory information and analytical tools than had been needed in the past. The development of forest simulation models, and in particular the Green Woods model, played a useful role in understanding and managing the problems caused by the budworm outbreak.

The Green Woods model was originally developed in 1980 by researchers of the Green Woods Project to predict the impact of different integrated forest management strategies on several demonstration areas in Maine (Seymour *et al.* 1985). These demonstration areas were established in Maine with CANUSA funding and the cooperation of several landowners.

The Green Woods model simulates spruce-fir forest growth, natural and budworm-caused mortality, protection, and harvest at the forest level, not the stand level. The forest is divided into softwood and mixedwood types, each broken

down by percent of host species (spruce and fir) and by 1-year age classes. Each stratum is further subdivided by protection status if a simulated budworm outbreak is underway. Growth, mortality, and removals are calculated annually, and the volumes in each stratum are updated.

The model was deliberately designed with few default functions, forcing the user to specify not only the initial forest structure, but also most of the model parameters. Forest structure is categorized by type areas, protection areas, age structure, species composition, and stocking levels. The model parameters include forest development functions, timing and severity of budworm attack, forest protection levels, and level and nature of timber harvest (Seymour 1985, Seymour *et al.* 1985).

The Green Woods model was first applied to Maine's entire spruce-fir resource in 1980 in response to the threatened abandonment of subsidies to the spray program by the US Forest Service. The model has been used by many large private and industrial landowners to plan protection and harvesting strategies, and was used by the Sewall Co. (see Chapter II) to project future wood supplies in Maine (Sewall Co. 1983).

By focusing attention on the age class distribution of the forest, rather than on periodic growth data derived from CFI plots, the Green Woods model helped to bring about a basic change in the way Maine foresters and land managers thought about the forest. This led to a reversal of thinking about the adequacy of wood supplies, both in individual ownerships and in the state as a whole.

The model gained wide acceptance among forest managers, even those who had been skeptical of previous research efforts. Ten interview respondents said that simulation models in general, and the Green Woods model in particular, were useful in analyzing the wood supply and setting an allowable cut, and sensitizing people to the potential losses due to budworm damage. Two land managers specifically cited the Green Woods model as a catalyst in bringing about a change in budworm and forest management policies for their companies.

There are two principal reasons for this wide acceptance. First, the model addressed a critical management need in the early 1980's, by helping managers understand the short and long-term consequences of expensive protection and harvesting decisions. Second, the model included managers in its decision process, by forcing them to specify model parameters, and by manipulating data in a simple and understandable way. Thus managers could perform sensitivity analyses and understand the significance of the results. The model was "transparent," rather than being a "black box." By focusing attention on data on forest yield, protection effects, etc., the model helped to integrate this information and highlight areas where knowledge was inadequate.

However, the model's strength—that it forces users to specify parameters—

can also be a weakness, since it will readily model biologically impossible situations. Further, the model is not a population dynamics model, and provides no information about the interaction between the insect and forest structure.

The model's biggest limitation is that it aggregates data over broad areas, so that the "areas" in the model do not correspond to actual locations on the ground. Thus the model cannot be used to analyze the results of particular local activities, such as thinning. Primarily because of this limitation, there is no further development work being done on the Green Woods model. Instead, attention has now turned to developing models which will handle stand level detail.

The role of silviculture in the future

Silvicultural management to reduce budworm vulnerability is not the panacea that some thought it would be at the beginning of the 1970's budworm outbreak. One manager interviewed for this study spoke with disappointment about his preconception that his company's prescriptions had created an "asbestos forest." Most of the other land managers interviewed agreed that silvicultural actions had relatively little effect in preventing budworm damage.

As noted previously, part of this disillusionment stems from the incompleteness of prior knowledge, and from the fact that silviculture had been "oversold" as a management technique for budworm. Thus, few people were prepared for the magnitude of spruce losses that occurred in some situations, although these losses were consistent with those observed in the 1910's outbreak. Also, little intensive silviculture was in use prior to 1970, and hasty efforts to put this in place during the outbreak were initiated too late.

On the other hand, two western Maine landowners whose representatives were interviewed were very confident of their ability to prevent budworm losses through silvicultural means, and have developed silvicultural prescriptions for stands of varying composition and site quality to this end. They expect their forests to be virtually invulnerable to future outbreaks. Likewise, silviculturalists working in the US Forest Service's Penobscot Experimental Forest, in Bradley, were very satisfied with the relative invulnerability of spruce stands which had been carefully managed prior to the budworm outbreak. It should be noted, however, that all of these forests were on the fringes of the outbreak. One should be cautious in extrapolating these results to northern and eastern Maine, where the outbreak was of longer duration.

It will never be possible to "budworm-proof" Maine's entire forest, if only because of the spatial and temporal scales needed for such an enterprise to succeed (Baskerville, Mott interviews). Land holdings which have been managed to reduce vulnerability may nevertheless be swamped with insects when surrounding forests become infested. A New Brunswick task force has observed that areas of 10–20 million acres would need to be managed in concert for

vulnerability to be substantially reduced (Baskerville 1976). The time scale necessary to substantially alter species composition is equally daunting. In a region where the aggressive and fast-growing balsam fir constitutes nearly half of the spruce-fir resource, a significant reduction of the fir component would certainly take at least a rotation.

But to say that silviculture has been oversold in the past, and will not be the single "solution" to the budworm problem, does not suggest that silviculture has no role to play. In fact, silviculture should be an essential ingredient of integrated pest management strategies. Silviculture may not "budworm-proof" the forest, but it can make the forest both easier and less expensive to protect, and more worth protecting.

Conditions now exist which make the execution of such approaches much more feasible. Market conditions have changed dramatically, as the former overabundance of spruce and fir has become a situation of scarcity. Access to stands is also much better than it was 15 years ago, thanks to the extensive road building undertaken to carry out salvage and presalvage operations. Not only has silvicultural knowledge improved, but simulation models have been developed to allow managers to better understand the effects of silvicultural operations and the implications for other management considerations.

At the stand level, it seems that the "classical" silvicultural prescriptions are still valid. By attempting to manage spruce-fir stands to produce vigorous, healthy red spruce, vulnerability to budworm is clearly reduced. While stands may still need to be protected, protection costs will probably be reduced, since spruce can sustain an infestation longer than fir before being seriously damaged. Further, managing for spruce gives a landowner more options in the event of a budworm outbreak, since spruce can be grown on a longer rotation, and for higher valued products, than fir. This does not mean that there is no point in growing fir, where that species predominates in the stand. But fir stands should be grown on a relatively short rotation, and may have higher protection costs during a budworm outbreak.

Silviculture may also be used to help manage for budworm at the forest, rather than the stand level. Intensive forest management of budworm host species can be concentrated on those sites which are the most productive and the most "protectable," with the best access, fewest buffers, etc. By concentrating timber production on a smaller acreage, protection costs may be reduced even when spraying is necessary.

Fortunately, the type of silviculture that may make future budworm outbreaks less costly is basically consistent with the forest management that will be needed to ameliorate the impending spruce-fir shortfall. Thus, at least some of the prescriptions outlined above are already being undertaken by many Maine landowners.

CHAPTER VII

OUTCOMES: HOW DID THE OUTBREAK AFFECT THE FOREST AND DID SPRAYING, SILVICULTURE, AND RESEARCH HAVE AN EFFECT?

This chapter offers an overall assessment of how the outbreak has affected the resource, and how the various management programs may have affected that outcome. In addition, we offer a general description of principal social and environmental effects of the outbreak. Our analysis focuses primarily on timber growing properties and does not attempt to describe the impacts of the outbreak on the management objectives of special areas managed for recreation (Allagash Wilderness Waterway), wildlife (game management areas) preservation and recreation (Baxter Park, The Nature Conservancy areas), or research.

Any attempt to determine how the forest is different as a result of the outbreak and of the management interventions attempted in the 1970's and 80's must posit some description of how the forest would have been otherwise. This is not possible in any rigorous scientific sense. Since many things were changing at once, partitioning them among causes is difficult. Hence, a high degree of uncertainty attends any effort to determine outbreak and management effects. It is not within the scope of this project to attempt an economic analysis of the programs employed against budworm, or to estimate the volume lost to the outbreak.

Effects of the outbreak on the resource

This section reviews outbreak effects on the resource as a whole and on future timber supply, as affected by the management programs actually applied.

As previous discussions show, the spruce-fir inventory volume peaked in the 1971–81 period and continued to decline through 1986. This was a complex change caused by five interrelated factors:

- budworm caused mortality, growth loss, and damage to regeneration.
- age structure of the forest and increasing decline of fir due to aging, to rot, and to suppression.
- higher cutting levels due to increased mill capacity, and strong wood products demand.
- higher cutting levels stimulated by the outbreak itself which motivated considerable salvage cutting above recognized longterm allowable cut levels.
- spraying and silvicultural efforts which attempted to reduce mortality from budworm feeding.

The measured changes in the resource over this period result from the joint action of all these factors. The problem of separating the effects of these five

factors is an awesome one and cannot reliably be disposed of with the resources available to this project. But we can offer a few summary observations.

First, a considerable volume of spruce-fir timber was killed by the outbreak. By 1982, 21% of all fir trees in the Maine forest were dead. From 1976 to 1981, about 7 million cords of spruce and fir were tallied as directly killed by budworm, with budworm a major cause of an additional 8 million cords of blowdown (Schiltz *et al.* 1983:24). The losses are surely far larger by now. But there was considerable additional mortality from other causes. These estimates are subject to measurement ambiguities resulting from the frequent difficulty of attributing causes of mortality to a tree observed a few years after death. This overestimates the economic significance of the loss because much of the volume lost was in small trees that might have later died from suppression in any event. Also, much of the loss was in small volumes per acre and in scattered patches which could not be salvaged. On the other hand, an estimate based on surveys would not count many trees that were prematurely harvested before they could die in accelerated pre-salvage cuttings. Over a decade and a half this was undoubtedly a substantial volume.

Still, the 1986 mid-cycle survey showed that spruce gross volume was down by 14% from 1980 to 1986, while fir gross volume was down by 43%. This was a total reduction of 2.8 billion cubic feet due to the complex of causes mentioned above. Worse, only 58% of the standing fir volume is sound.

Based on past relationships, we can assume that the mortality and growth loss caused by this outbreak are not yet complete. If there is no resurgence of populations, we will need to wait until the 1991 survey before we will be able to determine the extent of post-outbreak recovery of tree condition and vigor as expressed in volume growth.

Second, by 1975, much of the spruce-fir volume was at or beyond planned normal rotation ages, though the spruce was still "young" in biological terms. Because of this condition, and all of the other conditions that are changing, the aggregate effects of the past outbreak probably cannot be extrapolated forward to any future outbreak. While the relationships between the insects and the trees that occur may not change at the stand level, the aggregate effects will differ because of differing forest structure. The different forest structure, plus the increased ability to influence developing stands and to mount outbreak responses earlier, suggest that the dynamics of the developing outbreak itself could differ significantly from past experience.

Third, the outbreak imposed severe growth loss in surviving stands as well as quality losses due to topkill. In the aggregate the growth loss is extremely large, though there are some ambiguities in interpreting its true significance. Since budworm is a natural part of the forest ecosystem, attempts to impute growth loss by comparing attacked stands with hypothetical unattacked stands

are assuming that in fact "no budworm" growth curves are normal and attainable, when in fact they are not. Nonetheless, the decline in growth certainly does affect landowner estimates of future supply potential.

Fourth, the outbreak has undoubtedly affected the current and future age class and size structure of the forest in significant ways. By killing and by motivating the early harvest of significant acreages of mature timber, it has exacerbated the supply crunch that would have emerged in any case because of the previous unbalanced age class distribution.

Finally, the outbreak had a significant effect on regeneration through several related pathways. It hindered cone and seed production in most years. Budworm from infested canopies damaged understory regeneration and even young well-established trees. By requiring extensive clearcutting, the outbreak created extensive areas of young stands with more severe brush competition than might have occurred in the absence of budworm.

Effects on landowners

The budworm outbreak has had a powerful effect on Maine's forest landowners. The costs of protection programs were a serious financial burden, so that some owners opted to leave the program and take their chances with the budworm. The outbreak forced landowners to accelerate roading and salvage programs and to deviate from planned allowable cuts. While salvage programs may have momentarily increased total cashflow from many properties, now that the harvest must subside, cash revenues to owners will decline.

The outbreak and its effects have led landowners to support intensified research, to strengthen staff capacity and improve inventories, to intensify management of the New Forest, and to become more concerned with improved inventory and allowable cut planning. The outbreak even led several owners to carry out their own spray programs.

Effect of spraying

What effect did spraying have on the course of the outbreak? There are several significant points that relate to this question.

First, there is no clear evidence that the spray program prolonged the outbreak, as has often been considered a possibility. If spraying had any such effect, it could only have been a modest one, since the outbreak ran its course across the state in about the time period normally cited, or perhaps just a bit longer.

Second, there is abundant evidence that in specific local situations, aggressive spraying treatments did in fact lead to considerable differences in forest condition over time and to differences in ultimate survival and tree vigor. It is far more difficult, however, to generalize these observations to the forest as a whole. No more than one to two million acres were subjected to consistent pro-

tection over the duration of the outbreak, though perhaps five million were treated at least once.

That this outcome is difficult to quantify does not mean that it is unimportant. It will mean a great deal to the particular landowners who have protected aggressively. It will increase their revenues and their range of management choices during the next few decades. By moderating the wood supply crunch to some degree, it will benefit the wood using industry.

Estimating the effects of spraying on long-run supply potential poses severe methodological and data problems. Essentially, such estimates suppose an ability to construct "spray" and "no-spray" timber inventory scenarios not only over the period of an outbreak but for 3 to 6 decades into the future. Simulation models using the Forest Survey data for 1971 and 1981 have attempted to quantify the impact of spraying on long-term timber supply potential. They have found that even aggressive spraying does not alter the overall course of inventory declines into the coming three or four decades. But spraying does considerably increase the end-of-period growing stock compared to the no spray scenario.

Future supply potential will be strongly affected by the amount and effectiveness of investment landowners make in intensive treatments. This is difficult to forecast over such a long period.

Effects of silvicultural treatments

As described in previous chapters, silvicultural treatments to reduce losses to budworm do not appear to have had a strong record of success in the 1970–85 Maine budworm outbreak. While some landowners report that previously treated stands did seem to survive better or respond to spray treatment better than uncut stands, the acreages involved were small relative to the total resource. As to fir only cuts and other treatments conducted during the outbreak itself, there is actually little published scientific testing of their costs and efficacy. But it would be fair to say that few land managers interviewed would place any reliance on such treatments based on recent experience.

This experience must be viewed with care before being uncritically applied to the future. For example, there were few acres in the forest in the 30–50 year age class in 1975. There was no opportunity to try hazard reduction treatments in such stands. The potential of hazard-reduction treatments applied in a timely manner—well ahead of the onset of the outbreak—should continue to be fully considered. In many cases, those treatments will have benefits in improving stand composition and volume growth apart from any benefit of reducing susceptibility. At a minimum, effects of intensive treatments on spruce budworm susceptibility ought to receive consideration in planning future silvicultural programs.

Anticipatory hazard reduction treatments are often oversold. They should not be seen as an all-or-nothing alternative to pesticides or to salvage and pre-sal-

vage. They will not affect the course of an outbreak, but they should reduce future needs for spraying. The experience of the past 15 years has taught much about such treatments, but can hardly be called a fair test of their future utility.

The joint effects of the budworm mortality and the resulting salvage and pre-salvage cutting were significant. First was a strong shift toward clearcutting, especially on ownerships where clearcutting had previously been avoided. Early experience showed that previous approaches to partial cutting simply would not work in a budworm infested forest; this is especially true of thinnings from above, in contrast to thinnings throughout the diameter distribution.

Landowner acceptance of the prediction that there will be a supply shortfall led several of them to invest heavily in growth-increasing treatments in established stands, principally pre-commercial thinning in stands as young as five years of age. At least one landowner sought out stands of ages 10–30 to thin them in hopes of accelerating their rotation ages. In several cases, these treatments proved to be too risky while an outbreak was in progress, as thinned stands began to display damage from feeding.

Due both to the increased mortality in partially cut stands and the extensive areas under stress, the landowners' responses to the outbreak produced extremely large areas of contiguous clearcuts, far larger than were initially intended and than would have been planned under normal circumstances. These large cuts generated criticism of forest practices and undoubtedly produced a measure of aesthetic loss, and change in wildlife habitat, as well as generating concern over erosion and nutrient loss. They also stimulated interest in new management practices for bringing clearcuts, with a tendency to become inundated by brush, into production promptly. In many cases, these large openings have regenerated naturally to dense conifer stands, far better than many foresters would have predicted at the time.

Another important effect is that all of our silvicultural research of this period is biased to an unknown degree by the contemporaneous effects of at least low level budworm feeding.

Finally, markets for wood did adjust to some extent to the glut of budworm salvage wood. Some plants adjusted their processes to use dead wood, and a market appeared in the form of the biomass fuel consumed by wood fired electric generating plants. In addition, sawmills began learning how far they could go in using salvage wood. Prior to 1979–80 few sawmills had had any experience with dead wood and there was some uncertainty as to how it could be used for lumber.

Effect of outbreak on the environment

The outbreak had extensive environmental effects. By hastening the conversion of an extensive, economically mature forest to a much younger one it has changed wildlife habitat, aesthetic values, and fish habitat. The management ac-

tivities designed to cope with the outbreak or its effects have also had environmental effects. Effects of cutting on wildlife and fish habitat are well reviewed elsewhere (Bissonette 1986). The effects of insecticides on the environment is a complex subject that is not within the scope of this project.

The fish and wildlife of the spruce-fir forest have endured previous budworm outbreaks and have adapted over time. They have changed in response to previous waves of cutting and land use change. What is important is to determine how the changing forest and the changing management techniques affect the long-term picture.

There is no doubt that the need to respond to the outbreak accelerated the long-term trend toward better road access and more intensive management of the forest. Whether this is good or bad is not for us to determine here. Certainly the increased road access has a number of positive and negative effects on traditional recreational uses of the Maine woods. Increased access has increased hunting and fishing pressure, at the same time as the mortality and cutting have put pressure on wildlife and fish habitat.

Deer wintering areas, low-lying and dense softwood stands, are especially likely to be both susceptible and vulnerable to budworm. In fact, LURC regulations to control cutting in a deer wintering area triggered litigation at one point. Certainly the budworm infestation aggravated previous tensions among landowners, regulators, and the wildlife community over the proper management of these areas. Spraying was prescribed for deeryard management in Vermont but was not considered in Maine for that purpose.

In some instances, budworm mortality has diminished fish habitat as stands adjacent to streams died, eliminating streamside shading. It is in these low-lying areas that the dense fir thickets, most vulnerable to budworm damage, lie. They were priority stands for salvage and presalvage when the outbreak's severity became clear. When no-spray buffers were imposed to reduce pesticide deposit in streams, these areas suffered disproportionately from both mortality and aggressive salvage cutting. In some cases, blowdown into streams degraded habitat further and hindered access for fishing.

The outbreak clearly resulted in some elevation of fire hazard. In the wake of the 1910–20 outbreak, there was apparently no upsurge in fire incidence according to MFS records. But the extensive areas of standing dead trees, of slash piles following salvage, and the patches of blowdown in affected stands are cause for concern for at least several years. The Whiting fire of 1986 showed how intense fires can be in budworm-damaged stands, and how dangerous the fine dry material in the crowns can be in promoting spotting ahead of the fire.

Economic and social effects

The economic and social effects of the outbreak have been significant, though

they have been little studied so far. Considering that the shortfall remains ahead of us, many important effects are still in the future. For this project, only a brief listing of important effects can be given.

Effects on forest landowners have been listed above, focusing on their silvicultural practices. But landowners more generally were affected by losses, especially small owners who were not alert enough to salvage promptly or who were prevented from doing so by lack of markets. Many of these owners will have regeneration problems since they will not be able to afford to plant or to release young stands with herbicides. To the extent that large companies shifted to internal wood supplies, some small owners had more difficulty marketing their wood.

The glut of salvage wood on the market has helped keep pulpwood prices low for landowners large and small. While this supply of low cost wood has been used in some unexpected ways, for example for wood energy and waferboard, the burden of low prices has been real for many landowners. As the supply tightens, prices will increase, as they have already begun to do. Competition for wood will increase, benefiting anyone with surviving timber. In addition, forest owners with other species will benefit as mills begin to substitute other species for spruce-fir, as is already happening to a limited extent.

The cash flow situation of many forest landowners will become severe during the 1990's, unless current timber supply predictions are radically wrong or unless significant changes occur in world wood product markets. This will affect not only their ability to fund intensive management and provide returns to owners but will place intense pressure on the Tree Growth Tax and the Commercial Forest Excise Tax, which are already controversial.

Workers in the woods and mills have been affected. The increase in logging has expanded production but has also stimulated more mechanization. While this reduces jobs per unit of wood cut, it increases safety, productivity, and wage levels for those employed. On the other hand, working in damaged stands is more dangerous than in healthy stands. Woodsworkers may have been exposed to the insecticides used. While there is no reason to believe that this poses any health risk, it is a source of concern to some people.

As the wood supply tightens, mills have already begun to adjust their output and their employment patterns. It is a virtual certainty that jobs will be lost in both Quebec and Maine as lumber capacity shrinks. This will affect the individuals concerned as well as small, timber-dependent communities.

As is the case with other points, however, it is important to note that we cannot properly compare a future output and employment scenario between a forest with and one without budworm—the latter does not exist.

The budworm outbreak had another effect. It prompted a period of severe conflict among the landowner community, state and federal agencies, residents

living near the spray area, environmental groups, and many others. A protracted series of bitter political battles occurred which at times dominated the state's forest policy scene. The bitter divisions and litigation which ensued had an expected but significant effect of the large-scale use of pesticides, the accelerated harvesting, and other effects of the outbreak and the methods employed to deal with it.

CHAPTER VIII

THE FUTURE: PREDICTIONS, ROLES AND RECOMMENDATIONS

The underlying purpose of this report is to assist forest managers, researchers, state officials, and other policymakers in facing the future of the Maine spruce-fir forest. Based on our own experiences, on the interviews with land managers and scientists, and on our analysis of the extensive scientific literature, we can offer a few observations that should be helpful. First, we offer what predictions we can about the future, mentioning the important uncertainties as well. Next we suggest key roles for the different interested groups and agencies concerned with the spruce-fir forest. Finally, we suggest some general recommendations for how the spruce-fir forest should be managed in the future. These recommendations are no surprise to those familiar with the problem. We recognize that not all of them will be easy to carry out, and some will meet with at least mild dissent. Also, future experience will undoubtedly suggest a need to revise these recommendations to some degree.

Predictions and uncertainties

These predictions are reasonably well founded in the experience and research to date, but they are also formed by our own judgments. Some of them will be subject to dispute by at least some observers. In addition, locally significant exceptions will be found in many cases. We are observing a historical ecological process that has gone on for thousands of years, but we have only a sample of one imperfectly-studied outbreak on which to base predictions for the future. Moreover, the forest conditions as they will be modified by harvesting and management have never occurred to any extent before in the Maine forest. This makes extrapolating from past experience even more hazardous.

1. The next outbreak's timing and intensity are uncertain but predictions are possible

The recent outbreak showed erratic ups and downs of populations (see graphs of populations trends and light trap catches, Figures 1–4). But, it is clear that populations at this writing have declined to orders of magnitude below anything experienced since 1967. Populations also have collapsed in the regions to our north and west, and are showing trends towards collapse to our east. It is quite likely that we are entering a period of quiescence in the budworm cycle that will last for several years.

It can be argued that the outbreak could resurge at an early date, and that must be considered as a possibility. We have fir and spruce resources left that might

support an infestation, and we have remnants of the outbreak remaining in the Southeast Coastal region that could burgeon and spread. However, we argued earlier (Chapter I) that the fir and spruce resources remaining are probably mostly of low quality for the budworm. Our remaining infestation is unlikely to spread anywhere except to the east with the prevailing winds. And, there are few surging populations to our west or north to send us moth flights. We appear to be entering a period of almost nonexistent budworm, as occurred between 1920 and the mid-1940's. If we must make a prediction, that is it; but it must be understood that the prediction is made not on absolutes but on probabilities.

If this prediction turns out to be true, the next question is when to expect a new outbreak. Some will argue that Maine might expect to not endure another outbreak at all because its forests will be younger overall and more diverse in age and composition, and theoretically less vulnerable to budworm than at any time in the past. However, the cartographic histories of past outbreaks suggest that the next one is likely to originate to our west, in Ontario and Quebec. Those forests are not now as intensively managed as our own and for the next cycle at least are not likely to be. Once the forests of western Quebec regenerate and mature, the stage will be set for a new outbreak, and moth flights will certainly invade Maine. The conditions of our forests at that time cannot prevent us from seeing increases in budworm numbers in that event. But, with diverse forests, young forests, and good road access, the problem should be more easily managed than in the recent outbreak. When will that occur? If the regular oscillation theory of population dynamics is correct, its beginning should be about 35 years from the beginning of the recent extensive outbreak, which in Maine, was 1970 to 1972. That places the start of a next one about 2005 to 2010. If the double equilibrium theory of population dynamics is correct, a new outbreak should not occur until fir forests to our west have matured. That, again, would be, at minimum, 30 to 40 years from now.

Because of the great uncertainty of these predictions, Maine land managers would be prudent to expect the possibility of renewed outbreak at any time. As each year goes by, the impact of human activities on the biosphere increases, and natural cycles such as the budworm cycle could well be modified by inputs such as intensified forest management, atmospheric pollution, and other effects that we cannot anticipate.

2. *Forest conditions of 1970 will not recur*

The intense budworm outbreak of the 1970–85 period was made more severe by the relatively extensive and mature forest of that period. The rapid accumulation of volume from the 1950's to the mid 70's was accompanied by increased overstocking, larger tree sizes, and modest harvesting rates. In addition, the extensive conversion from river driving to truck hauling began only in the mid-

60's and meant that by the mid-70's, mainline haul roads had not yet been built into many of the more remote areas. As a result there existed extensive unroaded areas of mature fir and spruce. These were producing large crops of staminate flowers and many stands were declining in vigor, especially in the fir component. At the same time, access for salvage or management was difficult. This was a perfect recipe for a severe and damaging outbreak.

These conditions will not recur. The forest of 2000 or 2020 will be readily accessible, and will be a much younger forest than that of 1970. Demand for wood will be high in relation to annual growth, not low as it was in the 1950's and 60's. Landowners' knowledge of and ability to implement intermediate cuttings to affect stand structure, composition, and growth is far greater than it was. Over time, all of these facts mean that the future forest's structure will be far different than in 1970, and its average age will be lower. Just how this will affect budworm susceptibility and vulnerability is not entirely clear, but the classic scenario of outbreak eruption will likely not apply. The extensive stands of overmature trees will not be there. Also, fir could be more abundant than it is now unless many stands receive intermediate treatments.

It is hard to be certain that the budworm will not adapt to this. It is also hard to know how forests in adjacent Quebec and to the West will develop—and those have been past epicenters of the continent-wide outbreaks.

3. Our knowledge is greater, but still limited

As managers faced the 1970's outbreak, they had little well-documented research and past experience to go on. The detailed work at Green River (Morris 1963) was used to understand budworm dynamics, but how widely those relationships could be extrapolated over space and time was uncertain. Individual landowner files contained extensive data on the forest conditions after the 1912–20 outbreak, but there was little empirical basis for making most important management decisions. Also, early in the outbreak it was widely felt that insecticides alone would be able to substantially fend off the threat.

In facing a future outbreak, we can draw upon a much larger base of data, information, hypotheses, and models, but many important questions are still not well understood. This, together with the changes in future forest conditions, means that continued research and critical thinking will be essential.

4. Early warning will be better

In the late 1940's, experts warned that Maine faced a serious budworm outbreak. In the event, the intense outbreak came later than they had expected it would. Timber harvest levels were too low for cutting to have had much impact on forest vulnerability in any case. Arguably, better early warning would have been of little value then.

In the future, we will have the benefit of recent experience which demonstrates the importance of advanced planning and early warning. Land managers will be able to monitor moth populations with pheromones and light traps and to be alert to early developments in central Canada. They will be able to watch for the onset of staminate flower crops in younger stands and to track spring temperature patterns to be alert for the classic warm spring weather patterns that may have played a role in outbreak release in the past.

Managers who carry out risk-rating in emerging young stands will be better able to exploit the added advantage of early warning. Also, they will be able to benefit from past experience and modeling which indicate that earlier spray intervention than was used in the 1970's would be wise.

5. Future response options will be richer

With improved road access, the higher demand for wood, and the ability to carry out anticipatory treatments, management responses to the next outbreak will be much further ahead of the game and will use a richer mix of tools than previously. If managers in fact take advantage of their improved early warning capability, it will mean a quantum increase in their ability to manage the impact of the next outbreak, even if that outbreak turns out to be severe.

6. More planted and treated stands

An important factor changing the forest is the fact that many more acres, by 2000 or 2020, will be planted or treated stands. Plantations will still not dominate the forest in acreage, but they will support a disproportionate share of the production. It is difficult to predict how different a planted stand will be from a natural one at ages 30–50, since many volunteer trees appear in plantations, and we cannot predict how many planted acres will receive cleanings or thinnings during that period. Plantations not treated at all may closely resemble natural stands after 40 years, complete with interspersed hardwoods.

Stands, natural or planted, that receive intermediate treatments will provide different budworm habitat and hence different degrees of susceptibility and vulnerability from the 1970's natural stands. Points of difference include:

- Herbicide treated stands will develop rapidly, may express dominance faster, and will have smaller hardwood components than natural stands, particularly on former mixed wood sites.
- Spaced or thinned stands will undoubtedly display more vigorous diameter growth than untreated stands, but they will develop deeper crowns that may be better budworm habitat. How this better budworm habitat will trade off against stronger stand vigor will be difficult to predict.
- Market dynamics will profoundly affect the rotation ages to which these stands are carried. If current projections are correct, there will be extremely

tight sawlog and studwood markets in the 1990's and later. This could lead to early harvest of stands that develop rapidly to small sawlogs, or it could boost prices to a point that will lead more owners to carry stands longer to capture sawlog value growth. Extreme pressures on pulpwood supplies could also lead to premature cutting of some stands. In fact, anything that does lead to early harvest of some of these stands would be to the good since it would further interrupt the development of a new, extensive age class approaching budworm vulnerability at the same time.

Intensive treatments are costly and cannot be expected to cover really large areas over the next 20 years. On poorer sites and in some other conditions they will not pay economically and will probably not be applied. Still, at present rates of application, the effects of intensive treatments will certainly be far more visible in the forest of 2020.

7. We don't know how susceptible/vulnerable the new forest will be

Considering the many changes that can be anticipated, it is hard to guess how the growing stands of the New Forest will compare to those of 1970's mature forest in susceptibility and vulnerability to budworm attacks. But even if these factors change little, the changes in access, age class distribution, and breaking up of large areas of mature forest will assist managers in responding to an outbreak.

8. Practicality and efficacy of hazard reduction treatments continues to be uncertain

In smaller diameter stands, there will be difficulty in finding economical methods of intermediate stand treatments to maintain vigor, anticipate normal mortality, and shift stand composition toward less vulnerable species. The strong demand for softwood will increase the incentives for solving this problem, however.

Given the extreme wood supply difficulties expected, we can expect treatments to be geared to developing prompt regeneration, producing high conifer volume growth, and shortening rotations. To what extent classical hazard reduction techniques ("cut the fir") can be incorporated into such regimes is uncertain.

Further, in view of the many changes in the forest, and the budworm's adaptability, it would be hazardous to rely too heavily on classical hazard reduction measures alone.

9. Post-outbreak secondary pest problems could arise

The forest continues to recover its foliage complement, root mass, overall vigor, and growth in the wake of the cessation of the outbreak. But the stress

has been extremely severe and prolonged in many areas. It is not uncommon for other secondary beetle or disease problems to arise under such conditions, especially when trees are additionally stressed by drought or harsh winter or spring weather conditions.

Roles for key actors

The virtual disappearance of budworm populations brings with it a risk that key participants in the budworm issue will turn attention to other problems and not maintain the programs and capabilities that would best position the state to respond to an early resurgence or to benefit in future silvicultural planning from past experience. For this reason, it is an apt time to consider what roles should be played by the major interested agencies and groups.

1. Landowners and industry

Landowners and industrial wood users will determine how the forest is managed and harvested. Their role should be to maintain a constant awareness of how year-to-year actions might affect future susceptibility and vulnerability, as well as to maintain strong control over future age class distribution. The landowner and industrial community should pursue strong efforts in the following areas:

a. Support targeted applied research on how the changes in the forest will affect susceptibility and vulnerability and how management techniques designed to increase fiber volume growth will relate to budworm management considerations. A serious joint effort is needed to determine specifically what should be done.

b. Conduct internal "institutional memory" exercises just like we have done, to assure that the owner's staff experience is captured and learned from and that key records are preserved. Some of this information may be suitable raw material for scientific analysis.

c. Prepare senior management for the possibility that resurgences of the outbreak could occur in the short term and that a new outbreak is likely in the 21st century.

d. Continue using improved inventory and forest modeling techniques to analyze future harvest flows, plan silvicultural strategies, and understand the dynamics of the New Forest.

e. Cooperate with the MFS on an extensive, field oriented early warning effort, and help assure that a viable Survey and Detection effort continues.

f. Maintain a strong effort at stand risk-rating for both the old forest and the new.

2. State: Maine Forest Service

The state's principal role should be to maintain its key capabilities so that they can be available if needed, and to urge all others to do likewise. Someone must assure that 10 or 15 years from now the key preparations for the next outbreak have not been forgotten in the press of other business.

This is all the more important considering that by the year 2000 most of the MFS people with extensive budworm survey and control experience will have retired.

a. Monitor key aspects of ongoing timber supply/demand trends. This probably means a need for a 1996 midcycle survey. There is an indication that existing methods seriously undercount the drain on the forest. Better data on drain must be developed.

b. Maintain expertise and leadership in survey and detection and early warning systems, including improvements, as available, in technology for this purpose. Include consideration of pest population health and vigor as well as tree and stand health. Cooperate with landowner staff in the field aspects of this work.

c. Maintain expertise on insecticides and application techniques against future need. Coordinate with the industry and the USFS to advocate continued availability of needed pesticides. Maintain strong liaison with all budworm activities in eastern Canada.

d. Continue supporting modeling and applied research on budworm issues.

e. Maintain vigilance concerning secondary pest occurrences and fire hazard aspects of the changing forest.

f. Consolidate this synthesis project by assuring its distribution, following up on loose ends, and assuring that all MFS files on budworm are preserved in usable order.

g. Assure that the SBW program doesn't become a stepchild. Assure that staff are able to attend meetings and stay current with both applied and scientific developments.

3. USDA Forest Service

The Forest Service is the logical national agency to maintain leadership in control and survey and detection technology as well as in overall insecticide development and registration and forestry research. With its extensive technical staffs, it plays a prominent role in technology transfer as well.

a. Sustain progress in developing new and improved insecticides and application technologies, especially biological materials.

b. Maintain and publish the bibliography on spruce budworm on a periodic basis.

c. Continue strong liaison with the EPA and the Congress on pesticide regulatory issues affecting the forestry community.

d. Continue research on the silvicultural and pest management issues in the northeastern spruce-fir forest. Avoid the temptation to declare the war won and shift to newly urgent fields.

e. Assure that the experience of the early 50's is not repeated. In the 50's an extensive USFS investment was made in establishing field plots to help evaluate changes in forest vulnerability to budworm. By the 1970's, when this information was needed, the plots could not be located so the investment was lost.

4. University

The University should maintain its leading role in research, teaching, and technology transfer.

a. Assure that a thorough budworm archive exists so that information retrieval is easy when needed.

b. Maintain the annual spruce budworm research conferences.

c. Continue to seek support for a targeted CFRU effort on emerging applied research issues in the budworm area.

d. Examine the curriculum in forest protection to assure that it adequately reflects the management needs of future years.

e. Maintain a planned technology transfer/extension effort on spruce budworm issues.

Managing the future forest

1. Make cultural investments on the best sites and try to tailor them to site conditions.
2. Avoid reliance on a single species.
3. Do not extensively convert mixed wood to conifer.
4. Keep the fir . . . welcome its rapid early growth; but be ready to cut it later in intermediate treatments.
5. Manage the forest to try to minimize the area and cost of future spray protection.
6. Keep check plots so we can see what happens in untreated conditions...surprises are not uncommon.
7. Conduct aggressive survey and detection and work for early warning (*e.g.* pheromone and light traps).
8. Watch closely for secondary pests in budworm damaged stands.
9. Make smaller clearcuts where possible—do not create more extensive uniform stands.

10. Use partial cutting systems with care, to create vigorously growing stands with stronger spruce representation where possible. But note that the resulting deep crowns may create high vulnerability.
11. Whenever possible, use intermediate treatments or even premature harvests to break up the large even-aged areas created in the wake of 1970–80 salvage operations.
12. Keep possible effects on budworm susceptibility/vulnerability in mind when planning treatment regimes.
13. Maintain the capability to spray earlier in the outbreak than was done in the 1970's.
14. Pilot test and adapt new ideas on monitoring tree and forest vigor and health over large areas.
15. Keep watching. Be alert to unexpected changes and to new ideas.

LITERATURE CITED

Allen, D.C., L. Dorais, and E.G. Kettela. 1984. Survey and detection. pp 21-36 *In*: Managing the spruce budworm in eastern North America. USDA Agric. Handbook No. 620, D.M. Schmitt, D.G. Grimble, and J.L. Searcy, tech. coords. 192 pp.

Anderson, R.S., R.B. Davis, N.G. Miller, and R. Stuckenrath. 1986. History of late- and post-glacial vegetation and disturbance around Upper South Branch Pond, northern Maine. Can. J. Bot. 64:1977-1986.

Anon. 1979. Maine spruce budworm policy. Maine Dept. of Conservation, Augusta. Report of the Spruce Budworm Policy Review Committee. 83 pp.

Anon. 1983. Creating a new forest: a discussion paper based on the Maine spruce-fir supply demand analysis. Maine Dept. of Conservation, For. Serv., Augusta. 21 pp.

Anon. 1987. Preliminary report of the 1986 midcycle resurvey of the spruce-fir forest in Maine. Maine Dept. of Conservation, For. Serv., Augusta. 36 pp.

Baskerville, G.L. 1975a. Spruce budworm: super silvi-culturalist. For. Chron. 51:138-140.

Baskerville, G.L. 1975b. Spruce budworm: the answer is forest management: or is it? For. Chron. 51:157- 160.

Baskerville, G.L. 1976. Report of the task force for evaluation of budworm control alternatives, prepared for the Cabinet Committee on Economic Development, Province of New Brunswick. Department of Natural Resources, Fredericton, New Brunswick, Canada. 210 pp.

Baskerville, G. 1983. A critique and commentary on the 1983 supply/demand analysis for the spruce-fir forest of Maine. Maine Dept. of Conservation, Augusta. Proc. 56 pp.

Batzer, H.O. 1973. Net effect of spruce budworm defoliation on mortality and growth of balsam fir. J. For. 71:34-37.

Bissonette, J.A. (ed) 1986. Is good forestry good wildlife management? Misc. Publ. No. 689, Maine Agr. Exp. Sta. 377 pp.

Blais, J.R. 1952. The relationship of the spruce budworm (*Choristoneura fumiferana* (Clem.)), to the flowering condition of balsam fir (*Abies balsamea* (L.) Mill). Can. J. Zool. 30:1-29.

Blais, J.R. 1964. Account of a recent spruce budworm outbreak in the Laurentide Park region of Quebec and measures for reducing damage in future outbreaks. For. Chron. 40:313-323.

Blais, J.R. 1981. Mortality of balsam fir and white spruce following a spruce budworm outbreak in the Ottawa River watershed in Quebec. Can. J. For. Res. 11:620-629.

Blais, J.R. 1983. Trends in the frequency, extent, and severity of spruce budworm outbreaks in eastern Canada. Can. J. For. Res. 13:539-547.

Blais, J.R. 1985. The ecology of the eastern spruce budworm: a review and discussion. pp. 49-59 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada. 527 pp.

Blum, B.B., and D.A. MacLean. 1984. Silviculture, forest management, and the spruce budworm. pp. 83-102 *In*: Managing the spruce budworm in eastern North America. USDA Agr. Handbook No. 620, D.M. Schmitt, D.G. Grimble, and J.L. Searcy, tech. coords. 192 pp.

Blum, B.B., and D.A. MacLean. 1985. Potential silviculture, harvesting, and salvage practices in eastern North America. pp. 265-280 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada. 527 pp.

Brann, T.B., G.A. Reams, and D.S. Solomon. 1985. Spruce budworm impact study: 1982 Report. Misc. Rept. 302, Maine Agr. Exp. Sta., Univ. Maine at Orono. CFRU Res. Note 15. 53 pp.

Brown, C.E. 1970. A cartographic representation of spruce budworm *Choristoneura fumiferana* (Clem.), infestation in eastern Canada, 1906-1966. Can. Dept. Fish. For., Ottawa, Can. For. Serv. Publ. 1263.

Burke, R.E. and C.T. Hulsey. 1979. Spruce budworm research in Maine: a user's guide. Dept. of Conservation, For. Serv., Augusta. 175 pp.

Clemens, B. 1865. North American Micro-Lepidoptera. Proc. Ent. Soc. Philad. 5:139.

Clowater, W.G. and P.W. Andrews. 1981. An assessment of the damage caused by the spruce budworm on spruce and balsam fir trees in New Brunswick. For. Manage. Br., New Brunswick Dept. Nat. Resour., Fredericton. Rep. No. 0-88838-087-9.

Craighead, F.C. 1924. Studies on the spruce budworm (*Cacoecia fumiferana* Clem.). Part II. General bionomics and possibilities of prevention and control. Can. Dept. Agr. Tech. Bull. 37(ns), pp 28-91.

Craighead, F.C. 1925. Relation between mortality of trees attacked by the spruce budworm (*Cocoecia fumiferana* Clem.) and previous growth. J. Agric. Res. 30:540-555.

Devine, M.E., H. Trial, Jr., and N.M. Kotchian. 1978. Assessment of spruce budworm damage in the Moosehorn National Wildlife Refuge. Maine Dept. of Conservation, Bureau of Forestry, Env. Tech. Rep. No. 4, 32 pp.

Devine, M.E., and J.Y. Conner. 1980. Resurvey of spruce budworm damage in

the Moosehorn National Wildlife Refuge. Maine Dept. of Conservation, Bureau of Forestry, Env. Tech. Rep. No. 16. 21 pp.

Dimond, J.B., G.Y. Belyea, R.E. Kadunce, A.S. Getchell, and J.A. Blease. 1970. DDT in earthworms and robins associated with contaminated forest soils. Can. Ent. 102:1122-1130.

Dimond, J.B. 1982. Effects of aerial sprays of undiluted *Bacillus thuringiensis* formulations on spruce budworm. Misc. Rept. No. 274, Maine Agr. Exp. Sta. 9 pp.

Dimond, J.B. and O.N. Morris. 1984. Microbial and other biological control. pp. 103-114 *In*: Managing the spruce budworm in eastern North America, USDA Agr. Handbook No. 620, D.M. Schmitt, D.G. Grimble, and J.L. Searcy, tech. coords. 192 pp.

Dimond, J.B., R.S. Seymour, and D.G. Mott. 1984. Planning insecticide application and timber harvesting in a spruce budworm epidemic. USDA For. Serv. and CSRS, Spruce Budworms Handbook. Agr. Handbook 618. 29 pp.

Dimond, J.B., R.S. Seymour, and D.G. Mott. 1985. Targeted spray application and harvesting in a spruce budworm epidemic. Misc. Rep. No. 303. Maine Agr. Exp. Sta. 52 pp.

Dorais, L., and E.G. Kettela. 1982. A review of entomological survey and assessment techniques used in regional spruce budworm, *Choristoneura fumiferana* (Clem.) surveys and in the assessment of operational spray programs. Report of the Committee for Standardization of Survey and Assessment Techniques to the Eastern Spruce Budworm Council. Quebec Dept. Energy and Resources. 43 pp.

Falk, J. 1980. Wind-damage in spruce-fir stands. Misc. Rep. No. 225. Maine Agr. Exp. Sta. 25 pp.

Ferguson, R.H., and N.P. Kingsley. 1972. The timber resources of Maine. USDA For. Serv. Res. Bull. NE-26. 129 pp.

Fleming, R.A., C.A. Shoemaker, and J.R. Stedinger. 1984. An assessment of the impact of large-scale spraying operations on the regional dynamics of spruce budworm (Lepidoptera: Tortricidae) populations. Can. Ent. 116:633-644.

Frank, R. 1985. Building new spruce-fir stands—a longterm localized strategy for reducing spruce budworm impact. pp. 365-366 *In:* Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada. 527 pp.

Ghent, A.W., D.A. Fraser, and J.B. Thomas. 1957. Studies of regeneration in forest stands devastated by the spruce budworm. I. Evidence of trends in forest succession during the first decade following budworm devastation. For. Sci. 3:184-208.

Gorham, J.R. 1961. Aquatic insects and DDT forest spraying in Maine. Bull. No. 19, Maine For. Serv., 48 pp.

Greenbank, D.O. 1957. The role of climate and dispersal in the initiation of outbreaks of the spruce budworm in New Brunswick. II. The role of dispersal. Can. J. Zool. 35:385-403.

Greenbank, D.O. 1963. Host species and the spruce budworm. pp. 219-223. *In*: The dynamics of epidemic spruce budworm populations. R.F. Morris, ed. Ent. Soc. Can. Mem. 31. 332 pp.

Greenbank, D.O., G.W. Schaefer, and R.C. Rainey. 1980. Spruce budworm (Lepidoptera: Tortricidae) moth flight and dispersal: new understanding from canopy observations, radar, and air-craft. Ent. Soc. Can. Mem. 110. 49 pp.

Hardy, Y., M. Mainville, and D.M. Schmitt. 1986. An atlas of spruce budworm defoliation in eastern North America, 1938-80. USDA For. Serv., Coop. State Res. Serv., Misc. Publ. No. 1449. 52 pp.

Harvey, G.T. 1985. The taxonomy of the Coniferophagous *Choristoneura* (Lepidoptera: Tortricidae): A review. pp. 16-48 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada. 527 pp.

Hazelton, L.W. 1976. Wood supply: forest industry point of view. pp. 142-146. *In*: J.F. Chansler and W.H. Klein, Proceedings of a Symposium on the Spruce Budworm, Alexandria, VA, Nov. 11-14, 1974, USDA For. Serv. Misc. Pub. No. 1327, 188 p.

Heller, R.C., J.L. Bean, and J.W. Marsh. 1952. Aerial survey of spruce budworm damage in Maine in 1950. J. For. 50:8-11.

Irland, L.C. 1983. Improving the EIS process: a case study of spruce budworm control. pp. 375-391 *In*: S.L. Hart, G.A. Enk, and W.F. Hornick, Improving Impact Assessment. Boulder: Westview Press.

Irland, L.C. and T. Rumpf. 1987. Cost trends for *B. thuringiensis* in the Maine spruce budworm control program. Bull. Ent. Soc. Amer. 33:86-90.

Jennings, D.T., F.B. Knight, S.C. Hacker, and M.E. McKnight. 1979. Spruce budworms bibliography. Misc. Rept. No. 213, Maine Agr. Exp. Sta., 687 pp.

Jennings, D.T., S.C. Hacker, F.B. Knight, and M.E. McKnight. 1981. Spruce budworms bibliography, supplement 1. Misc. Rept. No. 255, Maine Agr. Exp. Sta., 193 pp.

Jennings, D.T., S.C. Hacker, F.B. Knight, and M.E. McKnight. 1982. Spruce budworms bibliography, supplement 2. Misc. Rept. No. 268, Maine Agr. Exp. Sta., 75 pp.

Jennings, D.T., S.C. Hacker, F.B. Knight, and M.E. McKnight. 1983. Spruce budworms bibliography, supplement 3. Misc. Rept. No. 292, Maine Agr. Exp. Sta., 59 pp.

Keenan, R.E. and M.C. Moritato. 1985. Protection of red spruce from spruce budworm defoliation. Maine Dept. of Conservation, For. Ser., Augusta. 57 pp.

Kemp, W.P., and G.A. Simmons. 1978. The influence of stand factors on parasitism of spruce budworm eggs by *Trichogramma minutum*. Environ. Ent. 7:685-688.

Kemp, W.P., and G.A. Simmons. 1979. Influence of stand factors on survival of early instar spruce budworm. Environ. Ent. 8:993-996.

Kettela, E.G. 1983. A cartographic history of spruce budworm defoliation 1967-1981 in eastern North America. Can. For. Serv., Ottawa, Ont., Inf. Rep. DPC-X-14. 8 pp.

Kleinschmidt, S.M., G.L. Baskerville, and D.S. Solomon. 1980. Reduction of volume increment in fir-spruce stands due to defoliation by spruce budworm. Faculty For., Univ. New Brunswick, Fredericton, N.B. Res. Pap. 37 pp.

Lund, Wilk, Scott, and Goodall, Attys. 1979. Study of alternatives to state management of spruce budworm spraying. Maine Dept. of Conservation, For Serv. 189 pp.

MacLean, D.A. 1980. Vulnerability of spruce-fir stands during uncontrolled spruce budworm outbreaks: a review and discussion. For. Chron. 56:213-221.

MacLean, D.A. 1985. Effects of spruce budworm outbreaks on forest growth and yield. pp. 148-175 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada. 527 pp.

MacLean, D.A., A.W. Kline, and D.R. Lavigne. 1984. Effectiveness of spruce budworm spraying in New Brunswick in protecting the spruce component of spruce-fir stands. Can. J. For. Res. 14:548-555.

Maine Forest Service. 1987. Preliminary report of the 1986 midcycle resurvey of the spruce-fir forest in Maine. Augusta: Dept. of Conservation. 36 pp.

Mattson, W.J., and N.D. Addy. 1975. Phytophagous insects as regulators of primary production. Science 190:515- 522.

Mattson, W.J., S.S. Slocum, and C.N. Koller. 1983. Spruce budworm (*Choristoneura fumiferana*) performance in relation to foliar chemistry of its host plants. pp. 55-65 *In*: R.L. Talerico and M. Montgomery, eds. Proc. Forest defoliator-host interactions: a comparison between gypsy moth and spruce budworms. USDA For. Serv., Gen. Tech. Rep. NE-85.

Mattson, W.J., and R.A. Haack. 1987. The role of drought in outbreaks of plant-eating insects. Bioscience 37:110-118.

McLintock, T.F. 1947. Silvicultural practices for control of spruce budworm. J. For. 45:655-658.

McLintock, T.F. 1955. How damage to balsam fir develops after a spruce budworm epidemic. USDA For. Serv. Northeast For. Exp. Sta., Res. Pap. NE-75.

Miller, C.A. 1975. Spruce budworm: how it lives and what it does. For. Chron. 51:136-138.

Miller, C.A., E.G. Kettela, and G.A. McDougall. 1971. A sampling technique for overwintering spruce budworm and its applicability for population surveys. Can. For. Serv. Info. Rep, Maritimes For. Res. Cent., M-X-25. 11 pp.

Miller, C.A., and E.G. Kettela. 1972. An additional note on sampling overwintering spruce budworm. Can. For. Serv. Inf. Rep., Maritimes For. Res. Centre. M-X-34.

Miller, C.A. and E.G. Kettela. 1975. Aerial control operations against the spruce budworm in New Brunswick, 1952-1973. pp. 94-112 *In*: Aerial control of forest insects in Canada, M.L. Prebble, ed. Inf. Can. cat. no. Fo23/19/1975, 330 pp.

Montgomery, M.E. 1985. Host plant nitrogen dynamics and the spruce budworm. pp. 120-121 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16 -20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada. 527 pp.

Morris, R.F., ed. 1963. The dynamics of epidemic spruce budworm populations. Ent. Soc. Can. Mem. 31. 332 pp.

Morris, R.F., and R.L. Bishop. 1951. A method of rapid forest survey for mapping vulnerability to spruce budworm damage. For. Chron. 27:171-178.

Morrison, T.A. and J.B. Dimond. 1978. Field trials for control of spruce budworm in Maine: a history and bibliography. Tech. Rept. No. 6, Ent. Div., Bur. For., Maine Dept. of Conservation, Augusta. 13 pp.

Mott, D.G. 1963. The forest and the spruce budworm. pp 189-202 *In*: The dynamics of epidemic spruce budworm populations. R.F. Morris, ed. Ent. Soc. Can. Mem. 31. 332 pp.

Mott, D.G. 1980. Spruce budworm protection management in Maine. Maine For. Rev. 13:26-33.

Nevel, R.L., Jr., P.R. Lammert, and R.H. Widmann. 1985. Maine timber industries—a periodic assessment of timber output. USDA For. Serv. Res. Bull. NE-83. 42 pp.

Oliveri, S. 1986. Buffer zones for Maine's spruce budworm suppression operations. In Trial, J: unpublished, forthcoming in Buffer Zone Workshop proceedings.

Osawa, A. 1986. Patch dynamics of spruce-fir forests during a spruce budworm outbreak in Maine. PhD dissertation, Yale University, New Haven, Conn. 128 pp.

Osawa, A., C.J. Spies, III, and J.B. Dimond. 1986. Patterns of tree mortality during an uncontrolled spruce budworm outbreak in Baxter State Park. Tech. Bull. 121. Maine Agr. Exp. Sta. 69 pp.

Otvos, I.S., and B.H. Moody. 1978. The spruce budworm in Newfoundland: history, status, and control. Can. For. Serv., Newfoundland For. Res. Centre, Inf. Rep. N-X- 150. 76 pp.

Pistell, A. and D. Harshberger. 1979. The spruce budworm in Maine. Maine For. Serv., Augusta. 89 pp.

Powell, D.S. and D.R. Dickson. 1984. Forest statistics for Maine 1971 and 1982. USDA For. Serv., Res. Bull. NE-81. 194 pp.

Powell, D.S. 1985. The spruce-fir resource of Maine. pp. 59-67 *In*: Spruce-fir management and the spruce budworm. SAF Region VI Tech. Conf. USDA For. Serv. Northeastern For. Exp. Sta. Gen Tech Rep. GTR-NE-99.

Regniere, J. 1984. Vertical transmission of diseases and population dynamics of insects with discrete generations—a model. J. Theor. Biol. 107:287-301.

RISI. 1987. Report on the demand for forest products in Maine. Maine Dept. of Conservation, Augusta. 65 pp.

Royama, T. 1984. Population dynamics of spruce budworm (*Choristoneura fumiferana* Clem.): a reinterpretation of life table studies from the Green River Project. Ecol. Monogr. 54:429-462.

Rumpf, T., S. Blackmer, and L. Irland. 1981. Spruce budworm policy in Maine: tradition, conflict, and adoption. J. For. 3:91-95.

Rumpf, D.L., E. Melachrinoudis, and T. Rumpf. 1985. Improving efficiency in a forest pest control program. Interfaces 15:1-11. (see also J. For., Feb. 1988)

Sanders, C.J. 1980. A summary of current techniques used for sampling spruce budworm populations and estimating defoliation in eastern Canada. Can. For. Serv., Inf. Rep. O-X-306. Great Lakes For. Res. Centre. 33 pp.

Sanders, C.J. 1985. Sex pheromone traps for monitoring spruce budworm populations. p. 234 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds., Ottawa, Canada. 527 pp.

Sanders, C.J., and G.S. Lucuik. 1985. Effect of weather on spruce budworm populations. pp. 90-91 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds., Ottawa, Canada. 527 pp.

Sanders, C.J., R.W. Stark, E.J. Mullins, and J. Murphy. 1985. Recent advances in spruce budworm research. Proc. CANUSA Spruce budworms Res. Symp., Sept. 15-20, 1984, Bangor, ME. 527 pp.

Schiltz, H.M., G.A. Reams, W.S. Warner, T.J. Corcoran, T.B. Brann, and D.S. Solomon. 1983. Impact of the spruce budworm in Maine 1975-1980. Misc. Rep. No. 290. Maine Agr. Exp. Sta. 35 pp.

Schmitt, M.D.C., M.M. Czapowskij, D.C. Allen, E.H. White, and M.E. Montgomery. 1983. Spruce budworm fecundity and foliar chemistry: influence of site. pp. 97-103 *In*: R.L. Talerico and M. Montgomery, eds. Proc. Forest defoliator interactions: a comparison between gypsy moth and spruce budworms. USDA For. Serv., Gen. Tech. Rep. NE-85.

Schmitt, D.M., D.G. Grimble and J.L. Searcy, tech. coords. 1984. Managing the spruce budworm in eastern North America. USDA For. Serv., Agr. Handbook No. 620, 192 pp.

Sewall, James W., Co. 1983. Spruce-fir wood supply/demand analysis. Final report to Maine Dept. of Conservation. James W. Sewall Co., Old Town, Maine. 94 pp. plus appendices.

Seymour, R.S. 1980. Vulnerability to spruce budworm damage and 100-year development of mixed red spruce-fir stands in northcentral Maine. PhD dissertation, Yale University, New Haven, CT. 161 pp.

Seymour, R.S. 1985. Forecasting growth and yield of budworm-infested forests. Part I. Eastern North America. pp. 200-213 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada. 527 pp.

Seymour, R.S., D.G. Mott, S.M. Kleinschmidt, P.H. Triandafillou, and R. Keane. 1985. Green Woods Model: forecasting tool for planning timber harvesting and protection of spruce-fir forests attacked by the spruce budworm. USDA For. Serv., Northeastern For. Exp. Sta. Gen Tech Rep. NE-91. 38 pp.

Seymour, R.J. and R.C. Lemin, Jr. 1987. Adopting FORMAN for timber supply analysis in Maine. IUFRO Forest Growth Modelling and Prediction Conference, Minneapolis. 8 pp.

Seymour, R.S. 1987. Analysis of the future supply of forest resources in Maine. Maine Dept. of Conservation, Augusta. Mimeo.

Shepherd, R.F. 1985. A theory on the effects of diverse host-climatic environments in British Columbia on the dynamics of Western Spruce Budworm. pp. 60-70 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada. 527 pp.

Simmons, G.A. 1980. Use of light trap data to predict outbreaks of the spruce budworm. Dept. Ent., Mich. State Univ. Inf. Rep. 80-b. East Lansing, MI. 13 pp.

Sippell, W.L. 1984. Planning now to reduce, postpone, or prevent the next spruce

budworm outbreak. pp. 59-67 *In*: Proc. of Symposium: new and improved techniques for monitoring and evaluating spruce budworm populations. USDA For. Serv. Gen. Tech. Rep. NE-88.

Smith, D.M. 1981. The forest and Maine's future. pp. 79- 90 *In*: Proc. Blaine House Conference on Forestry. Maine Dept. of Conservation, Augusta.

Solomon, D.S. 1984. Foliage weight production and bole growth of balsam fir trees defoliated by the spruce budworm. pp 25-34 *In*: D.P. Ostaff, M.D. Cameron, and E.J. Mullins, eds. Proc. Damage Assessment Working Group, CANUSA Spruce Budworms Program, Oct. 25-26, 1983. Bangor, ME.

Solomon, D.S. 1985a. Growth responses of balsam-fir damaged by spruce budworm. pp. 105-111 *In*: Spruce- fir management and the spruce budworm. SAF Region VI Tech. Conf. USDA For. Serv. Northeastern For. Exp. Sta. Gen. Tech. Rept. GTR-NE-99.

Solomon, D.S. 1985b. Impact of spruce budworm on the growth response of trees in the spruce-fir forests of the Eastern United States. pp. 246-247 *In*: Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworm research symposium, Bangor, ME, Sept. 16-20, 1984. C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy, eds. Ottawa, Canada.

Solomon, D.S. 1988. Coop-impact 10-year Report (in progress).

Spies, C.J., III, and J.B. Dimond. 1985. Some populational relationships between spruce budworm, *Choristoneura fumiferana* (Lepidoptera: Tortricidae) and spruce coneworm, *Dioryctria reniculelloides*(Lepidoptera: Pyralidae). Can. Ent. 117:193-202.

Stedinger, J.R. 1977. Spruce budworm management models. PhD dissertation, Harvard University, Cambridge, MA. 260 pp.

Stedinger, J.R. 1984. A spruce budworm - forest model and implications for suppression programs. For. Sci. 30:597-615.

Talerico, R.L. 1984. General biology of the spruce budworm and its hosts. pp 1-10 *In*: Managing the spruce budworm in North America. USDA Agric. Handbook No. 620, D.M. Schmitt, D.G. Grimble, and J.L. Searcy, tech. coords. 192 pp.

Tilles, D.A., and N.E. Woodley. 1984. Spruce budworm parasites in Maine: a reference manual for collection and identification of common species. USDA For. Serv., Coop. State Res. Serv., Agric. Handbook No. 616. 35 pp.

Trial, H., Jr., and M.E. Devine. 1983. Spruce budworm in Maine: results of the 1982 project, biological conditions in 1982, and expected infestation conditions for 1983. Maine Dept. of Conservation, For. Serv., Div. Ent., Tech. Rep. No. 20. 75 pp.

Trial, H., Jr. 1984. Status of red spruce protection in Maine. pp. 2-9, Proc. Spruce Protection Symp., Maine Dept. of Conservation, For. Serv. Oct. 23, 1984, Bangor, ME. 75 pp.

Trial, H. Jr., M.E. Devine, and J.Y. Conner. 1984. Spruce budworm in Maine: Results of the 1983 project, biological conditions in 1983, and expected infestation conditions for 1984. Maine Dept. of Conservation, For. Serv., Div. Ent., Tech. Rep. No. 20. 75 pp.

Trial, H. Jr. and J.B. Dimond. 1987. An evaluation of split applications and new formulations of *Bacillus thuringiensis* against the spruce budworm in Maine. Div. Ins. Dis. Mgmt., Maine For. Serv. Tech. Rept. No. 26, 18 pp.

Trial, J.G. 1986. Environmental monitoring of spruce budworm suppression programs in the eastern United States and Canada—an annotated bibliography. Misc. Rept. No. 312, Maine Agr. Exp. Sta. 36 pp.

USDA 1982. Spruce budworm environmental assessment: proposed cooperative spruce budworm integrated pest management program, Maine, 1982. Lead agency, USDA For. Serv., Northeastern Area, State and Private Forestry. 59 pp. USDA 1983.

Warner, K. and O.C. Fenderson. 1962. Effects of DDT spraying for forest insects on Maine trout streams. J. Widl. Mgmt. 26:86-93.

Weed, D. 1977. Spruce budworm in Maine, 1910-1976: infestations and control. Maine Dept. of Conservation, For. Serv. 100 pp. (compiled from annual Entomology Division reports)

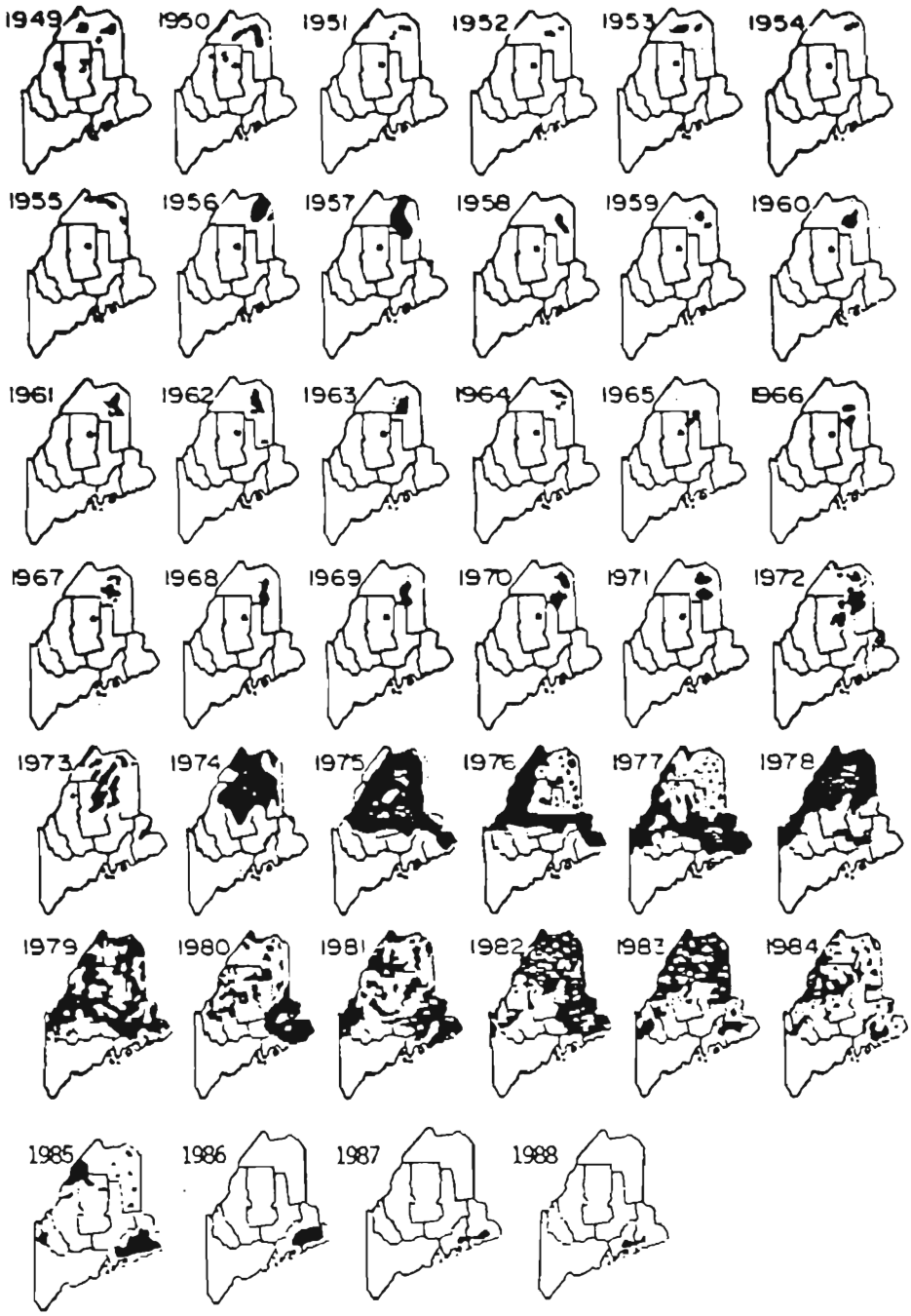
Wellings, F.R., and R.E. Bailey. 1982. Cumberland County budworm losses. Nova Scotia Dept. Lands Forests, Truro, N.S. For. Tech. Note No. 4.

Westveld, M. 1946. Forest management as a means of controlling spruce budworm. J. For. 44:949-953.

White, T.C.R. 1976. Weather, food, and plagues of locusts. Oecologia 22:119-134.

Williams, J.R. 1985. A private landowner perspective of state policy, economics, and responsibility in spruce budworm control. For. Chron. 61:388-393.

Witter, J., D. Ostaff, and B. Montgomery. 1984. Damage assessment. pp. 37-64 *In*: Managing the spruce budworm in eastern North America. USDA Agric. Handbook No. 620, D.M. Schmitt, D.G. Grimble, and J.L. Searcy, tech. coords. 192 pp.



Appendix A. Maps of spruce defoliation in Maine, 1949 to 1988. Updated (1985-1988) from Osawa (1986).