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MANAGING TREES AND STANDS SUSCEPTIBLE TO WESTERN SPRUCE BUDWORM
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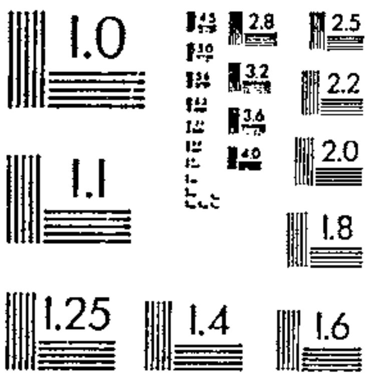

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Technical Bulletin No. 1695

Managing Trees and Stands Susceptible to Western Spruce Budworm

In 1977, the United States Department of Agriculture and the Canadian Department of the Environment agreed to cooperate in an expanded and accelerated research and development effort, the Canada/United States Spruce Budworms Program (CANUSA), aimed at the spruce budworm in the East and the western spruce budworm in the West. The objective of CANUSA was to design and evaluate strategies for controlling the spruce budworms and managing budworm-susceptible forests to help forest managers attain their objectives in an economically and environmentally acceptable manner. This manual is one in a series on the western spruce budworm.

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Technical
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Managing Trees and Stands Susceptible to Western Spruce Budworm

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Canada/United States Spruce Budworms
Program-West

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Preface

Despite extensive aerial spraying, outbreaks of the spruce budworm in the East and the western spruce budworm in the West have caused considerable damage to susceptible forests and show no signs of abating. As many as 900 million acres (365 million ha) have been infested in 1 year in the eastern part of the continent. About 5 million acres (about 2 million ha) are infested annually in the West, and about 247 million acres (100 million ha) of western forests are considered susceptible. A new approach to budworm problems was clearly needed—one that could include direct suppression but would emphasize forest management to reduce susceptibility.

In 1977, the United States Department of Agriculture and the Canadian Department of the Environment agreed to pool the expertise and facilities of both countries; together they embarked on a 6-year research and development program in 1978. Objectives were to design and evaluate economical and environmentally acceptable strategies to suppress the budworms and to manage forests susceptible to them. Part of the planning was to assure that new information and technology would be available for application by forest managers as soon as possible.

So that the information would be in forms most useful to forest managers, administrators in the western segment of the program (CANUSA-West) appointed a working group (see appendix 1) to plan the distribution of research results to all appropriate audiences. Meeting annually, the group identified the major audiences and developed a framework for reaching them. A major part of the effort is this series of three books. *Western Spruce Budworm* is a synthesis of current knowledge about the insect and its hosts. It summarizes most of the known information on the western spruce budworm and provides background for the recommendations contained in two management books: this book, *Managing Trees and Stands Susceptible to Western Spruce Budworm*, and *Western Spruce Budworm and Forest Management Planning*.

This book is a guide for detecting and evaluating effects or potential effects of budworm on the forests being managed, comparing management strategies, and providing support for decisions related to budworm. It is focused on effects of budworm on trees and stands, outlining operations for detection, evaluation, and control.

It is not intended as a key to the scientific literature on which its recommendations are based. Readers accustomed to research papers may be surprised at how few literature citations are included. Full documentation for the underlying concepts and current theories related to budworm is provided in *Western Spruce Budworm*. Refer to its exhaustive index for quick access to specific topics of interest.

For convenience, "budworm" or "western budworm" in this book means the western spruce budworm, *Choristoneura occidentalis* Freeman. The spruce budworm, *C. fumiferana* (Clemens), is called "eastern budworm."

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Chapter 8

Acknowledgments

We are proud of the Pacific Northwest Station's role as host to CANUSA-West. Headquartered at our Portland Forestry Sciences Laboratory, the Program was guided and shaped by Max W. McFadden for the first 3 years. R. W. Stark took over in 1981, and J. J. Colbert became Program Manager in 1984. Their leadership was ably supported by Research Coordinator J. J. Colbert; Applications Coordinators Thomas H. Flavell (until February 1982) and Russel G. Mitchell; and Information Coordinator Martha H. Brookes.

To them, to the researchers and authors, to the many organizations in both the public and private sectors that contributed to this research, development, and applications effort—especially the dedicated members of the Technology Transfer Working Group, who shared their skills and expertise to determine how the Program's products should be presented—I extend my sincerest thanks.

Robert L. Ethington

Robert L. Ethington,
Director

Editors' Acknowledgments

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Chapter 1
Historical Considerations

Wyman C. Schmidt[1]

[1]Authors' affiliations can be found in appendix 3.

Three major factors have done much to shape the character of coniferous forests in the West—fire, insects and disease, and timber harvesting. Harvesting was not a factor before European settlement, but fire, insects, and diseases certainly were. Native Americans played a particularly important role in shaping the character of the forests by their use of fire. This, in turn, was related to earlier attacks of insects and diseases, which set the stage for wildfires by killing the trees. Thus, the natural cycle was fire, forest regeneration and development, insects and disease, fuel buildup where biomass accumulation exceeded decomposition, and—again—fire.

Timber harvesting did not become a significant factor until the turn of this century. Since then, timber harvesting has accelerated throughout most of the West and has largely replaced fire in the forest cycle on managed lands.

Fire suppression was hardly a part of the vocabulary until around 1900, when forest managers began to realize that forests of the West were not limitless. From about the mid-1800's to the beginning of the 20th century, mining, building railroads, and logging to supply wood for these activities did much to alter the character of the forests, primarily by increasing the incidence and extent of wildfires. Little or nothing was done to control wildfires. The turn of the century saw the beginnings of fire-control philosophies, but the technology to control extensive fires, such as those of 1910 in the northern U.S. Rockies, had not been developed. These fires may have been a mixed blessing: they converted millions of acres of decadent old-growth stands to what are now 70-year-old stands. The drought of the 1920's and 1930's provided burning conditions that resulted in several large wildfires, but the emphasis on fire control and gradually improving fire-control technology greatly reduced the number and extent of major fires. Also—and perhaps most important to the budworm—intensive fire control practically eliminated the less conspicuous surface fires that had burned so commonly in the past.

Only in the last decade has fire-control philosophy changed substantially. In some wilderness and park areas in the West, natural fires are now allowed to burn under specific, thoroughly planned conditions.

Budworm host forests throughout the West have one dynamic ecological factor in common—all have felt the heat of forest fires some time in their past. These natural fires ranged from relatively cool fires on the forest floor to holocausts that consumed nearly everything in their paths. Fires in forests that burned frequently were generally of low intensity because less fuel had accumulated. Fuels accumulated where fires occurred infrequently, and conflagrations were more intense. The lower elevation ponderosa pine and associated species typically had more frequent but less intensive fires than the spruce–fir forest types on the cooler, moister sites. The spruce–fir forests burned infrequently; when they did, enough fuel had accumulated for major fires when correct temperature, moisture, and ignition conditions coincided.

Before European settlement of North America, fire passed through the lower, drier ponderosa pine/Douglas-fir forests at 5- to 25-year intervals. Fire intervals in the cooler, but still relatively dry, interior Douglas-fir forests averaged about 25 to 60 years. Mid-elevation Douglas-fir, white fir, and grand fir combinations apparently burned at frequencies intermediate between those of the drier Douglas-fir found at lower elevations and the higher elevation, cool–moist conditions of the spruce–fir type, which had fire intervals of about 50 to 300 years. The inland maritime forests, characterized by a wide variety of species—such as western redcedar, western hemlock, Douglas-fir, western white pine, and western larch—are moister and also warmer than some of the previously described areas. Summer drought in this type is common, however, and moderate to very hot wildfires occurred here at intervals averaging between 60 and 350 years.

Although lightning has historically been credited with starting most fires before the settling of the West, increasing evidence suggests that Native Americans also played a major role. Nearly half the fires in the lower elevations are thought to have been caused by Native Americans, with a lesser proportion in the higher elevations. Some fires started in the lower elevations likely spread upslope into the subalpine forests during the short warm–dry periods characteristic of many of the upper elevation zones in the West.

Succession is the gradual replacement of the biota on an area by one of a different character. This successional trend is readily apparent in the coniferous forests of the West. Left undisturbed, all forest types succeed toward increasing proportions of shade-tolerant, climax species. Given enough time and with no major disturbance, these forests eventually consist almost entirely of species that can reproduce under their own shade and forest-floor conditions. Fire and other disturbances interrupt this natural succession toward climax forests and set all vegetation back toward early successional seral stages.

In western coniferous forests, early successional stages are dominated by seral species, such as ponderosa pine, lodgepole pine, and western larch. Of these, only larch is fed on by budworm, and that feeding is confined primarily to stems instead of foliage. Late successional stages are dominated by the climax, shade-tolerant species, primarily the true firs (such as grand fir, subalpine fir, white fir, and silver fir) and the spruces (Engelmann, blue, and white). All of these are hosts for the budworm. Interior Douglas-fir plays diverse roles in the successional picture—seral in some habitat types and climax on others. When climax, it serves as the primary host of the western budworm; otherwise budworms feed more heavily on its more shade-tolerant associates, such as subalpine and grand firs.

Both relatively cool surface fires and hot conflagrations result in increased proportions of seral species and corresponding decreases in climax species. Thick bark and the high-branching habit of some of the seral species, such as ponderosa pine and larch, permit them to survive even the hotter fires. Conversely, even light surface fires kill species such as the true firs, spruces, and young Douglas-fir because of various combinations of low, flammable crowns and thin bark. Thus, increasing fire frequencies discriminate against shade-tolerant climax species—true firs, spruces, and interior Douglas-fir—and increase the relative importance of seral conifers—ponderosa pine, lodgepole pine, and western larch. Lodgepole pine does not survive fires well, but because of its serotinous cones, regenerates prolifically after fire.

Increasingly effective fire prevention and suppression during this century have eliminated most major fires and nearly all surface fires. As a result, forests that have had no other disturbances, such as timber harvesting, have succeeded steadily toward climax and, consequently, an abundant and expanding source of the budworm's favorite food—the shade-tolerant species.

Fire suppression has affected not only species composition, but also the structure of forests. Stand structure is the vertical and lateral distribution of trees in a stand. Differences in shade tolerance largely dictate what position western conifers occupy in the stand. By and large, shade-intolerant species, such as ponderosa pine, lodgepole pine, and western larch, cannot regenerate successfully under closed canopies and, if regenerated, must occupy the upper strata in the forest to survive. Conversely, shade-tolerant species can regenerate under their own canopies and develop in any vertical stratum of the forest.

A continuous vertical and lateral crown canopy of shade-tolerant species increases the number of favorable landing sites for budworm larvae during dispersal; fewer larvae fall to the forest floor where they succumb to various biological and physical factors.

Wide acreages of western forest lands are set aside for uses other than timber production—primarily in parks and wilderness, scenic areas, and wildlife and natural area preserves. For most of this century, fires have been routinely suppressed in these areas—most effectively for the last 30 to 40 years. Forests in these set-aside areas have greater proportions of decadent old-growth and climax species associations. Some of these forests—susceptible to insects, diseases, and fire—are already being attacked, and most are increasingly ripe for attack.

Growth loss and mortality caused by budworm are not problems on these set-aside lands because the timber volumes are not included in the base for determining allowable cuts and sustained yields. Esthetic, watershed, and wildlife values are important to forest managers; but the timber, by law, cannot be harvested.

The set-aside areas often abut areas where timber production is an important objective. Managers of adjacent forests being intensively managed for timber production are concerned about insects, such as budworm, coming into these forests from the set-aside areas. Just how much of a threat this is to forests that are being managed silviculturally to reduce budworm susceptibility and vulnerability has not been adequately assessed.

A half century of economic-selection cutting and associated inadequate site preparation discriminated against intolerant species and enhanced opportunities for shade-tolerant ones. This, coupled with intensive fire protection, has resulted in uneven-aged stands of the true firs, interior Douglas-fir, and spruce. Typical are the broad areas where ponderosa pine originally grew on habitats that are in the Douglas-fir, grand fir, or white fir climax series (fig. 1-1). Before settlement, frequent fires kept Douglas-fir and true firs as a minor constituent of the stand and the fire-resistant ponderosa pine as a major one. Also, economic-selection cuttings removed a disproportionate share of the more valuable ponderosa pine, leaving behind decrepit stands composed largely of damaged and suppressed budworm host species. Site preparation for subsequent establishment

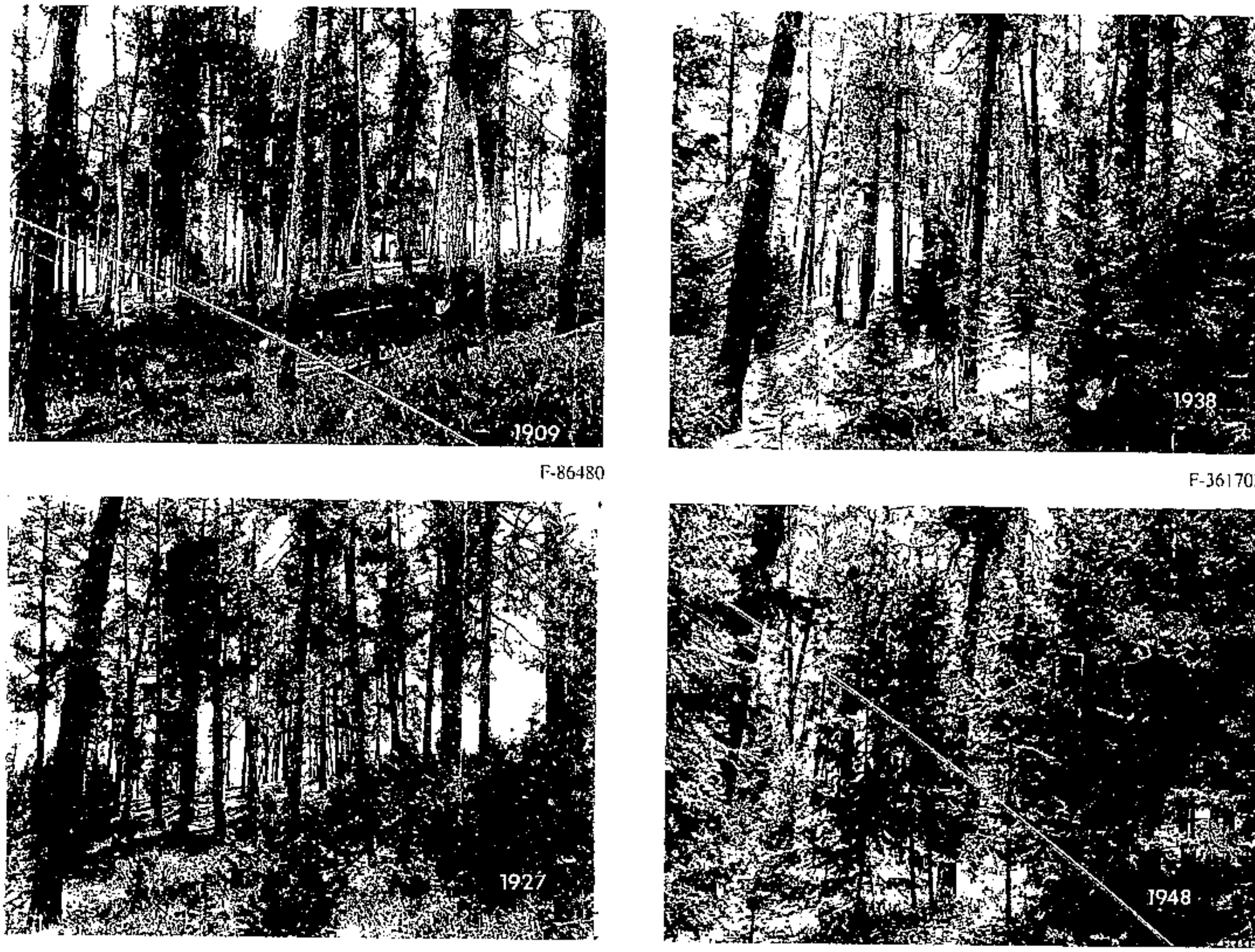

Figure 1-1—Succession after single-tree selection cutting of a ponderosa pine/Douglas-fir forest in a Douglas-fir habitat type (Schmidt and others 1983).

of seral species such as ponderosa pine was limited. Economic-selection cutting reduced the growth potential of residual stands and accelerated the march toward climax forests—favored food of the budworm. Thus, along with aggressive fire suppression, economic-selection cutting ultimately helped produce extensive areas of favorable habitat for the budworm. All that the budworm needed to go from low to outbreak populations, apparently, was the right weather pattern.

Thus, the stage was set and the budworm responded. From a relatively insignificant insect in the western forest, budworm rapidly became a major pest. The decade from 1947 to 1957 saw aerially detectable budworm defoliation in western North America increase from a little over half a million to nearly 8 million acres (0.2 million to 3.2 million ha) (fig. 1-2). Although detectable defoliation fluctuated from year to year westwide and regionally, it averaged about 5 million acres (2 million ha) annually for the next two decades, peaked again in 1977, declined briefly, and then reached a new high of almost 11 million acres (4.5 million ha) in 1983.

Managers rapidly responded to the budworm threat in the late 1940's with the most effective methods available at that time—aerial application of insecticides. Aerial technology developed in World War II, along with the highly effective DDT, was available. In 1949, one-fourth of a million acres

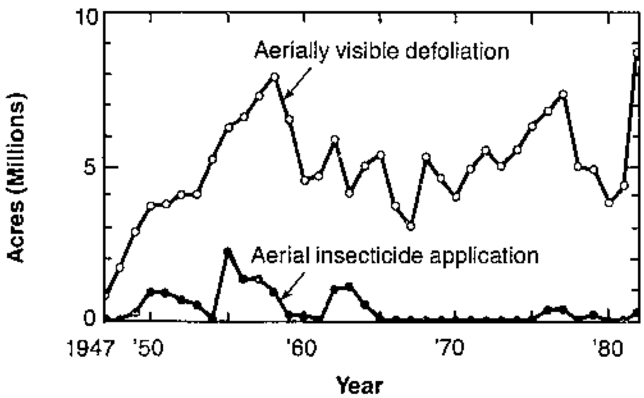

Figure 1-2—Defoliation visible from the air and application of insecticide in budworm host forests of Western Canada and the United States. 1947 to 1982.

(0.1 million ha) were sprayed. Spray treatments increased rapidly, peaking in 1955 when about 2 1/4 million acres (0.91 million ha) were treated with DDT. This mode of treatment with DDT continued until the mid-1960's when other insecticides came into use, but after that, relatively few acres were treated with insecticides. The following sections describe both budworm population and treatments more fully.

Although vast acreages of western forests are still highly suitable substrate for the budworm, current forest-management practices are beginning to reverse the successional trends toward climax described earlier. Silvicultural systems—using seed-tree, shelterwood, and clearcutting—have now mostly replaced the economic-selection cuttings used in the first half of this century. Even-aged stands are being established—with greater species diversity and a higher composition of seral species than those found under economic-selection-cutting methods. Many forests still exist where ecological considerations or specific management objectives dictate the use of uneven-aged management. Here persistent budworm problems may have to be tolerated or dealt with more directly.

Chapter 2
Western Budworm and Its Hosts

David G. Fellin

Distribution of budworm host species is described, followed by budworm taxonomy, life history, habits, and natural regulating factors.

2.1 Hosts and Distribution

Western budworm occurs widely through western North America (fig. 2-1). Most of the early outbreaks lasted for a few years and then subsided naturally while others persisted, at times without spreading over large areas. The absence of any typical pattern and the irregular intervals of outbreaks indicate that future outbreaks cannot be predicted on the periodicity of past ones. From aerial mapping of visible defoliation, forest type, and climate, 16 zones of infestation have been described (fig. 2-2, table 2-1).

Western budworm outbreaks may rise and fall, but they are not like those of the Douglas-fir tussock moth and the pine butterfly, which characteristically explode and then collapse over a 2- to 4-year period. The size and nature of the geographic or forested area must be specified when defining and interpreting budworm outbreaks. For example, the northern U.S. Rocky Mountains have had a regionwide outbreak for the past 35 years; during this period, however, shorter and more intense outbreaks have occurred in some areas.

Budworm larvae feed on all age classes of several species of coniferous trees. The most common are Douglas-fir, grand fir, subalpine fir, white fir, Engelmann spruce, and western larch. Occasional hosts are white spruce, Colorado blue spruce, Pacific silver fir, mountain hemlock, western hemlock, lodgepole pine, ponderosa pine, western white pine, limber pine, and whitebark pine.

Some of these trees are also hosts of other species of budworm and associated Lepidoptera; larvae of one or more of these species sometimes feed on the same trees or in the same general area as the budworm. Stevens and others (1984) provide keys for identifying these associates.

In the northern Rocky Mountains of Montana, the budworm infests coniferous forests in 46 of 64 habitat types in the following series: Douglas-fir, spruce, grand fir, western redcedar, western hemlock, and the lower subalpine fir subseries (Pfister and others 1977).

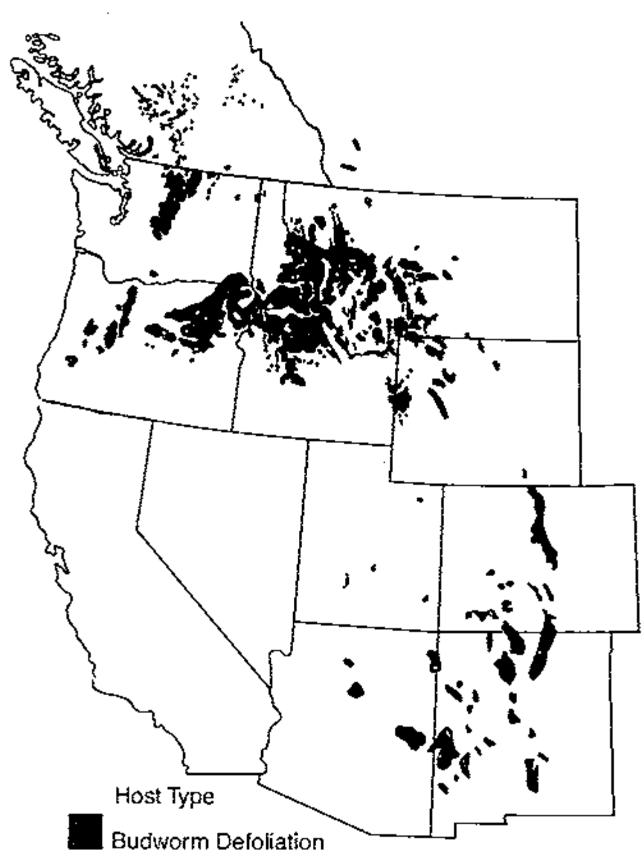

Figure 2-1—Area of host type and defoliation recorded from aerial surveys, 1947-83.

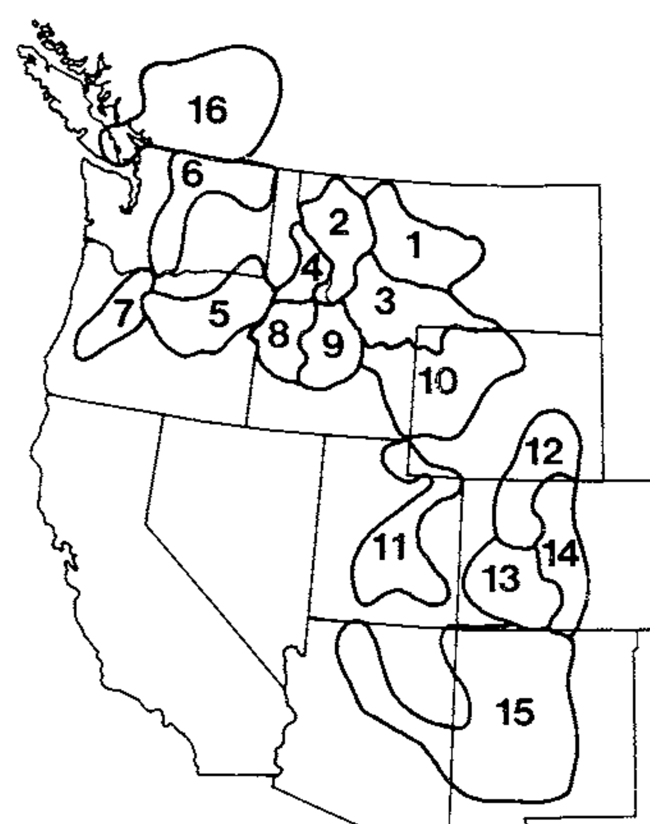

Figure 2-2—Zones of infestation based on aerial defoliation trend, forest type, and climate (courtesy of Lawrence E. Stipe).

Table 2-1 —Outbreak history from 1947 to the present for the 16 zones in figure 2-2

Zone number	Zone name	Outbreak history[1]
1	North-central Montana	Outbreaks increased from 1947, climaxing in 1959 when 2,100,000 acres were defoliated; declined to near zero in 1970; minor fluctuations up to 600,000 acres since
2	Clark Fork	Slow but steady increase to 900,000 acres from 1949–66; explosive eruption to 1,500,000 to 1,800,000 acres from 1967–77; declined to near zero in 1980; increasing to 700,000 acres by 1982
3	Yellowstone	One major outbreak from 1952–60 (up to 2,100,000 acres); moderate until 1974; from 1974 to present, fluctuated about 900,000 acres
4	Clearwater	No major outbreaks until 1960's; from 1968–75, from 1,500,000 to 2,000,000 acres per year; declined to zero in 1978 to present
5	Blue Mountains	Major outbreak (up to 2,700,000 acres) from 1946–59; zero to low until 1980; new outbreak increased to 1,500,000 acres by 1982
6	Inland Washington	Minimal defoliation until 1972; outbreak from 1971–81 reached 1,200,000 acres; declined from 1977–82 to near zero
7	Central Cascades	One minor outbreak (less than 300,000 acres) from 1947–54; zero defoliation since
8	Boise	Beginning in 1953, periodic outbreaks (up to 900,000 acres)—1953–58; 1975–80, acreage increasing up to 1,000,000 by 1982
9	Upper Salmon River	First outbreak in 1954, increased with minor fluctuations to 2,000,000 acres in 1964; declined to near zero from 1967–76; acres increasing—up to 600,000 acres by 1982
10	Upper Snake River	Zero to small (less than 200,000 acres) until 1976; increased steadily from 1974 to 900,000 acres in 1982
11	Intermountain	No outbreaks until 1980; about 200,000 acres from 1980–82
12	Central Rockies	No outbreaks during entire period
13	Southern Rockies	Small outbreaks (less than 300,000 acres) 1949–51, 1955–69, 1975–79; acreage increased from 1981 to 600,000 acres in 1982
14	Front Range	Small (less than 300,000 acres) from 1958–72; steady increases from 1973, reaching 1,400,000 acres in 1982
15	Southwest	No activity to 1952; outbreak from 1952–56 reached 900,000 acres; declining to near zero in 1956, but rebounding to 1,100,000 by 1961; gradual decline to near zero by 1968; minor fluctuations to 1979; increasing trend to 300,000 acres by 1982
16	Canadian	Outbreak from 1948–58—up to 200,000 acres; zero until 1967; outbreak increased to 600,000 by 1976; trend downward to 1982, increase in 1983

[1]Multiply acres by 0.4047 to get hectares.

2.2 Taxonomy

Infested forests in western Montana and northern Idaho are usually characterized by high site indexes with deep soils and considerable precipitation; forests east of the Continental Divide in Montana generally have lower site indexes, shallow soils, and low precipitation. Although the budworm does well on both sides, the species appears to prefer warmer and drier environments.

In the Pacific Northwest, budworm outbreaks occur in three major forest types: the true fir/Douglas-fir type, where these host species predominate; the ponderosa pine type, which is characterized by a true fir and Douglas-fir understory; and the white fir type. Generally, the ponderosa pine type occurs at the lower reaches of the true fir/ Douglas-fir type, where forest and rangelands meet.

In British Columbia, budworm infestations occur primarily on Douglas-fir in the interior Douglas-fir biogeoclimatic zone (Krajina 1965) with extensions into the interior and coastal western hemlock zones. Past infestations have also occurred on Douglas-fir and grand fir in the coastal Douglas-fir zone.

The white fir type occurs in the Cascade Mountains and in the ranges immediately to the east in Oregon and southward in the Siskiyou Mountains of southern Oregon and northern California. Stands in the white fir type are often pure over considerable areas. In mixed stands, white fir grows intermixed with Douglas-fir, ponderosa pine, sugar pine, and other species of fir.

Budworm outbreaks in the Okanogan highlands of north-central Washington and in the Blue Mountains in northeastern Oregon occur where conditions are similar to those already described for the northern Rocky Mountains.

In the central and southern Rocky Mountains, outbreaks, forests, and forest types are more discontinuous than in the northern Rocky Mountains and the Pacific Northwest. Douglas-fir and white fir are the most common hosts. They grow in several habitat types (Henderson and others 1976) and in two of the six major vegetation zones (Daubenmire 1943)—the Engelmann spruce/subalpine fir zone and the Douglas-fir zone. Douglas-fir grows as a seral species in habitat types in the Engelmann spruce/subalpine fir zone and as a climax species in types in the Douglas-fir zone. White fir grows sparingly as a climax species on the mesic types of the Englemann spruce/subalpine fir zone and, in the Southwest, occasionally as a seral species in the subalpine fir habitat.

In western North America, four species of budworm in the genus *Choristoneura* are common defoliators of coniferous trees. The most common and widely distributed species is the western spruce budworm, *C. occidentalis* Freeman. The others, which are much more locally distributed, are the 2-year-cycle budworm, *C. biennis* Freeman; the Modoc budworm, *C. retiniana*; and a species found only in coastal British Columbia, *C. orae* Freeman. A large complex of species, including *C. lambertiana* (Busck), occurs on various species of pines in the Western United States, but they have caused little damage. The eastern budworm, *C. fumiferana* (Clemens), comes as far west as the northeastern corner of British Columbia.

Adult moths of the western spruce budworm are about one-half of an inch (13 mm) long and have a wingspread of 7/8 to 1 1/8 inches (22 to 29 mm). Moths of both sexes look alike, although females are a bit more robust than males. Moths of both sexes fly. The gray-brown or orange-brown forewings are banded or streaked, with a conspicuous white dot on the margin. Eggs are oval, light green, about three sixty-fourths of an inch (1.2 mm) long, and overlap like shingles.

Larvae develop through six instars. Newly hatched larvae are yellow green with brown heads. In the next three instars, larvae have black heads and collars and an orange-brown or cinnamon-brown body. In the fifth instar, larvae have reddish-brown heads marked with black triangles, black collars, and pale olive-brown bodies marked with small whitish spots. Mature larvae are 1 to 1 1/4 inches (25 to 32 mm) long, with tan or light chestnut-brown heads and collars, and with large, ivory-colored areas superimposed on olive-brown or reddish-brown bodies. Pupae are one-half to five-eighths of an inch (13 to 16 mm) long, broad at the head end, but tapering toward the tail. They are brownish yellow or sometimes brownish green when first formed, and later turn reddish brown.

With few exceptions, this description of the life stages applies to all species of *Choristoneura* found in the West. The larvae of the Modoc budworm are much greener than the others, and adults of the pine-feeding forms are usually smaller, lighter in color, and have fewer spots than other species.

2.3 Life History and Habits

Timing of budworm life cycles differs considerably over their range, probably because of climatic differences. The budworm usually develops from egg to adult in 1 year (Fellin and Dewey 1982). In the northern Rockies of the United States, moths emerge from pupal cases in mid to late July or early August; in the southern Rockies, adults often begin emerging by early July. After mating, which occurs within a day or so of emergence, the female moth deposits her eggs, usually on the underside of conifer needles. Eggs are laid in masses containing a few to 130 eggs (average, 25 to 40). Females usually lay some eggs where they emerge and mate, then disperse to deposit the remaining eggs.

Larvae hatch about 10 days after eggs are laid. The tiny larvae do not feed, but disperse to the underside of bark scales or in and among lichens on the tree bole or limbs. They spin silken tents or shelters, called hibernacula, and remain there through the winter (fig. 2-3).

Figure 2-3—Second instar in its hibernaculum under a Douglas-fir bark scale. The hibernaculum has been cut open to expose the larva and the shed head-capsule of the first instar.

Larvae disperse from early May to late June (fig. 2-4), and mine or tunnel into needles or vegetative or reproductive buds. As the new shoots flush, larvae spin loose webs among the needles and begin feeding on the new foliage. Adjacent shoots are often webbed together as the shoots continue to elongate. Larvae prefer new foliage, but also feed on older foliage when new foliage is in short supply. On western larch, larvae not only feed on the needles, but also mine the woody portion of the shoots (fig. 2-5). Many shoots are completely severed (fig. 2-6). This type of feeding often reduces height growth and can result in crooked stems, multiple leaders, and bushy tops. Such damage appears to lessen as trees approach maturity.

Figure 2-4—Tiny larva about to disperse by spinning out of the foliage on a silken web. Another larva is just leaving its feeding site in the foliage.

Larvae feed on staminate and pistillate cones and seeds of several species of trees, particularly Douglas-fir and western larch. Developing seed and pollen conelets are particularly vulnerable because their buds open about the same time that small larvae emerge from overwintering sites.

Larvae of the western budworm, as well as larvae of some other western *Choristoneura* species, feed on various species of pines, particularly lodgepole and ponderosa. The young larvae feed on clusters of staminate flowers, mine the fascicle sheath, and feed within the newly developing needles in May and June.

Figure 2-5—Mature budworm larva emerging from feeding tunnel in developing shoot of western larch. Although the shoot is still alive, it is no longer erect and will eventually fall off.

Figure 2-6—Terminal of young western larch severed by a budworm larva, which also has cut off several lateral shoots and defoliated nearly the entire terminal shoot.

Budworms pupate in webs of silk spun either at the last feeding site or elsewhere on the tree. The pupal stage usually lasts about 10 days, after which moths emerge from the pupae to begin the cycle again.

For many years, spruce budworm in the West was assumed to be the same as in the East, and eastern research results were extrapolated and applied in attempts to cope with outbreaks in the West. Extrapolation should be made with caution, however, because biological and behavioral differences between the species can be significant. Differences between the species can affect timing of insecticide application, dispersal patterns, resurgence and reinvasion of populations, and response to environmental factors—especially spring and fall weather—and probably other factors as well.

2.4 Natural Regulating Factors

Budworm larvae, pupae, and adults are parasitized and preyed upon by several groups of insects and other arthropods, small mammals, and birds.

Parasites have not been shown to be a major source of mortality. Outbreak trends have not changed significantly even with high parasitism, although parasites are reported to have contributed to collapse of outbreaks in British Columbia and Colorado.

At least 40 species of primary parasites have been reported for the western budworm. Of these, perhaps the two most common are *Apanteles fumiferanae* Viereck (Hymenoptera: Braconidae) and *Glypta fumiferanae* (Viereck) (Hymenoptera: Ichneumonidae). Adults of both of these species lay their eggs in the larvae just before budworm hibernation. Some parasites kill budworm larvae; others emerge from pupae (fig. 2-7).

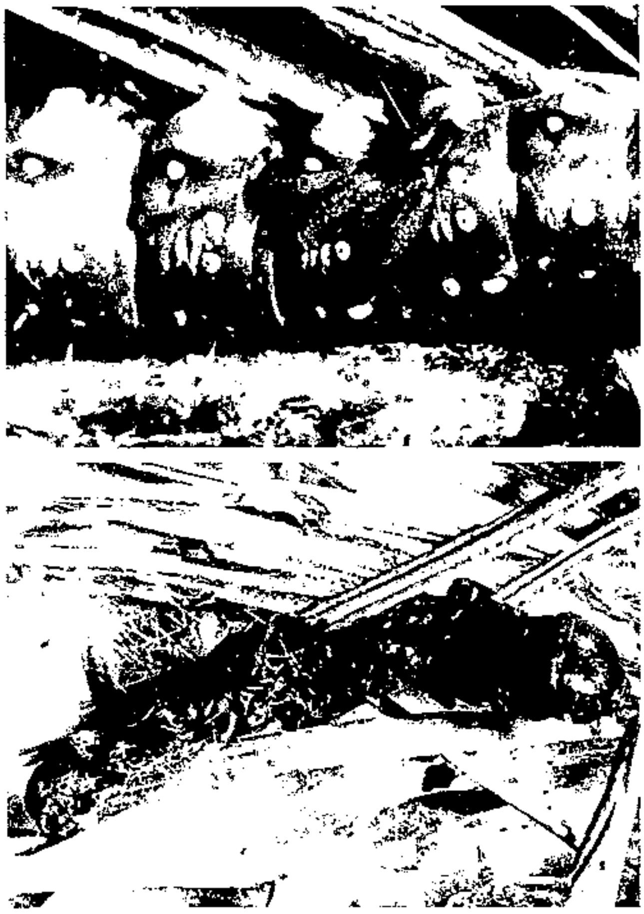

Figure 2-7—Parasite larvae feeding externally on the abdomen of a budworm larva (top); dried and desiccated cadaver of the budworm larva after the parasites have completed their feeding (bottom).

Predators, like parasites, are generally ineffective at high budworm densities but have demonstrated effectiveness at low densities.

Spiders, ants, snakeflies, true bugs, and larvae and adults of certain beetles (fig. 2-8) feed on the budworm, as do chipmunks, squirrels, shrews, voles, and other rodents. Ants, in particular, have been shown to be of value in keeping budworm populations low. Keys to ants associated with the western spruce budworm have been developed by Shattuck (1985).

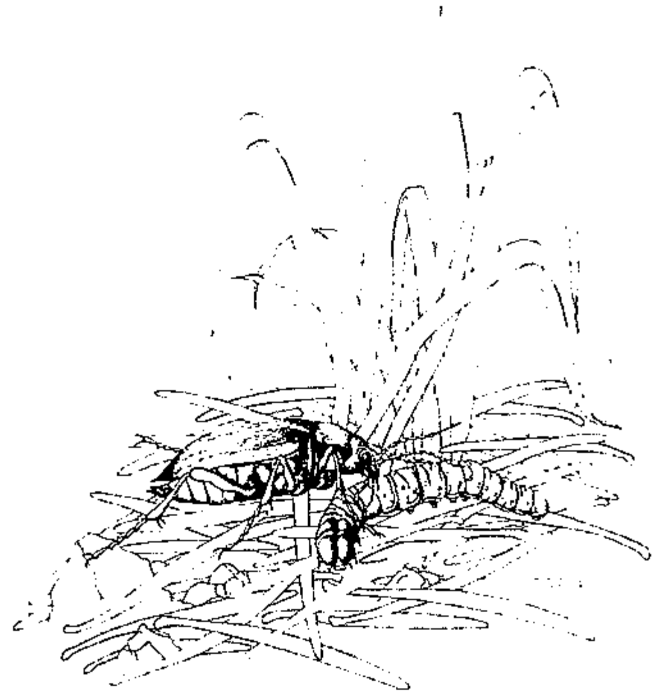

Figure 2-8—Ground beetle (Carabidae) feeding on a mature larva on the forest floor.

Birds have also shown effectiveness at low budworm densities. Birds known to feed on the budworm include grosbeaks, warblers, thrushes, sparrows, flycatchers, tanagers, siskins, and waxwings. Populations of flocking species, such as grosbeaks, respond to increases in prey density, but most bird species do not. In some western forests, birds had no apparent effect on trends of increasing budworm populations.

Although the larvae are susceptible to several types of pathogens, mortality from disease has been very low. Pathogens do not appear to regulate budworm populations.

Perhaps the most dramatic natural factor affecting budworm populations is weather. Several investigators have found that periods of warm, dry weather have preceded major outbreaks. Weather may also cause short-term reduction in populations. Unseasonable fall or spring frosts can act directly through freezing of larvae or indirectly through destruction of food supply. In 1969, early June temperatures plummeted in western Montana when budworm larvae were actively feeding on newly developing foliage. Populations were reduced by nearly 90 percent. But despite the destruction of populations by the frost, the effect was short lived; by 1972, populations resurged to nearly pre-1969 densities. Long periods of warm weather in the fall deplete nutritional reserves in hibernating larvae; after emergence, they may be too weak to locate and penetrate needles or buds. Starvation can also be an important cause of mortality during prolonged outbreaks.

The individual or combined effects of all of these natural factors can be responsible for the waning of budworm populations. But the combined effect of natural agents does not prevent or reduce population resurgences when climatic and forest-stand conditions are favorable to the insect.

Chapter 3
Effects of Infestations on Trees and Stands

G. A. Van Sickle

The effects of budworm defoliation and bud-kill on seed production, radial and height growth, top-kill, tree defect, mortality, and host vigor of trees and stands are summarized in this section.

3.1 Effects on Trees

Defoliation and discoloration are the most obvious effects after bud-mining and consumption of mainly current-year needles (fig. 3-1). Partially consumed needles on the webbed branch tips turn bright reddish brown at midsummer, but become less conspicuous as rains wash the destroyed foliage from the trees. Light and moderate feeding reduces the amount of new foliage, especially in the upper portion of the tree crown. Vegetative buds and developing shoots may be killed in their formative stages; with persistent, heavy feeding, most of the new foliage may be consumed during several successive years. Sustained heavy attack may cause nearly complete defoliation in 4 to 5 years in the overstory, earlier in the understory. As a result of increased photosynthesis of previously shaded foliage, decreased demand for carbon, and altered water and mineral status, the photosynthetic capacity of the tree is not diminished in proportion to the intensity of defoliation.

Figure 3-1—Defoliation and bud mining by budworm.

The amount of defoliation is often highly variable among stands, and even among trees within a stand, in part because of differences in tree phenology, foliar chemistry, and budworm populations. Considerable recent literature concerns the effects of natural and fertilizer-influenced variations in host chemistry on the selective feeding patterns and subsequent population development of budworm, but little knowledge yet exists of changes in host-foliage chemistry brought about by an extended period of defoliation.

Although the subsequent effects of defoliation on tree survival, increment, and top-kill can be substantial, foliage recovery is often dramatic; within a few years of cessation of feeding, some tree crowns may again appear almost normal, although the volume of the live crown may have been altered. Some grand fir trees severely defoliated by tussock moth exhibit dramatic foliage recovery after an outbreak ends, and Douglas-fir defoliated by tussock moth or budworm sometimes demonstrates surprising resilience and recuperative ability. With both true firs and Douglas-fir, stimulation of adventitious buds and epicormic branches may be largely responsible for maintenance or recovery of a functional crown during and after periods of defoliation.

Rootlet mortality has been shown to occur with severe, prolonged feeding by eastern budworm on balsam fir, but no comparable studies have been made with the western budworm or with other tree species.

Budworm feeding can reduce cone and seed production of host conifers directly by larval feeding on the male and female flowers or in the cones (fig. 3-2) and probably contributes to long-term reductions by reducing food reserves and weakening the trees. Budworm-caused top-kill and defoliation may be particularly damaging to cone production in true firs and spruce in which cones are concentrated in the upper crown.

Even when foliage feeding was light, 9 to 71 percent of the Douglas-fir cones in 13 stands were infested in Montana. Many of the conelets attacked in early June shriveled and died. In seed-production areas, budworm was the principal insect damaging cones of Douglas-fir, grand fir, and western larch. Average cone production was usually higher in lightly defoliated stands than in heavily defoliated stands, but losses are often difficult to quantify because of variation in defoliation and cone production among trees and sites.

Budworm affects tree height growth in at least three ways. A completely mined or destroyed terminal bud will not

Figure 3-2—Budworm feeding on Douglas-fir cone (from Hedlin 1974).

produce an annual internode; consecutive severe defoliations can cause top-kill (fig. 3-3) of one or more internodes; or if the terminal is not killed, growth may be reduced during periods of lighter defoliation or during recovery after feeding stops.

Height loss from destruction of the terminal bud is probably reported less frequently than it occurs because of the difficulty in sampling tall trees. Severely defoliated Douglas-fir in one semimature stand in British Columbia that was defoliated for 5 years produced no height growth from 1970 to 1976, and about three internodes predating the outbreak were killed as a result of the defoliation—for a total loss of 10 years of height growth. In Washington, with lighter defoliation, few instances were found in which a lateral did not quickly achieve dominance, and the proportional loss of height growth was similar to or less than that of diameter growth. In Idaho, 12.7 percent of the young defoliated trees did not increase in height during a 5-year study. Subalpine fir was more frequently affected than grand fir, Douglas-fir, or Engelmann spruce. The probability of loss increased with increasing defoliation and with height of the tree but was less in trees having the greatest crown ratios at the beginning of the study.

Figure 3-3—Dead top of Douglas-fir from budworm defoliation of 1970 to 1974 inclusive and new top developed from upturned branch.

Top-kill, severe enough to be observed during stand cruises, varied from light to over 60 percent in host species in individual stands in the Pacific Northwest. Most of these cruises recognized only the top-kill form of height loss. Surveys during outbreaks may overestimate the frequency of top-kill because of the difficulty in distinguishing trees with living defoliated tops from those with dead tops. After recovery, top-kill may be underestimated because smaller dead tops are hidden within the crown and are not visible from the ground.

By severing the stems of current-year shoots, budworm may also affect height growth and form on young western larch. In Montana, the net annual height growth of trees with severed terminals averaged 27 percent less than that of unaffected trees.

Height-growth recovery after outbreaks was variable, depending on the severity and duration of feeding and on the manner in which terminal dominance was reestablished. Height losses during the period of rapid juvenile growth most seriously affect tree volume and form, but trees that are semimature or mature when damaged may be harvested with the damaged portion still in the unused portion of the tree.

Insect defoliation has frequently been shown to reduce radial growth markedly, but only relatively few studies have quantified the losses or correlated them with the severity and duration of defoliation. Periods of budworm activity have been dated where trees in many areas have sustained up to five budworm outbreaks since 1900. Radial-growth reduction usually lags behind foliage removal by 1 to 3 years and, similarly, growth recovery lags behind refoliation. Variation in vertical distribution of incremental growth is widely recognized, with the earliest and greatest reduction from defoliation occurring in the bole within the defoliated crown.

Often, radial measurements are taken during infestations, and any reduction is expressed relative to preoutbreak growth rates. Only part of the total loss is usually recorded, however, because any reduced growth during recovery after the infestation is not included. The annual increments in Douglas-fir during earlier infestations were reduced by 40 to 80 percent compared to preoutbreak averages (fig. 3-4). When the loss was compared to potential growth, the average radial loss in four outbreaks ranged from one-eighth to one-half of an inch (3.28 to 11.02 mm), which altogether represented a 12-percent reduction in diameter, or a basal-area reduction of 22 percent, based on the size that the average tree should have reached by 1980. In the most recent infestation in Washington, the reduction in mean annual increment during the fifth year of consecutive defoliation reached 12.2 percent in Douglas-fir and 27.3 percent in true firs.

In Idaho, significantly more radial-growth depression was caused by budworm in grand fir than in Douglas-fir; the greatest 1-year growth loss of grand fir was nearly three times that of Douglas-fir in a stand that was 50 to 75 percent defoliated in 1952. These results agree with those from earlier studies, although they may be a reflection of the usually greater defoliation of grand fir.

The effect of budworm in reducing growth in both height and diameter is combined in the calculations of tree and stand volumes. The average volume loss of a stand as a percentage of the predicted growth over a 10-year period was 12.7 for subalpine fir, 11.0 for grand fir, and 4.7 for Douglas-fir in eastern Washington. In central Idaho in two selected areas with a history of three infestations, volume loss in grand fir trees averaged 10 percent, when increment reduction and associated cull resulting from deformities were combined.

With detailed measurements of height and radial increments in one severely defoliated Douglas-fir stand in British Columbia (fig. 3-5), average volume losses were 19.0, 16.7, 8.6, and 13.7 percent of the potential volumes after infestations in the 1920's, 1940's, 1950's, and 1970's, respectively. The cumulative volume loss of the four infestations was 45.7 percent of the potential cumulative volume. Annual defoliation estimates for individual trees were available only during the 1970–74 infestation, when volume losses ranged from 8.7 percent in trees less than 50 percent defoliated to 17.8 percent in the 90- to 100-percent class.

Budworm-caused volume losses have been measured in relatively few forest surveys and require careful interpretation. Unattacked stands truly comparable in climatic or site characteristics seldom exist, repeated outbreaks complicate site definition, and nonhost trees may respond with greater than average growth. Direct measurement of height and radial growth can be made only on surviving trees, and potential growth in the absence of budworm can only be estimated. Because variations in weather, severity and duration of feeding, stand density, and site factors influence growth, computer models developed to simulate these interactions have used a variety of approaches.

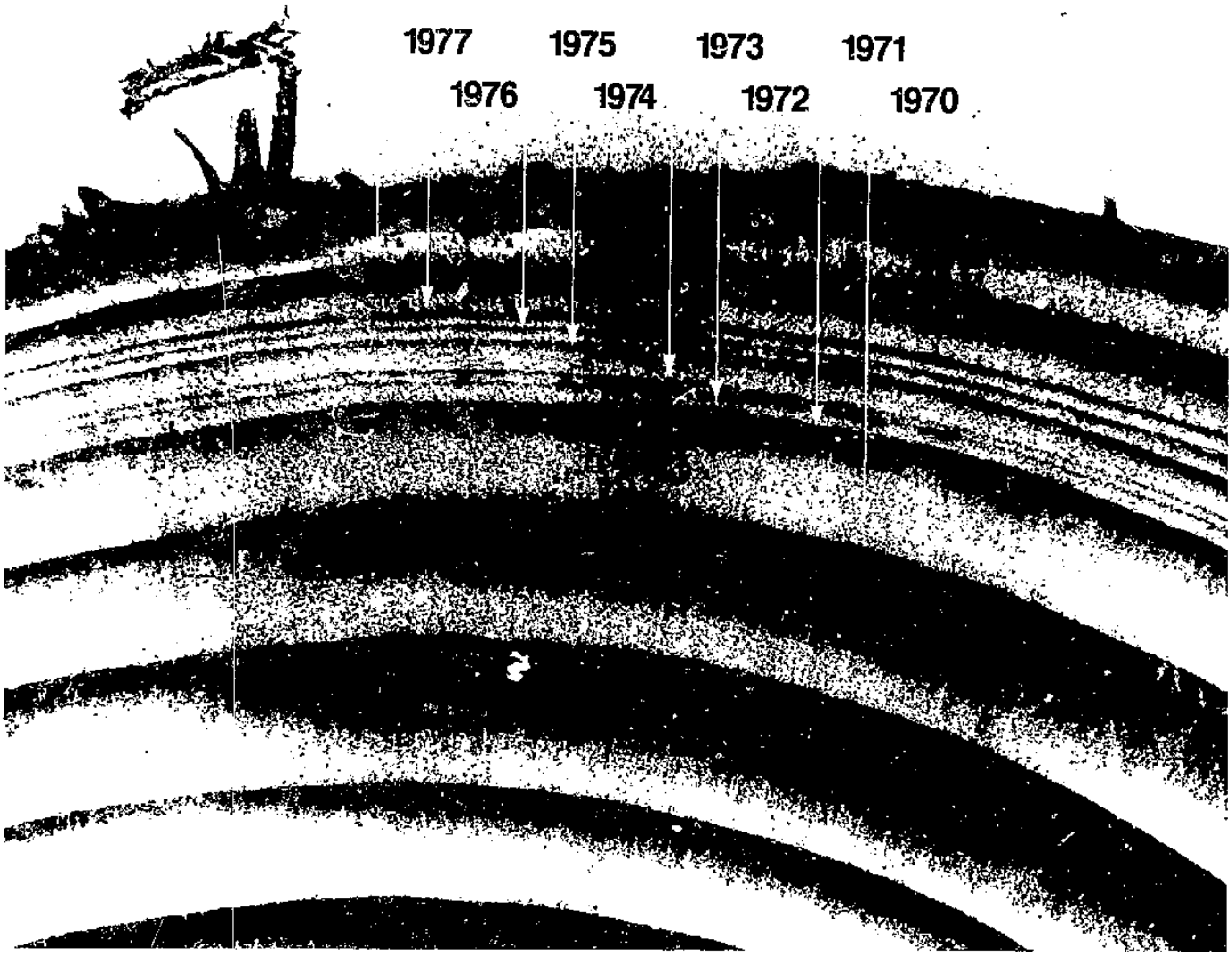

Figure 3-4—Effect of severe budworm feeding, 1970 to 1974, on annual-ring growth of Douglas-fir.

Assessing top-kill in standing trees can be difficult until they have recovered, and the frequency of top-kill is highly variable among stands and among the different tree species susceptible to budworm defoliation. The severity of top-kill, as well as its frequency, may influence the resulting losses. In a study in Washington of felled trees selected for obvious top-kills arising from earlier outbreaks, the average diameter at the base of the dead top was one-half of an inch (1.3 cm) in Douglas-fir and seven-eighths of an inch (2.3 cm) for true fir; both averaged about 5 years' loss of growth. In similar studies on Douglas-fir in British Columbia, the average dead-top diameter was 1¾ inches (4.4 cm) with up to 12 years' growth loss.

Douglas-fir terminals injured by budworm are seldom decayed. In British Columbia, none of many previous or current top-kills in Douglas-fir contained decay attributable to the dead tops serving as entry courts. Similar studies in Washington found only limited decay in one Douglas-fir and two grand fir trees. Grand fir may be more susceptible. In Idaho, 19 of 40 selected grand fir trees severely top-killed 60 years earlier had decay columns averaging 15 ft (4.7 m) in length.

Stem deformities that develop after top-kill may eventually be evident as forks and crooks—either of which may have a remnant of the original top as a spike—or as a crease,

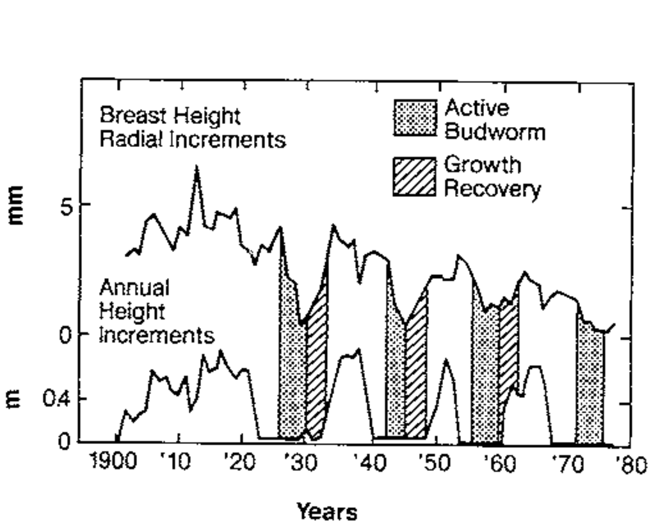

Figure 3-5—Pattern of annual height and radial growth in Douglas-fir affected by four budworm infestations. The zero height growth before each infestation results from top-kill.

which may result if the dead top is overgrown. Storms and other injuries may also cause terminal breakage resulting in bole deformities. Like top-kill, the frequency and severity of stem deformities are highly variable (0 to 70 percent) among stands.

Distortion of the stem is more often related to the method of recovery than to severity of top-kill, as determined by its diameter or length. When only the last year or two of the tops of Douglas-fir or true firs is killed, a lateral branch may quickly assume dominance and form a new top. If defoliation causes several years of top-kill, however, the loss can be more severe because laterals lower in the crown are less likely or slower to express dominance. Although top-killing to a large stem diameter often causes a more serious deformity and smaller kills may be overgrown, even a slightly damaged top may become forked if two or more branches or new terminals compete for dominance. The severity of distortion frequently depends on the point of origin of the new top.

Budworm-caused tree mortality, even after several consecutive years of defoliation, is usually light and frequently concentrated among smaller, suppressed trees. Individual stands may be more severely affected. Douglas-fir mortality caused by up to 7 years of moderate or severe defoliation averaged less than 1 percent in most stands in percent. Comparable averages in Washington and Oregon after 5 years of defoliation were 1.3 percent for Douglas-fir and 3.0 percent for grand fir. In Idaho, after 9 years of British Columbia, but individual stand extremes reached 53

percent. Comparable averages in Washington and Oregon after 5 years of defoliation were 1.3 percent for Douglas-fir and 3.0 percent for grand fir. In Idaho, after 9 years of variable defoliation, average percentages were 1.8 for Douglas-fir, 0.7 for grand fir, and 18 for subalpine fir.

The variable amount of food reserves, especially starch, in trees probably accounts for the commonly observed lag of one or more years between the onset of defoliation and reduction of radial growth. In both Douglas-fir and white fir, the starch measured in twigs at the time of budburst was reduced after defoliation by tussock moth. Defoliated trees without detectable starch content did not recover, and surviving trees with low starch content had fewer needles per shoot than trees with high starch content. Foliage recovery also depended on the weather after budburst, however, especially in water-stressed sites. Similar studies with budworm-defoliated trees have not been conducted.

General statements are common that mortality of defoliated trees increases when associated with root rots, drought stress, dwarf mistletoes, and bark beetles, but only the last is reasonably well documented. Although population increases of the fir engraver beetle and Douglas-fir beetle were closely associated with tussock moth outbreaks, observations in British Columbia indicated that budworm-defoliated trees were not suitable for beetle buildup. Although the Douglas-fir beetle occurred in some defoliated stands, it was absent in most; little evidence was found of an association between defoliation and the beetle. Also brood productivity was low, and the attacks eventually subsided. Following an increase in Douglas-fir beetle attacks in top-killed, mature stands in Montana, the order of preference for the beetle was reported as windthrown and windbroken trees, larger diameter logging debris, trees damaged by ice and snow, and defoliated trees.

3.2 Effects on Stands

Tree mortality from the budworm in western forests tends to increase the average diameter of trees in the stand because most of the mortality is of the smaller suppressed trees. Some dominant and codominant trees may lose their competitive position in the crown canopy through dieback and lack of height growth—sometimes several meters of a tree may be lost. Furthermore, if multiple or no new leaders develop, individual trees may fail to grow any commercially useful material above the point of injury.

Where greater mortality of true firs occurs, stand composition in mixed stands may shift in favor of Douglas-fir, larch, and any nonhost species. Also, an acceleration of growth in nonhost trees in defoliated stands may, in part, compensate for growth loss in host trees.

Cone and seed production can be largely destroyed by even relatively light budworm feeding. In addition, direct feeding on established understory regeneration can be severe. Seedling establishment may be affected over a prolonged period and may be particularly difficult if competitive vegetation becomes established. In the past, clearcut harvesting followed by planting has been a common practice in many Douglas-fir stands, and loss of natural regeneration has not been considered serious. On drier sites with shelterwood management, natural regeneration is of greater importance.

Despite the considerable reduction in growth caused by budworm, sometimes the long-term effects may not be as serious as first indicated. If a commercial, nonhost species comprises a large enough proportion of the stand, and if growth is accelerated by the thinning and reduced competition resulting from the defoliation, the growth loss may be at least partially compensated. Even if the stand is primarily of host species, if sufficient trees survive for optimum spacing and if the stand is near enough to harvest that any top-kill occurs mostly above the minimum usable top diameter, subsequent growth will be concentrated on the larger crop trees.

Unfortunately, few growth studies have been long term enough to measure the insect–stand dynamics during and long after infestations. In observations of stand recovery after infestations by eastern budworm, diameter growth substantially increased beyond predefoliation levels. Because stand density was reduced, however, the recovery in terms of volume per unit area was poor. When stand volumes were simulated over 20 years and over a range of defoliation histories for balsam fir defoliated by eastern budworm, volume increment recovered, but the stand volume did not reach that projected for healthy stands.

Chapter 4
Site and Stand Characteristics

N. William Wulf and Rex G. Cates

The concepts of forest susceptibility and vulnerability to budworms are defined and site and stand characteristics contributing to them are summarized in this chapter.

4.1 Susceptibility and Vulnerability

Susceptibility to budworms is the probability of infestation; vulnerability is the expected tree damage when an outbreak occurs. Susceptibility thus encompasses the influence forest conditions have on budworm populations, and vulnerability, the damage budworms cause to the forest. Susceptibility is a measure of the quality of budworm habitat and serves as an index to the population density supported by a stand during outbreaks. Vulnerability, on the other hand, is an expression of tree injury that accrues in a stand because of a budworm infestation.

The number of budworms in a stand is affected by the movement of budworms in and out, as well as by stand attributes and other factors. Thus, susceptibility may be imparted to a stand by its proximity to a stand with high budworm density. On the other hand, inherently susceptible stands isolated by clearcuttings or nonhost forest types may incur such a large net loss of population that the stand is rendered relatively nonsusceptible.

Some homogeneity of budworm habitat is a prerequisite for a sustained outbreak. Conceptually, a forest could be so diverse that budworm dispersal and migration losses would exceed its reproductive potential, and widespread outbreaks would be precluded.

4.2 Site and Stand Characteristics

Warm, dry sites are more susceptible than cool, wet ones. Budworms develop more rapidly in warm, dry environments. Trees growing on warm, dry sites tend to incur greater moisture stress. We believe this situation would improve foliage quality as food for budworms. Less defoliation has been observed on productive bottom land sites than on drier hill slopes. Defoliation is often more severe in warm, dry habitat types, at lower elevations, and on slopes facing south. Warm, dry sites are most susceptible to infestation but not necessarily most vulnerable to growth reduction. Given an infestation, the warm mesic sites—which are moderately productive—are apt to incur the greatest reduction in volume growth in absolute terms.

Susceptibility of host species differs considerably, depending on geographical location and habitat type. In mixed host-species stands, the most shade-tolerant host species usually sustains the greatest damage. Ranked least to most in susceptibility to budworms, the common host species are apparently also ranked least to most in shade tolerance (see p. 66).

Stand susceptibility and defoliation increase with the proportion of host. Nonhost trees also buffer the stand against growth reductions. Growth of nonhost species may accelerate in response to the defoliation of hosts. Even seral Douglas-fir have shown an increase in growth rate after adjacent climax grand fir sustained heavier defoliation. The most susceptible composition is pure stands of climax host trees.

Intraspecific genetic resistance to budworm feeding has been identified in Douglas-fir. The heritability of resistance in Douglas-fir appears sufficient to allow for some genetic improvement where intensive silviculture is practiced.

Stand density, in conjunction with stand composition, has an important influence on larval mortality associated with fall and spring dispersal. Such mortality is greater in open stands than in dense stands. Consequently, defoliation increases as crown closure increases. Although higher populations have sometimes been found on open-grown trees, more damage was noted in the closed stands. With other site and stand characteristics held constant, dense stands are more susceptible and vulnerable than open stands.

Forest insects respond to subtle changes in host-foliage quality brought about by such factors as aging, nutrient deficiencies, and moisture stress. Growth rate of trees is generally used as an index of their vigor; declining growth rate usually suggests decreasing vigor. Tree vigor, as expressed by 5-year radial-growth increment, has a negative effect on budworm feeding on Douglas-fir. Also, survival and fecundity of budworms is markedly higher on Douglas-fir placed under moisture stress than on nonstressed trees. This inverse relation between tree vigor and budworms may partially explain why outbreaks are often preceded by or coincident with periods of relative drought.

Tree vigor is inversely related to insect damage. Vigorous trees have more foliage per unit of biomass and more carbohydrate root reserves than nonvigorous trees. Given an equal amount of feeding, vigorous trees will have more remaining foliage than nonvigorous trees, which implies less reduction in growth. Also, with additional carbohydrate reserves, vigorous trees retain the ability to produce new foliage and recuperate once defoliation subsides.

The vigor of nonhosts in mixed-species stands containing hosts affects stand vulnerability to budworm damage by impacting the ability to accelerate growth when the trees are released by defoliation or death of neighboring hosts. The vigor of all trees within a stand is thus related to stand vulnerability to budworm damage.

Stand structure—in particular, height-class structure—affects susceptibility and vulnerability in several ways. Intermediate and understory hosts provide a suitable substrate for dispersing larvae. If no subordinate trees are present or if they are nonhost, the larvae will fall to the ground and perish or starve on inadequate foliage. Overtopped trees are more vulnerable to damage from dispersing larvae because the trees are generally suppressed and because they intercept many of the large dispersing larvae.

Stand structure that favors warming of the host-tree crowns increases larval development rates and enhances budworm survival. Even-aged structures are least susceptible, two-storied are intermediate, and uneven-aged are most susceptible.

Age of trees and stands also affects susceptibility and vulnerability. Young seedling stands represent poor habitat for budworms. Rarely are they used for egg deposition nor are they suitable for overwintering. Small seedlings present small targets for dispersing larvae; many will land on unsuitable sites and perish. And ant predation is greater on seedlings than on taller trees.

Stem and crown diameter—indicators of tree age—have been positively correlated with budworm survival. Average stand defoliation often increases with average host diameter. As a stand matures, foliage biomass increases, providing more food for larvae. Dispersal mortality and predation by ground-dwelling predators is reduced. As trees mature, they begin to attract egg-laying moths; as the bark becomes more furrowed, overwintering habitat expands. Competition increases, resulting in a decrease in vigor. The onset of flower production provides an additional high-quality food source—reproductive buds and cones. Mature stands are therefore more susceptible than younger stands.

The relation of stand age to vulnerability is not so obvious. With maturity, sites become fully occupied and tree vigor and stand growth rate gradually decline. As tree vigor declines, the growth-rate depression caused by defoliation increases. The absolute volume loss represented by this growth-rate depression, however, may be less than in younger, more rapidly growing stands.

Damage from top-killing would cause a greater loss in volume growth in immature stands than in older stands. Top recovery, on the other hand, would occur more rapidly in younger stands.

4.3 The Budworm as a Regulator of Forest Succession and Productivity

Outbreaks of western budworms are always associated with late successional and climax plant communities in Douglas-fir, white fir, grand fir, or subalpine fir habitat types. Intertree competition intensifies in the climax plant community, and moisture stress is accentuated because the climax tree species are less tolerant of drought than their seral counterparts.

Budworm infestations tend to retard succession on habitat types where host trees are climax and advance succession on habitats where nonhosts are climax. The degree of successional change varies depending on the intensity of infestation, the presence of nonhost trees, and the occurrence of secondary disturbances. In mixed stands on host climax habitats, seral trees are favored. Defoliation and mortality of the more shade-tolerant host trees promote growth acceleration of established, competing seral trees. Differential prevention of host-tree cone crops coupled with reduced stocking encourages regeneration of seral trees. In pure stands of climax host species, outbreaks are likened to a thinning from below. Secondary disturbances, such as bark beetle infestations, may further recharge the cycling nutrient pool, relieve moisture stress, and move the system toward a younger, more productive state. Infestations by the Douglas-fir bark beetle have occasionally been reported in forests heavily damaged by budworms.

The ecological niche of the budworm has greatly expanded because of changes in natural succession caused by forest-fire suppression. Fire has historically had a strong influence on the ecology and development of most western forests. Ground fires, which occurred frequently in the drier forest types, periodically eliminated understory trees and selectively reduced the stocking of shade-tolerant, fire-susceptible trees in larger size classes. Fires that destroyed stands entirely often burned during abnormally dry weather or sporadically where woody debris accumulations and stand structures with variable height classes provided fuel ladders to the main canopy. The frequency and intensity of natural fires varied by forest type and site conditions, but few stands—except the very wet western redcedar/western hemlock and upper subalpine types—escaped fire long enough for the climax community to become established. Now these climax forest communities on the drier sites are frequently infested by budworms, perhaps indicating these communities are inherently unstable in the long term—given sporadic periods of weather-induced moisture stress. To some extent, budworm infestations may be replacing the regulatory role played by fire in the past.

Chapter 5
Surveys and Sampling Methods for Population and Damage Assessment

Daniel B. Twardus

Surveys developed for western budworm pest management are described in this chapter. Surveys can be descriptive or analytical evaluations of insect occurrence and abundance and may incorporate one or more sampling methods. Most forest pest-management surveys are descriptive in that they provide certain information about a large population. Preliminary steps in the application of survey methods include defining survey objectives and the population to be sampled, specifying an acceptable amount of uncertainty in the survey information, and designing the survey to achieve desired results.

The survey methods discussed here have been divided into defoliation and tree damage, and population assessment.

5.1 Defoliation and Tree Damage

Estimates of defoliation and tree damage may be needed from individual forest stands or from geographically large areas encompassing hundreds of stands. The size of the area generally determines how the information can be collected. For large areas, some type of aerial survey is more efficient than a ground-based estimate. Ground-based estimates, however, provide better site- and tree-specific information.

5.1.1 Sketch-Map Surveys

Sketch mapping is the most commonly used aerial survey method. Sketch maps—so named because the location of an infestation is "sketched" or outlined on a map—provide direct information about budworm occurrence and degree of defoliation. Sketch maps indirectly provide an index of population density; when done over the same area for 2 years or more, they can be used to establish defoliation trend and potential for continuing tree damage.

Reliable sketch maps of defoliation and damage depend on trained observers, good viewing conditions, and appropriate timing. These surveys are primarily conducted in high-wing, light-weight airplanes capable of flying at ground speeds of 80 to 110 mi/h (about 130 to 180 km/h), 500 to 1,000 ft (about 150 to 300 m) above the terrain. Helicopters have also proved satisfactory, especially where detailed information is needed.

Defoliation is visible from the air as a color change in the forest canopy resulting from the reddening or disappearance of foliage and buds. This color change is not generally visible until at least 20 percent of the foliage and buds have been affected. The aerial sketch-map survey should be timed to coincide with peak expression of damage—late July to late August in most of the West. Surveying too early or too late may result in lightly infested areas being overlooked. When the survey is conducted too late, the dead and dying foliage has been "washed" from the tree crowns by wind and rain; defoliation may still show as thin crowns, however.

The completed sketch map shows areas of defoliation subjectively categorized as light, moderate, or heavy defoliation (fig. 5-1). Top-killing and tree mortality can be indicated on the map as trees per acre affected.

The aerial sketch-map survey provides considerable information at a reasonable per-acre cost. Aerial sketch maps have been correlated with ground estimates of defoliation, and aerially classified defoliation can be used as a general index of population density (see table 5-1).

Table 5-1—Appearance of eastern budworm from the air related to color, ground defoliation, and larvae in Minnesota (from Heller and Schmiege 1962); these observations were made under controlled conditions.

Aerially observed defoliation class	Appearance from the air	Current ground defoliation	Larvae per 15-inch (38-cm) twig
		Percent	*Number*
None	No visible change in foliage color or hue	0–10	0–2
Light	Light browning of crowns; may occur on scattered trees only	20–40	3–4
Moderate to heavy	Orange to light-brown cast to foliage	50–100	10–25
Severe	Entire crown appears gray; spike tops and tree mortality	50–100	5–15

The relation of aerial observation to ground estimates, however, is largely influenced by the experience of the observer and the quality of viewing conditions.

The principal disadvantage of the aerial sketch-map survey is that defoliation may not be visible until population density has increased sufficiently to cause at least 20 percent defoliation. Thus, the early stages of an outbreak may not be detected; how important this delay is should be weighed in the planning of individual pest-management programs.

5.1.2 Aerial Photography

Aerial photographic methods have been used to map and evaluate budworm-caused defoliation. Defoliation is evident on aerial photographs as changes in the color of the forest canopy. Two types of color film—color and color infrared—are available that register these changes with various degrees of success. Except during severe infestations, the changes do not register with sufficient contrast on black and white film.

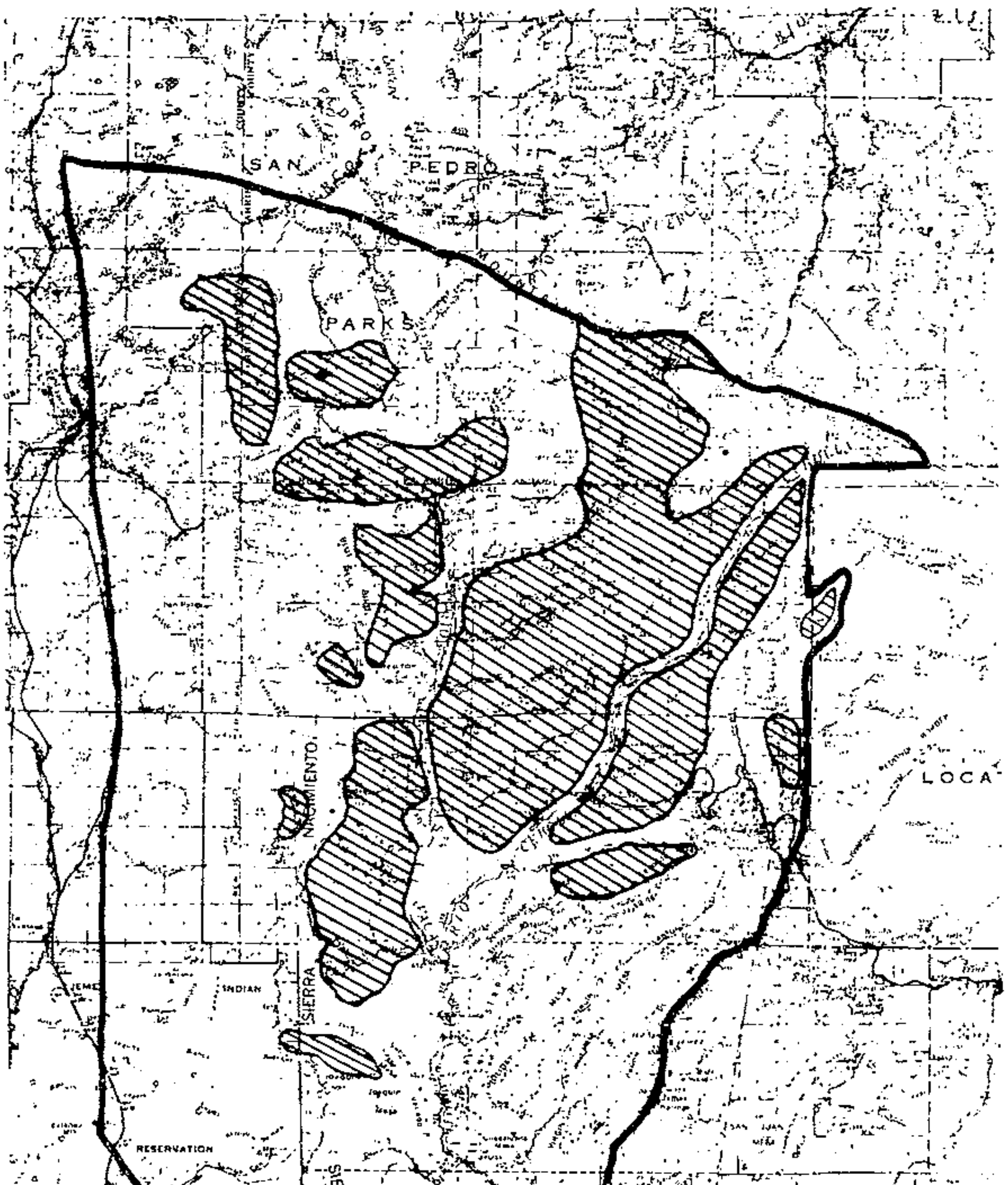

Figure 5-1—Aerial sketch map of budworm-caused defoliation.

Aerial color-print or transparency films register colors as seen by the human eye. Color film allows sufficient differentiation between current and previous year's defoliation to be useful as an evaluation tool. Large-scale (1:4,000) color transparencies have been used to record budworm defoliation, but defoliation intensities of less than 20 percent did not show on the photographs—a distinct disadvantage for monitoring any but the more severe damaging effects of budworm.

Color infrared (IR) photography is particularly useful in forestry because vegetation reflects in the infrared part of the spectrum. Color IR film produces false color images, however, and interpreting the photographs can be difficult, particularly for the inexperienced. Color summer imagery at scales of 1:15,840 and larger is considered best for evaluating current defoliation, but color IR fall photography is best for overall tree condition and mortality. Favorable results have been reported using high-altitude panoramic color IR photography to evaluate gypsy moth defoliation of hardwood species. This high-altitude panoramic color IR produces high-resolution photographs that cover large areas in a short time. It depends on the limited availability of high-altitude aircraft, and has yet to be successfully used to record budworm damage.

Satellite imagery (Landsat), airborne multispectral scanners, thermal IR scanners, and video cassette recorders have all been tested for mapping tree damage. The Landsat multispectral-scanner imagery has been specifically evaluated for mapping budworm defoliation. Results of these tests show that Landsat imagery alone is presently not sufficiently accurate nor consistent to be of value for budworm detection or evaluation.

Aerial photography or remote-sensing imagery in general has not as yet played a significant role in the detection and mapping of budworm defoliation. Several operational problems are responsible, including cost of obtaining the photographs; inability to register defoliation, especially at the lower intensities; and the short period for peak expression of damage. More important, aerial sketch mapping—although often a crude representation of budworm infestation—provides sufficient information for most management decisions. Compared to aerial photography, its low cost and immediate availability make aerial sketch mapping the most popular method of detecting and recording budworm defoliation and damage.

5.1.3 Ground Estimates of Defoliation and Tree Damage

Ground-based estimates of budworm-caused defoliation and tree damage are often supplemental to and supportive of earlier aerial-survey methods. They provide site- and tree-specific information related to the consequences of budworm infestation. Defoliation estimates for individual stands may be used to simulate budworm outbreak effects in the Prognosis–Budworm Model.

Ground-based estimates of budworm defoliation can be used as an index of population density. Tree damage (reduction in radial increment and tree height growth, top-killing, and tree mortality) is directly related to the intensity and duration of defoliation (Van Sickle 1985). Estimates of defoliation can be obtained by whole-tree assessments or by midcrown branch sampling.

5.1.3.1 Whole-Tree or Binocular Assessment—Whole-tree or binocular assessment is a subjective but rapid estimation method particularly useful for whole-stand evaluation. Defoliation is estimated by using a six-class system:

Code	*Percent defoliation*
1	0
2	1–25
3	26–50
4	51–75
5	76-99
6	100

The most common application of this method is by visually dividing the tree crown into thirds, then assigning a defoliation code to each third. Whole-tree defoliation can be expressed as the average of the three crown-level codes. Only the current year's defoliation is estimated. Estimates of the previous year's defoliation can be unreliable because of premature needle drop from various causes, such as rhabdocline needle blight on Douglas-fir or normal needle senescence.

Reliability of whole-tree estimates largely depends on the experience of the observer. Training can be gained by combining whole-tree estimates with midcrown branch samples from a few sample trees, which helps "calibrate" the eye.

5.1.3.2 The Midcrown Branch Sample—The most commonly used method of estimating branch defoliation is to clip branch samples of about 18 inches (46 cm) from the midcrowns of trees 23 to 46 feet (7 to 14 m) tall (fig. 5-2). One branch tip per tree is clipped with an extendible pole pruner. Each of 25 apical shoots per branch is rated for defoliation using the same six-class system described for the whole-tree estimates. The average defoliation class for the 25 shoots is assigned to the tree. Only the current year's estimations are reliable.

Stand estimates of defoliation using this method are complicated because midcrown branches on trees taller than 46 ft (14 m) are inaccessible. Where random selection of trees is not practical, defoliation for the stand is estimated by sampling midcrown branches from trees with accessible midcrowns only. If no trees have accessible midcrowns, the whole-tree method should be used. Preliminary findings suggest, however, that a high degree of variation exists between whole-tree estimates of defoliation and estimates of branches sampled from the midcrown, particularly when estimates of previous years' defoliation are included.

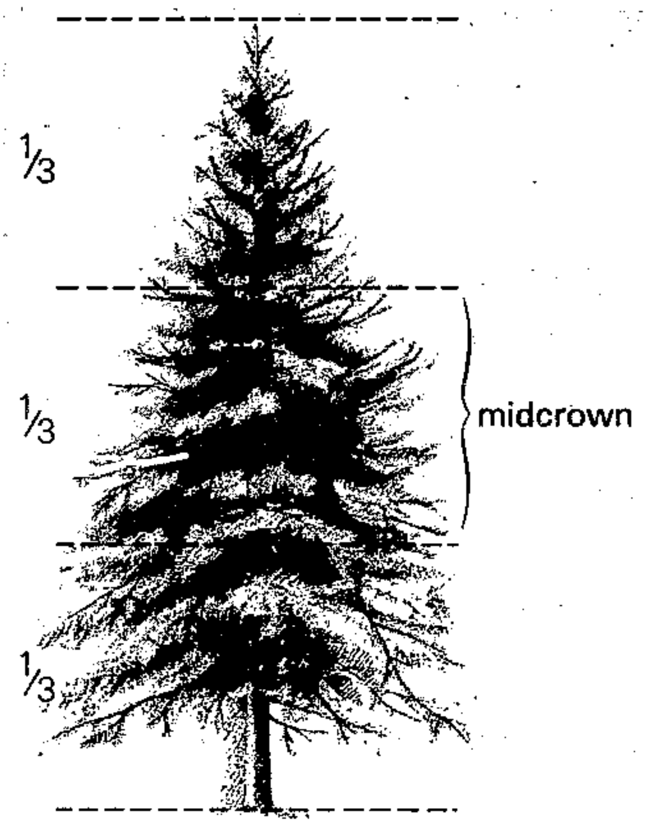

Figure 5-2—The midcrown of a sample tree is that portion of the crown originating from the middle third of the foliated trunk.

5.2 Population Assessment

Sampling and survey methods have been developed for population research as well as for operational pest-management programs; only the latter are discussed here.

The successful application of population-assessment methods depends on a clear definition of the sampling universe and its bounds. Too often sampling methods are used without adequate understanding of the population being sampled. For most, if not all applications, the sample universe is an area for which treatment can be prescribed. This area might be a forest stand, but usually it is a larger, geographically distinct area—such as a valley or drainage. Where treatment with insecticide is considered, the sample universe may be an "entomological unit"—an area generally thought of as susceptible host type isolated in some manner. Unfortunately for sampling, an entomological unit's supposed isolation may be the only unifying characteristic of the included stands. Another factor of importance is the definition of expected precision of the sample estimate. Expected precision should be directly linked to survey objectives. Many of the methods discussed here relate to stand estimates, and the precision associated with these methods is consequently of the individual stand estimate only.

Distribution of host foliage within trees is an underlying variable related to the development of population-assessment methods. Host-foliage distribution is discussed by Campbell (1985).

5.2.1 Egg-Mass Sampling and Surveys

The egg-mass sample has been one of the most routinely used methods of estimating population density. Several factors have contributed to its popularity. Compared to other life stages, egg masses remain in place longer; thus, sampling can continue over large areas without excessive time restriction. Planning insecticide treatment requires considerable advance preparation, and egg-mass density estimates have been used to predict subsequent population density and defoliation. Population trend has been estimated by comparing newly deposited egg masses with those from the previous year.

Three attributes of the egg-mass population, however, contribute to the complexity and cost of egg-mass sampling: eggs masses are small and concealed on the underside of host needles; egg masses deposited in one year can be present on the foliage in the subsequent year, and the egg-mass count of current population density must exclude old egg masses; and the budworm population is most aggregated at the egg-mass stage. Sample sizes necessary to reflect population density are thus proportionately larger than for other life stages. How to distinguish egg masses hatched in the current year from those hatched in previous years has been described by Twardus and Carolin (1984).

Multistage sampling of fixed-size plots has been the most commonly used method of egg-mass sampling. For operational use over large areas, the most common fixed-size-plot method of egg-mass sampling has been to use a plot of three trees, with two 30-inch (76-cm) midcrown branches per tree and "n" number of plots per area. Plot means are averaged over all plots within an area. The method was developed for use over large areas, and individual plot data have no statistical meaning. Numbers of plots (n) per area generally average 20 to 25 but depend on the size of the area and its inherent stand variability. For egg-mass surveys, a sample universe is usually defined as an entomological unit.

An observed linear relation of egg-mass density to subsequent infestation class (Carolin and Coulter 1972) has allowed egg-mass densities to be used to predict population density expected the following year. This apparent predictive ability of the egg-mass density estimate has resulted in the egg-mass sample becoming established as a routine survey method, particularly where insecticide treatment is being considered.

Unfortunately, modifications in the egg-mass sampling method (a branch tip instead of a whole branch, and small understory trees instead of dominant and codominant trees) negated use of the Carolin and Coulter predictive relation. Bullard and Young (1980) attempted to describe a new mathematical relation, based on the three-tree cluster plot, but found significant, unexplained variability in predicting defoliation class from egg-mass density. Apparent reasons for the discrepancy lie in inaccurate estimates of egg-mass density derived from the three-tree cluster plot and inaccurate, subjective defoliation estimates. Schmid and Farrar (1982) recommend that improvements in estimates can be obtained by increasing the number of trees per plot to six, while reducing the branches per tree to one. In their study, egg masses per branch varied significantly among trees and particularly among crown levels. Subjective defoliation estimates can be improved by comparing independent evaluations by several observers.

The pattern of egg-mass occurrence for populations of light to moderate density (fig. 5-3) is described by Campbell and others (1984). Egg-mass densities per unit of foliage

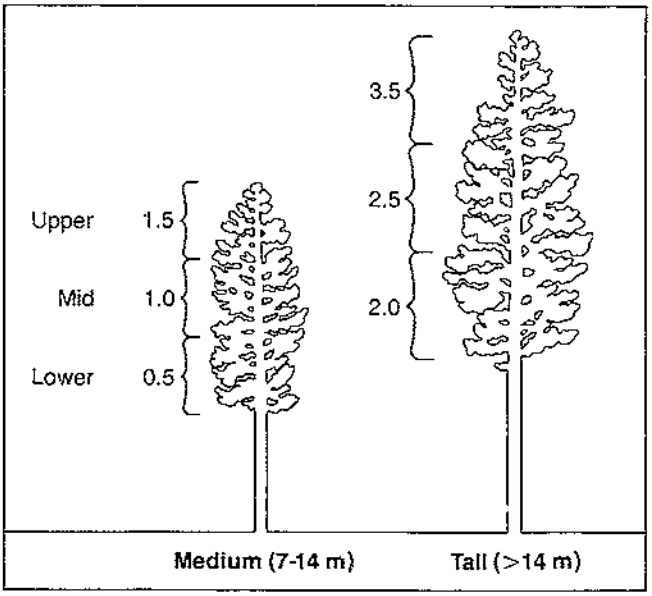

Figure 5-3—Approximate patterns of egg-mass densities found among crown strata in two tree size-classes. Density pattern is normalized with reference to midcrown whole-branch samples of medium trees. Terminal-tip densities per square meter of foliage are generally 1.2 times more than whole-branch densities (adapted from Campbell and others 1984).

increase from the lower crown third to the upper, and from trees 13 to 46 ft (4 to 14 m) tall to those greater than 14 m tall (Srivastava and others, in press). Egg-mass density for a plot can be estimated from densities of midcrown branch tips for trees 4 to 14 m tall as:

$$\text{Average whole-plot density (trees 4–14 m)} = 0.82\ (\overline{X}_M),\ r^2 = 0.88$$

where $\overline{X}_M$ is average density of egg masses obtained from midcrown terminal tips (45 cm).

Egg-mass density on tall trees (>14 m) is linearly related to the density found on trees 4 to 14 m tall. Hence, average egg-mass density for a plot containing a mixture of tree sizes is estimated on fixed-size sample plots as:

$$\text{Average plot egg-mass density (all tree sizes)} = 0.82\ (X_M) + F_t(0.953(X_M) + 4.121\ (ID))$$

where F_t is the proportion of foliage on tall trees (>14 m) within the stand; X_M is the egg-mass density obtained from 45-cm terminal tips of trees 4 to 14 m tall; and ID is defoliation index, based on the six-class system described above.

For extensive surveys, sequential sampling schemes can be more efficient than the fixed-size schemes just described. McKnight and others (1970) describe a sequential classification scheme for egg-mass sampling in entomological units. The scheme, developed for use in the central and southern Rocky Mountains, predicts subsequent defoliation based on new egg-mass counts obtained from 24-inch (61-cm) branch samples (see table 5-2). Srivastava and Campbell (1983 unpubl.) have also developed a sequential sampling method of egg-mass density estimation for small homogenous areas. The sequential count plan combines the efficiency of sequential sampling with the ability to obtain density estimates per unit sample. The difference between a sequential count plan and a sequential classification plan is important. Traditional sequential sampling as described by Waters (1955) provides a category of infestation based on a set of predetermined bounds. The sequential count plan is a method of estimating population density with a predetermined degree of precision. The method enables density estimates to be obtained with the least possible sample size. To use the

Table 5-2—Class limits for the sequential sampling plan for western budworm egg-mass surveys (McKnight and others 1970)

Class	New egg masses/ 24-inch branch =	New egg masses/ 1,000 in^2	Defoliation prediction[1]
	Number		
1	0.250 or fewer	1.0 or fewer	Undetectable
2	0.275 to 1.0	1.1 to 4.0	Undetectable in static infestations, light in increasing infestations
3	1.5 to 5.0	6.0 to 20.0	Light in static infestations, moderate in increasing infestations
4	5.5 or more	22.0 or more	Moderate or heavy

[1]Percent defoliation of current growth:
undetectable = 0 to 5
light = 5 to 35
moderate = 35 to 65
heavy = 65 and over.

sequential count plan, sampling within stands should be as random as operationally possible. In stands where more than 85 percent of the foliage is in tall trees (>14 m), lower crown branch tips are sampled. Otherwise a mixture of midcrown and lower crown branch tip samples is used. Selected branches are clipped, bagged, and taken to the laboratory, where they are examined at random until the stand is classified. Intentional extra sampling is often required, which reduces the efficiency of the method. An automated egg-mass counter is being developed to expedite foliage examination. The counter is being field-tested for operational use.

The values in tables 5-3 through 5-8 are approximations. In all probability, use of these approximations would cause considerable oversampling to achieve any specified precision. Final values will be published as one or more sampling guides in the USDA Agriculture Handbook series. Resource managers are cautioned to continue using current sampling methods until these guides are published.

To use the count plan, a precision level is fixed and the required cumulative total number of egg masses for density estimation (T_n) is calculated as:

$$T_n \geq \frac{2.03}{D_o^2 - (0.666/n)}$$ if samples include both lower crown and midcrown tips;

$$T_n \geq \frac{1.92}{D_o^2 - (0.394/n)}$$ if only lower crown tips are sampled;

where D_o = precision (0.15, 0.20, or 0.25) and n = number of 45-cm branch-tip samples. These equations are adapted from Srivastava and Campbell (1983 unpubl.)

The plot-density estimate is obtained by dividing the cumulative total number of egg masses (T_n) by the appropriate sample size (n). Tables 5-3 and 5-4 show required T_n for various precisions and sample sizes for trees 4 to 14 m tall and trees taller than 14 m, respectively. Calculated in this manner, density is expressed as egg masses per branch. If desired, this estimate can be converted to square meters of foliage by dividing by 0.082, the average foliage area of a 45-cm branch tip. Note that conversion to square meters of foliage adds a source of error to the density estimate. Whole-stand density is calculated with respect to the proportion of foliage on trees taller than 14 m in the sample plot.

Density estimates obtained in this manner can be used as within-stand population estimates. These estimates used by the Prognosis–Budworm Model can predict subsequent population density and stand damage.

Table 5-3—Sequential count plan for estimating egg masses based on one 45-cm terminal tip per tree from midcrown of trees 4 to 14 m tall and lower crown of trees greater than 14m tall (adapted from Srivastava and Campbell 1983 unpubl.)

n = number of trees	T_n = cumulative number of egg masses		
	D_o = 0.15	D_o = 0.20	D_o = 0.25
11	—	—	1,039
14	—	—	136
17	—	933	80
20	—	346	70
30	6,767	120	51
40	347	91	45
50	222	79	42
65	166	71	39

Table 5-4—Sequential count plan for estimating egg masses based on one 45-cm terminal tip per tree from lower crown of trees greater than 14 m tall (adapted from Srivastava and Campbell 1983 unpubl.)

n = number of trees	T_n = cumulative number of egg masses		
	D_o = 0.15	D_o = 0.20	D_o = 0.25
7	—	—	309
10	—	3,197	83
18	3,139	106	48
20	685	95	45
30	202	72	39
40	152	64	37
50	132	60	36
65	117	57	34

5.2.2 Larval Sampling

Larval development has been divided into three periods for sampling: overwintering larvae, larvae in opening buds, and later instars. The last two have received the most attention, primarily because of their use in evaluating insecticide treatments.

5.2.2.1 Overwintering Larvae—The cryptic habit and small size of hibernating larvae make this stage difficult, if not impractical, for extensive sampling. Although several population-sampling methods have been developed, none has received significant application.

Egan and Beckwith (personal communication) compared two methods of collecting hibernating larvae. Their results indicate that the most effective method is to collect infested bole or branch sections after the larvae have received sufficient cold treatment to complete diapause. The infested material is placed in rearing boxes where the larvae are attracted by a light source and counted. Sampling designs for estimating the density of overwintering larvae on boles, branch stems, and foliated twigs of Douglas-fir were developed by Egan (personal communication).

Carolin and Coulter (1972) report similar methods and show correlation between hibernating and subsequent feeding larvae. By this method, estimates of hibernating larvae have been infrequently used to check population potential before insecticide treatment.

5.2.2.2 Larvae in the Opening Buds—Larvae are found in opening buds primarily as third and fourth instars. For a given location, a period of about 10 days of relative population stability occurs in which a single host species can be sampled. Differences in bud development among host species make sampling more than one host species at a given location difficult. Because host bud development also varies among stands, extensive sampling at this stage must be correctly timed to assure comparable insect development among all sample plots.

An advantage of sampling at this time is that the larvae are webbed within feeding sites and foliage can be collected without risk of losing larvae. In addition, the larvae are active and easy to find.

As with egg masses, optimum sample allocation among trees and plots differs with population density and tree size. Variation among trees, however, is high regardless of population density. Based on larval pattern of occurrence (fig. 5-4), Srivastava and others (1984) indicate that midcrown tip density can be used to estimate whole-stand density on fixed-size sample plots as:

$W_{SL} = 0.238(X_M),\ r^2 = 0.98$,

where X_M is the average density of larvae per plot, using midcrown tips from trees 23 to 46 ft (7 to 14 m) tall. Estimates of required sample size can be found in Srivastava and others (1984).

Sample estimates of larvae in the opening buds are commonly used for pretreatment population evaluation. The most common design uses three-tree cluster plots, two

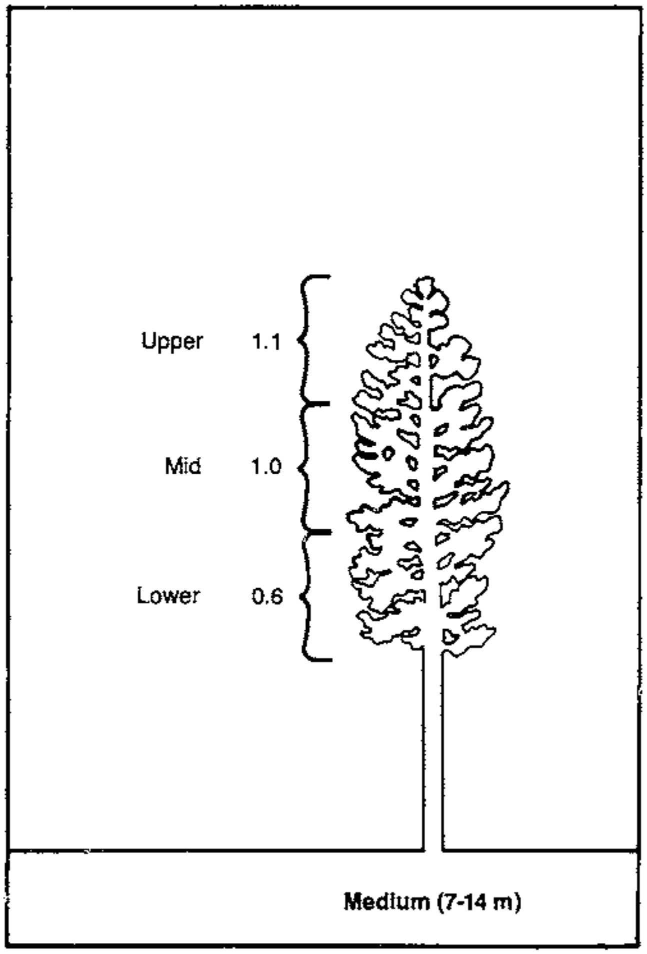

Figure 5-4—Approximate pattern of fourth-instar densities found among crown strata in medium-sized trees. Density per unit of foliage area is normalized with reference to midcrown whole-branch samples. Terminal-tip density is generally four times more than whole-branch density per unit of foliage area (adapted from Campbell and others 1984).

midcrown branch tips per tree, with "n" plots scattered across an entomological or treatment unit. Larval density is expressed as an average per 100 buds over all plots within an area. Because of the small sample size, information from individual plots is not reliable. Density estimates for single fixed-size plots can be obtained using the methods as described by Srivastava and others (1984).

For most survey applications, a more expedient method of early instar estimates is to use sequential sampling. Srivastava and Campbell (1983 unpubl.) have developed a sequential classification scheme and a sequential count plan, both for use with nominal fourth instars. The classification scheme classifies population density relative to a predetermined threshold.

Number of larvae per 45-cm tip	*Infestation class*
0–3	Light
4–7	Moderate
≥8	Heavy

The infestation class refers to defoliation expected as a result of larval feeding. Alternative hypotheses distinguish between light and moderate-to-heavy infestations (table 5-5) and light-to-moderate and heavy infestations (table 5-6).

Table 5-5—Sequential classification scheme for separating light from moderate-to-heavy populations of fourth instars at 95 percent confidence level (adapted from Srivastava and Campbell 1983 unpubl.)

Number of trees	Cumulative number of budworm larvae[1]	
	Light	Moderate to heavy
5	< 1	> 37
10	< 10	> 64
15	< 20	> 90
20	< 31	> 114
25	< 43	> 138
100	< 235	> 477

[1]If a count falls between the limits in the two columns, continue sampling.

Table 5-6—Sequential classification scheme for separating light-to-moderate from heavy populations of fourth instars at 95 percent confidence level (adapted from Srivastava and Campbell 1983 unpubl.)

Number of trees	Cumulative number of budworm larvae[1]	
	Light to moderate	Heavy
5	< 11	> 51
10	< 36	> 117
15	< 64	> 165
20	< 92	> 212
25	< 121	> 258
100	< 592	> 917

[1]If a count falls between the limits in the two columns, continue sampling.

Terminal tips (45-cm) are sequentially sampled from the midcrown of each tree within a stand until the cumulative number of larvae falls within one of the categories shown in the tables. A minimum of five trees per stand is recommended for classification. Ideally insect counts are made at the sample location. Where this is not practical, a minimum of 10 trees should be sampled in apparently high-density populations and 25 in apparently low-density populations. In the laboratory, branch samples are examined at random until the plot is classified.

The sequential count plan is similar to the classification scheme, except that it provides a density estimate per sample unit at specified precisions. The total number of larvae must equal or exceed the numbers shown (table 5-7). The stop-sampling lines for the count plan are adapted from Srivastava and Campbell (1983 unpubl.):

$$T_n \leq \frac{3.279}{D_n^2 - (0.149/n)}$$

where D_n = precision (0.15, 0.20, or 0.25) and n = number of 45-cm branch-tip samples.

Table 5-7—Sequential count plan for estimating fourth instars based on one 45-cm terminal tip per tree from midcrown. Sampling is terminated when cumulative number of larvae ≥ T_n at n trees (adapted from Srivastava and Campbell 1983 unpubl.)

n = number of trees	T_n = cumulative number of larvae		
	D_n = 0.15	D_n = 0.20	D_n = 0.25
3	—	—	256
4	—	1,193	130
7	2,700	176	80
10	433	131	69
15	262	110	63
20	219	101	60
25	199	97	58
30	188	94	57
50	169	89	55
75	161	87	54

Density per branch tip is calculated as the cumulative total number of larvae divided by the appropriate number of branches. For example, if 180 larvae are counted on the first seven branches, density is 180/7 = 25.7 larvae per branch. Srivastava and Campbell (1983 unpubl.) have estimated that the average 45-cm branch sample contains 0.082 m^2 of foliage. This can be used to convert the per-branch estimate to an estimate per unit of foliage.

5.2.2.3 Late Instars—Fourth through sixth instars occur for about 10 to 20 days, when shoots are completing development. Two factors affect use of this period for sample estimates: larvae drop on silk threads when the branch is disturbed, and the population is being reduced by natural mortality factors. Sampling must be carefully timed to assure that insect counts among plots are comparable. Several techniques are available for measuring larval dispersal; they may be used to determine the dispersal period, observe spread of larvae, and estimate dispersal mortality (Jennings and others 1984).

The most common application of sample estimates of this period are in evaluating the immediate effects of insecticide treatment. Most postspray larval estimates are based on sampling designs that are the same as the prespray design—26 plots, three trees per plot, and four 15-inch midcrown branch samples per tree. Schmid (1984 unpubl.) evaluated several fixed-size-plot sampling designs for later instars and found a three-tree/four-branch or a six-tree/one-branch scheme to be most precise. Trees within plots were not a significant source of variation, suggesting that a cluster design is less appropriate than scattered sample trees from throughout a stand.

Sampling variation in larval mortality estimates is inherently large. In applications where mortality ratios are obtained by sampling on two occasions (pretreatment and posttreatment), both bias and large sampling errors are found. The sample variance includes the distribution of the larvae between the two sampling dates, among trees within sample plots, and between sample branches on a tree. To date, an evaluation of the effects of these variance components on population-density estimates has not been performed.

Beckwith (personal communication) has developed a rapid method of indexing late-instar density. Three 45-cm branches at the bottom of the crown on each of 25 trees per plot are beaten in place over a hand-held cloth. The dislodged larvae are easily seen on the cloth, counted, and recorded per tree. The relation of larval numbers from lower crown branch beating to midcrown branch samples is illustrated in figure 5-5.

Whole-tree beating has been used to monitor late-instar populations (Harris and others 1972). The principal method is to lay a 7- by 9-ft (about 2- by 3-m) white cloth sheet beneath a tree and beat the branches with a 12-ft (about 4-m) pole for about 30 seconds; the larvae that drop to the ground are identified and counted. Three trees at each location are sampled. The resulting relative population indexes are used to establish trend.

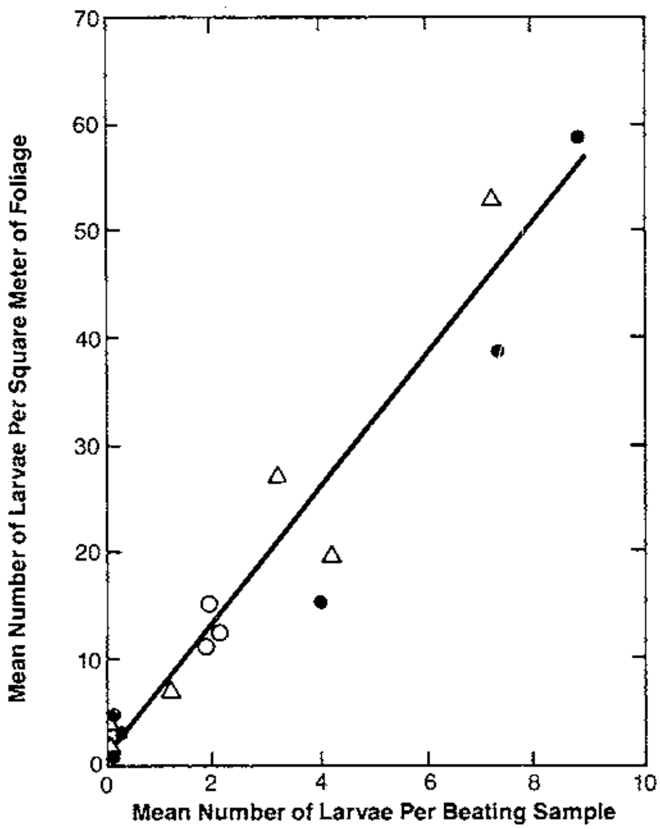

Figure 5-5—Relation of larvae from lower crown branch beating to larvae from midcrown branch samples.

5.2.3 Pupae

Pupae are stationary and easy to find on the foliage. The pupae are attached by silk strands, and most of the pupal cases remain on the foliage even after the moths have emerged.

Pupae are extremely vulnerable to parasites and predators, hence sample estimates should be obtained after this natural mortality has occurred. This is best accomplished by sampling when about 75 percent of the moths have emerged, as indicated by empty pupal cases. Waiting until all moths have emerged is not practical because empty pupal cases gradually break apart or are dislodged from the foliage.

Carolin and Coulter (1972) present a quantitative relation of pupae after mortality (residual pupae) to subsequent larvae in the opening buds:

$$\text{Larvae per 100 15-inch twigs} = -62.6 + 5.608x,\ r^2 = 0.91,$$

where x = average number of pupal cases per twenty 15-inch lower crown branch tips. If carefully timed and in the absence of unfavorable weather, determining the density of pupal cases provides a relatively quick method of predicting the subsequent populations. This method has not been field-tested, however, and it may be less reliable than using the egg stage for the same predictions. The advantage of the method in comparison to egg-mass sampling is that residual pupae are much easier to sample.

Srivastava and others (1984) found density of residual pupae to be lowest in the lower crown (fig. 5-6). Whole-stand density can be estimated from the average density on lower crown terminal tips as:

$$WS = 0.629\ (X_L),\ r^2 = 0.89,$$

where X_L is density of pupal cases in the lower crown per square meter of foliage obtained from lower crown 45-cm branch samples. Estimates of required plot size can be found in Srivastava and others (1984).

For extensive surveys, an estimate of pupal-case density can be obtained by using a sequential count plan developed by Srivastava and Campbell (1983 unpubl.). The plan uses one 45-cm terminal tip from the lower crown third of each sample tree. Trees are sampled until the cumulative number of pupal cases equals or exceeds the number shown for the appropriate tree number (table 5-8). Density per 45-cm branch tip is estimated by dividing the cumulative total by

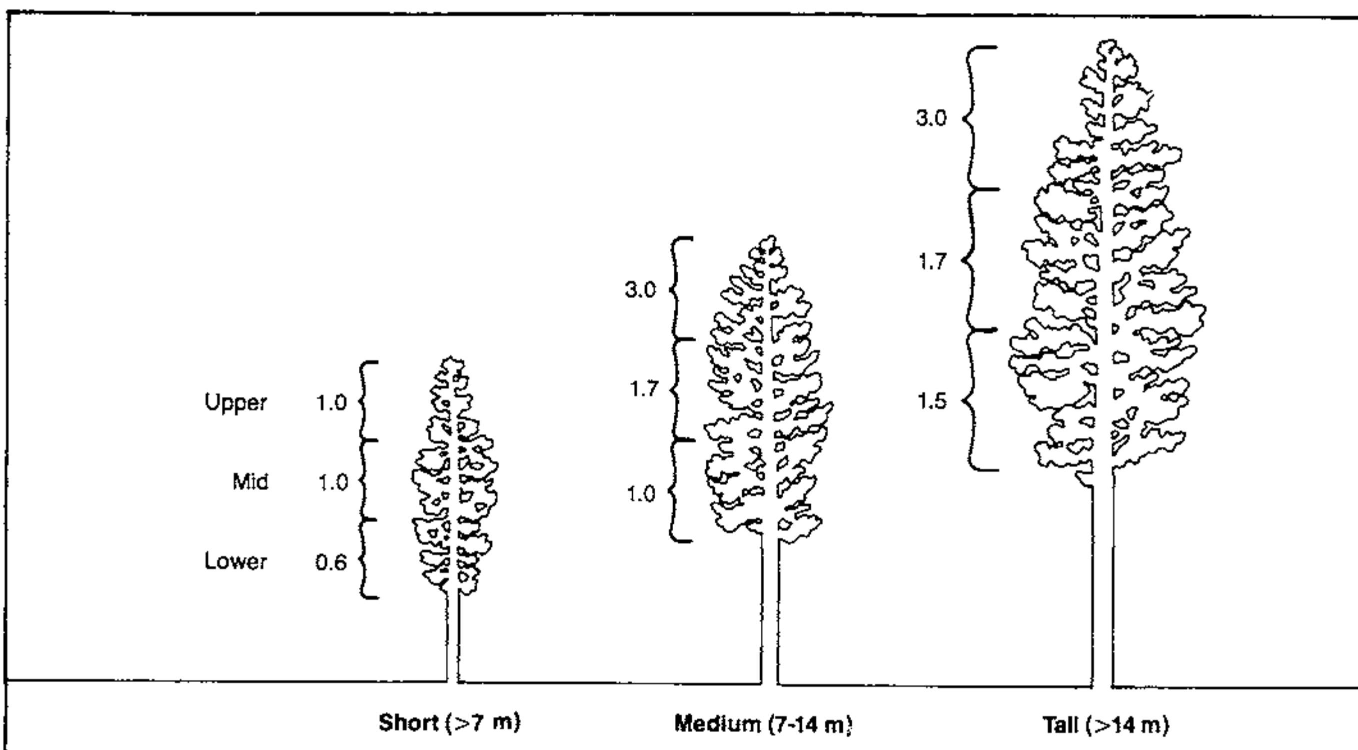

Figure 5-6—Approximate pattern of pupal densities found among crown strata in three tree size-classes. Density per unit of foliage area is normalized with reference to lower crown terminal-tip branch samples of medium-sized trees. Terminal-tip density is generally two to five times more than whole-branch density per unit of foliage area (adapted from Campbell and others 1984).

the number of trees. A minimum of six trees is recommended at each sampling location.

Table 5-8—Sequential count plan for estimating residual pupae based on one 45-cm terminal tip per tree from lower crown (adapted from Srivastava and Campbell 1983 unpubl.)

n = number of trees	T_n = cumulative number of pupae and pupal cases		
	$D_n = 0.15$	$D_n = 0.20$	$D_n = 0.25$
6	—	—	363
9	—	1,170	71
10	—	319	61
15	—	101	43
16	2,080	93	42
20	329	75	38
25	196	65	35
30	155	60	34
40	123	54	32
50	109	52	31

5.2.4 Adults

Two methods of sampling adult populations are known. One is the use of light traps, which can be used to monitor changes in low-density populations. The method may be useful for high-value areas, such as seed orchards, but is not practical for monitoring extensive forested areas.

The second method uses synthetic sex pheromone in sticky traps. A relation between trap catch of adult males and subsequent defoliation has been observed, but the method is still being developed.

5.3 Detection and Evaluation

Resource managers' decisions related to outbreaks of western budworm require information generated by surveys and sampling methods. Detection, monitoring, and evaluation describe the organization of these methods into a decision-support process for managers. Detection is the discovery of an infestation. Monitoring is the systematic observation of an infestation or potential infestation, and evaluation is the quantification of an infestation in absolute or relative terms. In a broad sense, evaluation is a continuation of monitoring to determine the course of an outbreak and anticipated damage. It is the basis both for prediction and for evaluating suppression efficacy.

The most common method of detecting incipient budworm outbreaks is by aerial sketch mapping of susceptible host types. Although an outbreak is generally not visible until more than 20 percent defoliation has occurred, the aerial sketch map allows extensive areas to be observed systematically and quickly. In special areas, where detection of sparse populations is important, other methods of detection may be used. These include lower crown branch beating and possibly pheromone trapping. Aerial sketch mapping is the least intensive and most extensive method of detection; for most applications over broad areas, it provides sufficient population monitoring information for making additional survey decisions.

Where more intensive population monitoring is required, a quantitative assessment can be made by first sketch mapping defoliation intensity and then making ground surveys, including branch-defoliation estimates, sequential pupal surveys, or sequential egg-mass surveys. The monitoring of results is usually needed only for relative numbers, to compare budworm activity for two or more successive years. Consequently, less attention is given to sample design and more to geographic coverage.

Pretreatment and posttreatment evaluations use methods designed to evaluate the effect of treatment—for example, larval samples before and after insecticide treatment. Evaluations must meet some established degree of statistical precision. As a consequence, more attention is given to sample design and plot allocation.

The objectives of detection, monitoring, and evaluation programs cannot be overemphasized. Sampling and surveys provide information about budworm outbreaks; how that information will be used influences how and when the information should be collected. To decide what sampling or surveys should be undertaken,

- Identify management objectives affected by budworm. Would something be done differently in light of information about budworm incidence or outbreak?
- Identify the scale of the potential problem. Will it affect a few high-productivity stands, all regulated stands, a geographic region? Sample estimates must be representative of the area concerned. What is the sampling universe?
- Identify damage and economic thresholds. When does the incidence of defoliation or top-killing become objectionable or an unacceptable loss? These thresholds help identify the necessary intensity of sampling methods.
- Identify treatment alternatives. Which of the available options are to be considered—insecticides, silvicultural treatment, microbials, do nothing? Knowing management alternatives helps identify how much time is available for data collection.

Addressing these considerations will provide choices of sampling and survey methods to initiate or undertake in a detection, monitoring, and evaluation program. Of particular importance, however, is the linkage between the biological information obtained through detection, monitoring, and evaluation—and management decisions. Each sample or survey should trigger an action, whether this be an additional sample or survey, or a resource management action.

Chapter 6
Rating Stand Hazard to Western Spruce Budworm

6.1 Introduction

Clinton E. Carlson

To set priorities for treatment, stands are ranked according to their susceptibility to budworm. This ranking—often called hazard rating—should integrate site and stand conditions known to influence budworm and should be usable throughout the budworm range. Five different methods of hazard rating are described: aerial surveys, a climatological regression model, photo interpretation with regression modeling, an empirical site-stand regression model, and a generalized indexing model. The first is generally applicable but somewhat imprecise; the next three thus far are applicable only to limited geographic areas; and the last method, although tested only in the northern Rockies of the United States, appears to have wide application.

6.2 Hazard Rating From Aerial Mapping

Lawrence E. Stipe

Numerous techniques have been developed for rating hazard to forest insects, but none have been based on aerial survey data. Such surveys provide a continuous historical record of insect activity from which the relative hazard of areas could be determined. Most conventional hazard-rating systems require extensive training, experience, and equipment—plus a large investment in data collection. They use stand data gathered by ground surveys and aerial photography. A technique based solely on aerial detection would need no additional data collection and would not require highly trained personnel. It would be somewhat less precise, however.

Aerial survey data for budworm infestations are available for most forested areas in the West for the past 30 years. Each year, areas of visible budworm defoliation are recorded on forest maps with scales of one-fourth and one-half inch/mi (0.4 and 0.8 cm/km). In most areas, defoliation is also classified as light, moderate, or heavy. At the scale of one-half inch/mi, infestations can easily be discerned on individual drainages.

Aerial mapping can be used to assess the likelihood of visible budworm defoliation and to estimate outbreak duration. Hazard rating based on aerial detection data may be general or detailed, depending on the resolution required. It may be as simple as a visual examination of a particular map sequence. Where more detailed information is required, acetate overlays can be used to accumulate a defoliation history over time. Only basic map information and simple drafting skills are required. Survey data can be digitized and then analyzed by computer.

6.3 Climatological Discriminant Model

William P. Kemp

Five climatological variables were considered in analyses to predict outbreak frequencies by region: January mean maximum temperatures, January mean minimum temperatures, July mean minimum temperatures, July mean maximum temperatures, and mean annual precipitation (table 6-1) (Kemp 1983). The four temperature variables were found sufficient in discriminant analysis to develop equations (table 6-2) for predicting the likelihood of high, medium, and low outbreak-frequency for a given location.

Table 6-1—Median values and ranges of five selected climatic variables by western spruce budworm outbreak-frequency class (from Kemp 1983)[1]

		Outbreak class		
Variable		High (class 1)	Medium (class 2)	Low (class 3)
January mean maximum	Median	= 28	32	40
	Range	= 24–34	24–42	28–50
January mean minimum	Median	= 4	16	28
	Range	= (−2)–14	4–22	10–36
July mean maximum	Median	= 80	84	80
	Range	= 72–88	72–92	63–88
July mean minimum	Median	= 44	48	48
	Range	= 36–54	40–56	36–54
Mean annual precipitation	Median	= 20	24	40
	Range	= 10–40	12–64	12–120

[1] Temperature given in degrees Fahrenheit. To convert to degrees Celsius: C = 5/9 (F − 32). Precipitation in inches. Multiply inches by 25.4 to get millimeters.

Table 6-2—Classification function coefficients to predict western spruce budworm outbreak-frequency class (from Kemp 1983) (Fisher's linear discriminant functions)

High	= −273.7934 + 2.9061 (JLMX) + 4.6138 (JLMN) + 4.4454 (JAMX) − 3.8127 (JAMN)
Medium	= −278.0519 + 3.0630 (JLMX) + 4.4940 (JLMN) + 4.1854 (JAMX) − 3.3452 (JAMN)
Low	= −264.8155 + 3.0181 (JLMX) + 4.1833 (JLMN) + 4.0867 (JAMX) − 2.8984 (JAMN)

where:

JLMX = July mean maximum temperature;

JLMN = July mean minimum temperature;

JAMX = January mean maximum temperature; and

JAMN = January mean minimum temperature.

For a given location, a score is calculated for each of the above functions. The location is assigned to the class having the highest calculated value.

Table 6-3 shows the classification results when the equations were applied to the validation data. Accuracies of 74 percent correct classification were found when the model was tested on 239 additional map points.

Table 6-3—Classification of outbreak areas as a function of climatic variables in Idaho, Montana, Oregon, and Washington

		Predicted outbreak class[1]		
Actual outbreak-frequency class	Number of points	High (class 1)	Medium (class 2)	Low (class 3)
High—1	60	50 83%	10 17%	0 0%
Medium—2	75	9 12%	56 75%	10 13%
Low—3	104	1 1%	31 30%	72 69%
Total	239			

[1] Pooled cases correctly classified, 75.15 percent.

In a practical example, a manager may obtain values from the National Oceanographic and Atmospheric Administration for 2 years for January and July mean maximum and minimum temperatures for a site (1968 and 1974). These values are put into each of the three equations in table 6-2, and a score is calculated for each equation. The site is then assigned to the class with the highest calculated value: JLMX = 72, JLMN = 52, JAMX = 44, and JAMN = 32. Using table 6-2, we would calculate the following:

High 248.95 = −273.7934 + 2.9061(72) + 4.6138(52) + 4.4454(44) − 3.8127(32)

Medium 253.28 = −278.0519 + 3.0630(72) + 4.4940(52) + 4.1854(44) − 3.3452(32

Low 257.08 = −264.8155 + 3.0181(72) + 4.1833(52) + 4.0867(44) − 2.8934(32)

The low-outbreak-frequency function had the highest score, and the point would be classed as typical of climates in the low-outbreak-frequency region of figure 6-1. Low outbreak-frequency means 0 to 11 years of visible defoliation expected in 100 years. Medium frequency is 7 to 48 years of defoliation per 100 years, and high frequency is 60 or more years of defoliation. Gaps and overlaps between classes are considered acceptable because the procedure was designed to provide general classification.

If the equations (table 6-2) are used for Idaho, Montana, Oregon, and Washington, outbreak-frequency classifications agree with the outbreak-frequency regions (fig. 6-1) about 75 percent of the time (table 6-3). In the remaining 25 percent, the equations indicate that a point, although physically located in a particular outbreak region, has climatic characteristics more similar to another outbreak-frequency region. Where this occurs, the classification should be used with other local information in determining hazard.

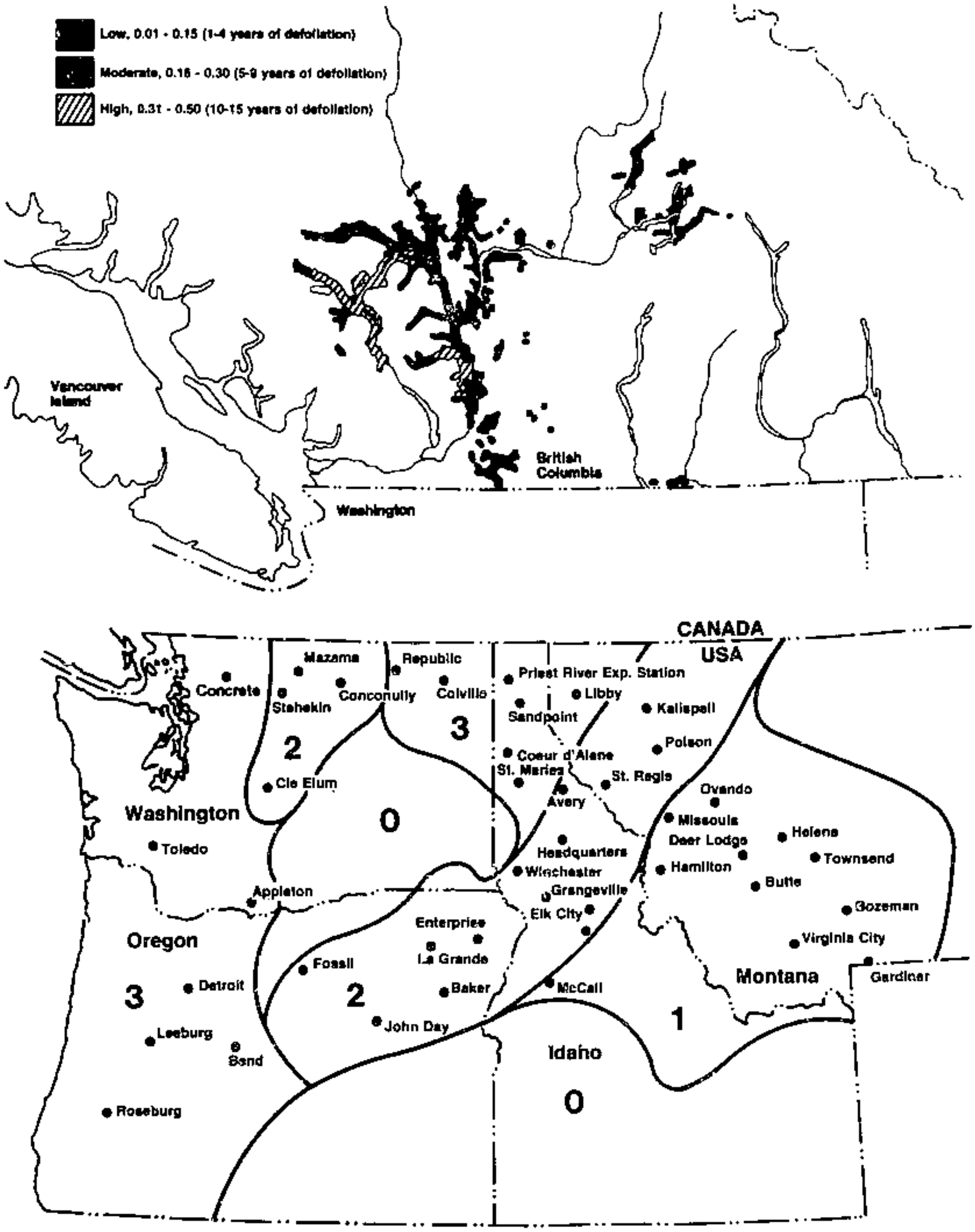

Figure 6-1—Classes of budworm outbreak-frequency (1947–78) developed for forested areas of Idaho, Montana, Oregon, and Washington are shown on the lower map. High outbreak-frequency = 1, medium outbreak-frequency = 2, low outbreak-frequency = 3, no forest susceptible to budworm = 0 (from Kemp 1983). The upper map (Van Sickle, personal communication) is based on a 31-year historical record.

6.4 Rating Stand Hazard to Western Spruce Budworm: Aerial Photo Interpretation Models

Robert C. Heller and Bruce L. Kessler

Budworm defoliation can be effectively and economically predicted for forest stands by using information obtained from aerial photographs (Ulliman and Kessler 1983 unpubl.). Models developed to predict budworm defoliation allow forest managers to assess large and inaccessible areas quickly before an outbreak occurs and to determine where budworm damage may be most severe. Techniques described in this section are general methods for all areas within the budworm range, but the mathematical models described are specific for the areas where the research was done. Research has shown that these models do well when applied where developed, but poorly elsewhere.

The desired end product of hazard-rating models is an appraisal of stand susceptibility to budworm. A color-coded map indicating prediction classes for each stand is a logical final product, and such a map focuses attention on stands most in need of silvicultural treatment. The forest manager has both a stand-by-stand rating of defoliation estimates and a visual display of where that defoliation will occur. Both are valuable tools for forest planning. Such models may also be used as simulators for assessing effects of silvicultural strategies.

The aerial photo approach appeals to managers because most tools are already available. Thus, large areas of forest can be examined and rated quickly. The approach is useful even if a model has not been developed for a particular locale. For example, a prediction model developed for the Douglas-fir tussock moth was applied with some modifications to 496 forest stands on the Palouse Ranger District of the Clearwater National Forest. Data for implementing this model were obtained from 1:24,000 black-and-white photos and topographic maps. A similar model with many identical variables was developed 1 year earlier on the Okanogan National Forest in north-central Washington. It predicted probability of defoliation from 4 to 99 percent.

Two families of empirical aerial photo models were developed for budworm: a model that predicts defoliation will be greater than some established threshold—for example, 20 percent (Heller and others 1981 unpubl.), and models that predict amount of defoliation (Ulliman and Kessler 1983 unpubl.). The major predictor variables in all these models not only agree with similar ground models developed by Stoszek and Mika (1983a unpubl.) but also appear biologically sound and can be used to identify conditions conducive to increases in budworm populations.

The model developed by Heller and others (1981 unpubl.), which predicts defoliation probability for a forest stand, was developed in the Payette National Forest near McCall, Idaho. The model can be implemented by collecting forest-stand data on elevation from topographic maps and topographic position and average crown diameter from resource-scale (1:24,000 or larger) color aerial photos. Stand purity is obtained from recent stand-examination data or large-scale color aerial photos (1:4,000 or larger). The relation is expressed:

$$P = 1/(1 + \mathrm{Exp} - (0.363206 + 0.1964589*E - 1.04756*F - 0.891844*\mathrm{Top1} - 0.0014125*\mathrm{Top2} - 0.044739*CD + 0.0386609*PU))$$

where:

P = probability that the stand will be defoliated by budworm during the next outbreak;
Exp = exponential function (natural logarithm base e);
E = elevation in feet of the forest stand divided by 1,000;
F = $(E - \overline{E})^2$, where E is as defined above and $\overline{E}$ = mean elevation of all plots studied in the McCall area (5,810 ft) = 5.81;
Top1 and Top2 = dummy variables for describing topography of the stand.

Topographic position (fig. 6-2) is interpreted stereoscopically from the

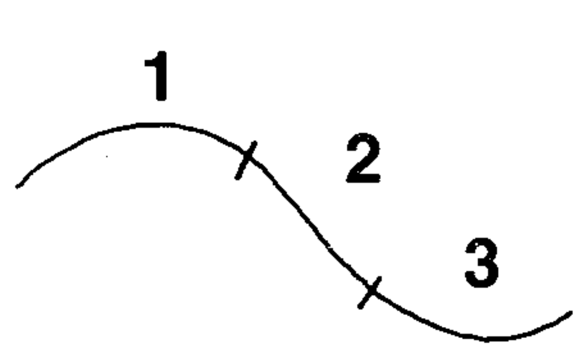

Figure 6-2—Topographic position. Codes are assigned by stand location on ridges (1), sidehills (2), or bottoms (3).

aerial photos and converted to Top1 and Top2 by the following chart:

Topo position	*Code 1*
1 (ridgetop)	1 for Top1 0 for Top2
2 (sidehill)	0 for Top1 1 for Top2
3 (valley bottom)	−1 for Top1 −1 for Top2;

CD = average crown diameter, estimated from measuring a representative sample of overstory tree crowns, and—by the scale at that point in the photograph—converting the average measure diameter to feet; and

PU = stand purity, figured as percentage of host trees (Douglas-fir, true firs, and Engelmann spruce) to total number of trees in the stand. This model was validated by Ulliman and Kessler (1983 unpubl.) 2 years after it was developed.

Two models were developed by Ulliman and Kessler (1983 unpubl.): one in the Malheur National Forest near John Day, Oregon, and the other in the Payette National Forest near McCall, Idaho (where Heller and others worked). These models estimate defoliation amounts for both forest stands and individual trees. The individual-tree models were intended to extend the versatility of the model, but they are difficult to apply from stand records or existing aerial photographs and thus are not included here. A listing and description of models developed by Ulliman and Kessler are in table 6-4. Examples using different models on forest stand data are in table 6-5.

The similarities between the two families of models are defoliation probability and defoliation amount. For instance, elevation plays a major role in the models, and a bell-shaped curve results when it is correlated with amount of defoliation. Defoliation is greater at some midpoint in each study area and is less at maximum and minimum elevations. Also, purity and the presence of true firs are positively correlated with defoliation. The importance of each variable differs, even among the most strongly correlated variables, perhaps because of differences in locale. Budworm dynamics apparently differ from area to area.

Table 6-4—Forest stand models developed for the Payette National Forest near McCall, ID, and the Malheur National Forest near John Day, OR

McCall stand model

$$P = -417.5 + 0.146*E - 0.000009851203*E^2 + 1.77*PU - 1.02*CD - 0.00031491*E*PU$$

John Day stand model

$$P = -28.5 + 18.58*A + 1.21*PU + 3.93*CD - 0.045*PU*CD - 6.05*PP\ cover - 4.43*PM\ cover - 0.09*AG\ cover - 40.17*AL\ cover$$

where:

P = predicted percent defoliation by budworm during the next outbreak;

E = elevation in feet;

PU, CD = stand purity and average crown diameter—collected the same as in the previous model;

A = aspect (0 = westerly, 1 = easterly);

cover = cover type that dominates the overstory (values of cover type are: 0 = type not present, 1 = type present); and

PP = ponderosa pine, PM = Douglas-fir,
AG = grand fir, PE = Engelmann spruce,
AL = subalpine fir.

Because of the complexities in a natural system, we really do not know whether the developed models accurately portray the physical environment where host-insect interaction takes place. Nevertheless, developing models from mensurational variables is logical and practical, and the information derived generally agrees with perceptions on host-budworm interaction. We are confident that the models adequately reflect real conditions in specific areas. If applied to other areas, however, the models must be adapted and tested.

6.5 Rating Stand Hazard to Western Spruce Budworm: Ground-Survey Models

Karel J. Stoszek and Peter G. Mika

Table 6-5—Use of the two different types of models with forest data

Forest stand A:

Elevation	Topographic position = 1	Average crown diameter	Purity
5,550 ft	Top1 = 1, Top2 = 0	23 ft	70

Forest stand B:

Elevation	Average crown diameter	Purity
6,500 ft	21 feet	50

Defoliation probability model for McCall using forest stand A:

$$P = 1/(1 + \text{Exp} - (0.363206 + 0.1964589*5.550 - 1.04756*(5.55 - 5.81)^2 - 0.891844*1 - 0.0014125*0 - 0.044739*23 - 0.0386609*70))$$

= 0.72 or 72 percent chance of defoliation greater than 20 percent in the next outbreak

Defoliation prediction model for McCall using forest stand B:

$$P = -417.5 - 0.146*6500 - 0.000009851203*6500^2 - 1.77*50 - 1.02*21 - 0.00031491*6500*50$$

80 percent defoliation

Percentage of defoliation of host trees can be predicted from a family of regression models developed by Stoszek and Mika (1983a unpubl.). The models were developed from research plots in the Clearwater and Salmon National Forests of Idaho. An important variable in the multiple-regression equations was the vegetation series of the sampling site; other variables included elevation, indexes of stand density, basal-area increment, stand age, variation of age, and amount of woody residue on the ground. Other variables found to be related to defoliation intensity included topography, aspect, depth of duff, proportion of host in stands, and successional stage.

Models developed for host stands in the subalpine fir vegetation series and western hemlock vegetation series on the Clearwater National Forest are presented in table 6-6. Vegetation classification is based on the system of Daubenmire and Daubenmire (1968) and includes grand fir climax types in the western hemlock series.

Model formulation differed by vegetation series. In stands associated with the warm and moist environment of the western hemlock series, defoliation increased with increasing elevation, decreasing stand density, and decreasing amount of woody residues on the ground. In the cool conditions of the high elevation subalpine fir series, however, defoliation increased with decreasing elevation, increasing stand density, and increasing amount of downed woody residues. In each vegetation series, defoliation was inversely related to both the average of and the deviation in tree age, indicating that codominant and dominant trees in even-aged, commercially immature stands (50 to 70 years old) were subject to higher defoliation than those in multistoried stands.

Other results indicated that budworm defoliation was higher in host stands in the seral stage of succession (determined only for stands in the western hemlock series); in stands on southerly aspects, ridgetops, and upper slopes; on sites in the grand fir and subalpine fir habitat types (compared to those in the western redcedar habitat type); and in host-dominated stands. True firs sustained heavier defoliation than Douglas-fir or Engelmann spruce.

The hazard model developed by Stoszek and Mika (1983a unpubl.) for host stands in the Douglas-fir vegetation series (table 6-7) is based on data from the North Fork Ranger District of the Salmon National Forest; Douglas-fir was the only host species present and tended to dominate the stands. The regression equation indicated that the percentage of defoliation of Douglas-fir in this sampling area was a quadratic function of elevation and was

Table 6-6—Multiple regression model[1] for budworm defoliation in the western hemlock (WH) and subalpine fir (SAF) vegetation series (based on Daubenmire and Daubenmire 1968) on the Clearwater National Forest of central Idaho

Regression coefficients for various predictor variables													
Predictor variable	Intercept		Elevation		Small fuels		Crown competition factor		Basal area		$\log_e(\sigma_{age})$[2]	Average age	
Vegetation series			*Ft*		*Tons/acre*				*Ft²/acre*				
	WH	SAF	WH	SAF	WH	SAF	WH	SAF	WH	SAF		Years	R^2
Model 1	23.4386	121.3052	0.0122	−0.0144	−24.9818	28.9354	−0.0195	0.0679			−5.7295	−0.1132	0.7181
Model 2	24.2069	117.5464	0.0125	−0.0135	−25.7394	32.6231			−0.0105	0.0895	−6.5949	−0.1151	0.7157
Model 3	11.3919	116.0682	0.0148	−0.0131	−22.6489	30.7229	−0.0239	0.0747			−8.0783		0.6844
Model 4	14.2464	111.9558	0.0146	−0.0124	−22.7954	33.6819			−0.0309	0.0925	−8.3681		0.6854
Model 5	11.5138	118.0351	0.0113	−0.0165	−25.3967	13.3711	−0.0368	0.0636				−0.1547	0.6880
Model 6	7.0053	114.6022	0.0120	−0.0161	−26.8985	15.3504			−0.0249	0.0783		−0.1591	0.6725
Model 7	16.0173	128.3643	0.0099	−0.0164			−0.0581	0.0926			−5.2036		0.5747
Model 8	16.8632	127.1634	0.0101	−0.0162					−0.0611	0.1160	−5.6920		0.5646
Model 9	17.7307	122.1830	0.0072	−0.0174			−0.0681	0.0757				−0.1034	0.5735
Model 10	9.4682	118.8217	0.0084	−0.0172					−0.0634	0.0921		−0.0875	0.5425
Model 11	−7.4910	111.6485	0.0112	−0.0164			−0.0746	0.0768					0.5360
Model 12	−9.9066	111.3661	0.0117	−0.0165					−0.0781	0.0888			0.5184

[1] The dependent variable for all models is percent defoliation per host.
[2] $\log_e(\sigma_{age})$ = the natural log of the standard deviation in age.

Table 6-7—Regression coefficients for the predictor variables for host stands within the Douglas–fir vegetation series on the Salmon National Forest in eastern Idaho

Intercept	Host basal-area increment	Elevation	Elevation
	In²/yr	*Ft*	*Ft²*
−331.8777	6.5873	0.1226	-0.1029×10^{-4}

positively correlated with basal-area increment of sampled dominant and codominant host trees. Other analyses indicated that budworm-susceptible stands were of low density, lacked a duff layer, and were composed of Douglas-fir with good but declining radial-growth increments; heaviest defoliation occurred at about 6,000 ft (1 830 m).

Model Application—The regression models presented can be used to rank existing stands in terms of impending or future budworm hazard (percent defoliation expected), to define possible habitats conducive to increase in budworm population, and to identify possible silvicultural measures to reduce budworm hazard.

The hazard-rating applicability of multivariate regression models is limited to stands in the vegetation series and areas where they were developed. Validation and use of other variables or coefficients may be necessary for areas with different histories, ecological conditions, or both. When the models are used for hazard rating, the pertinent vegetation series must be appropriately identified and used. For example, the classification system by Daubenmire and Daubenmire (1968) should be used for the Clearwater National Forest, and that of Steele and others (1981) for the Salmon National Forest.

The linear regression models presented have the following general form:

$$Y = a + b_1X_1 + b_2X_2 + \ldots + b_nX_n,$$

where

Y = predicted percent defoliation per host tree;
a = intercept (constant);
$b_1, \ldots, b_n$ = regression coefficients of predictor variables; and
$X_1, \ldots, X_n$ = plot values for predictor variables (real data collected by the manager).

As an example, a plot from the Salmon National Forest (table 6-7), for which defoliation is to be predicted, has an average basal-area increment of 8 square inches per host tree per year and is at an elevation of 6,000 ft above mean sea level. Thus, predicted defoliation (Y) is:

$$Y = -331.88 + 6.5873*(8) + 0.1226*(6000) - 0.00001029*(6000)^2;\ Y = 86 \text{ percent.}$$

Model Concepts—Relations portrayed by the hazard models permit assessment of the operational environments in which budworm populations are likely to increase. Such conceptualization may help in expanding and generalizing the model, and in identifying silvicultural measures to reduce budworm hazard.

The operational environment of outbreak-prone habitats in both cool and warm sites appears to reflect an ecosystem in which the mineral nutrient cycle is "discoupled" or nutrient uptake during periods of high demand is inadequate to permit synthesis of plant defenses against budworm feeding. The risk-predictive variables on the cool subalpine fir series suggest an environment characterized by lack of organic matter decomposition, tieup of mineral nutrients in the plant biomass, and impaired nutrient cycling. Poorly developed soils and increased soil acidity, both associated with higher elevations, may magnify the problem. Although different from the subalpine series in descriptive characteristics, the environment on warm, dry sites in the Douglas-fir series may have similar attributes. Poorly developed soils and low mineralization rates, combined with destruction of woody residues and duff by frequent fires, may have led to an impairment of the nutrient cycle. The inadequate uptake of nutrients—magnified by moisture stress—impairs the synthesis of plant defenses against herbivores, with consequences similar to those on subalpine fir sites. Nutrient stress, predisposing hosts to budworm feeding on warm, moist sites within the western hemlock series, is likely the result of an inadequate uptake of marginally available mineral nutrients. Such problems would be particularly evident in fast-growing host trees during high demand periods early in the growing season (Stoszek and Mika 1983b unpubl.).

Based on the premise that stress from nutrient deficiency increases hazard, silvicultural measures aimed at reducing risk to budworm should focus on protection and improvement of soil organic matter, nutrient cycling, and nutrient availability.

6.6 Generalized Indexing Model

N. William Wulf and Clinton E. Carlson

We have developed a model to calculate an index of the relative susceptibility of a given stand to budworm. The model is based on interpretation of budworm literature and general field observations throughout the West and reflects what is known about the interactions of the insect and its habitat. The model has been field-tested in western Montana and central Idaho and appears to perform reasonably well. The index values were derived for each variable subjectively and were assigned according to how important the variable apparently is to stand susceptibility. The mathematical basis for the index values is limited; the values may change as our knowledge of budworm accrues and as the susceptibility model receives rigorous testing.

The characteristics of site and stand that affect susceptibility to budworm have been described (Wulf and Cates 1985); those used in the model—and how they are believed to affect budworm dynamics—are:

Regional climate—General climate significantly affects budworm dynamics. Climate tends to be cool and moist where outbreak frequency is low, but warm and dry where outbreak frequency is high (fig. 6-1) (Kemp 1983).

Site climate—Given that the regional climate is favorable to budworm, stands on warm, dry sites are the most susceptible. Warm, dry conditions accelerate larval development and tend to stress host trees.

Species composition—Stands composed primarily of host species are more susceptible than mixed stands because more food is available to developing larvae and more sites are present for egg deposition. Furthermore, stands composed primarily of host species that are shade tolerant tend to be more susceptible than stands that have a sizable component of shade-intolerant host species.

Stand density—Dense host stands are more susceptible than relatively open stands because of increased foliar biomass and increased water and nutrient stress.

Height-class structure—Multistoried stands are more susceptible than one-storied, even-aged stands. The lower stories significantly reduce mortality of dispersing larvae and provide additional substrate.

Vigor—Stressed stands with low vigor tend to be more susceptible, and we believe the quality of the foliage as insect food is enhanced. Low-vigor stands tend to have an altered terpene regime that apparently weakens tree resistance.

Maturity—Older, mature host stands tend to be more susceptible than young stands.

Surrounding host type—Stands in close proximity to forests composed of host species tend to be more susceptible than relatively isolated stands. The probability of adult or larval invasion is much higher when large quantities of a suitable host are nearby.

Each of these stand characteristics is represented by one or more variables that collectively index the quality of budworm habitat. Classes were identified for each variable, and an index value is assigned to each class. A relative rating of stand susceptibility is the product of the index values for all variables. The range of the rating is 0 to 100: 0 denotes nonsusceptibility and 100 optimal budworm habitat. The variables and index values are:

1. Species composition

   A. Variable:

   $$\text{Percent host crown cover} = \frac{\text{host crown cover}}{\text{total crown cover}} \times 100$$

   Hosts considered are Douglas-fir (DF), grand fir (GF), subalpine fir (SAF), white fir (WF), Engelmann spruce (ES), and western larch (WL).

Percent host crown cover	*Index value*
1–10	0.1
11–20	0.3
21–30	0.5
31–40	0.8
41–50	1.0
51–60	1.3
61–70	1.6
71–80	1.8
81–90	2.1
91–100	2.4

   B. Variable:

   $$\text{Percent climax host crown cover} = \frac{\text{climax host crown cover}}{\text{total crown cover}} \times 100.$$

   Climax hosts considered are DF, GF, WF, SAF, and ES—depending on the habitat type. Only the major climax host species indicated for the habitat type is used, except within the GF and ES series, which include SAF when it is a minor climax species.

Percent climax host crown cover	*Index value*
0–10	0.6
11–20	1.0
21–30	1.3
31–40	1.6
41–50	1.8
51–60	2.0
61–70	2.1
71–80	2.2
81–90	2.3
91–100	2.4

2. Density

Variable:

Total percent crown cover (all tree species).

Percent crown cover	*Index value*
1–20	0.8
21–40	1.1
41–60	1.3
61–80	1.4
81–100	1.5
100+	1.6

3. Height-class structure

Variable:

Coefficient of variation ($sX/\bar{X}$) of host (climax and seral) tree heights. Hosts considered are DF, GF, WF, SAF, ES, and WL.

0–10	0.9
11–20	1.1
21–30	1.3
31–40	1.5
41+	1.7

4. Vigor

Variable:

$$\text{Relative stand density (with or without host-tree biotic stress)} = \frac{\text{total basal area}}{\text{average maximum basal area}} \times 100.$$

All tree species are used to calculate total stand basal area. The average maximum basal area for the stand is derived from the stocking level assessments of forest inventory data and is specific to subregion, habitat-type group, and quadratic mean stand diameter. In addition, the host species (DF, GF, WF, ES, SAF, and WL) are considered stressed by biological agents if more than 30 percent of host trees are infected with diseases or infested by insects that do not use or destroy budworm food (that is, new foliage).

	Index values	
Relative stand density	*Without biotic stress*	*With biotic stress*
1–40	0.9	1.0
41–60	1.1	1.2
61–80	1.3	1.4
81+	1.5	1.6

5. Maturity

Variable:

Basal-area-weighted mean host age. Hosts considered are DF, GF, WF, SAF, and ES. WL is purposely not included because older larch are only slightly susceptible.

Mean host age	*Index value*
1–25	0.3
26–50	1.0
51–75	1.1
76–150	1.2
150+	1.3

6. Site climate

Variable:

Habitat-type group or potential climax plant community. (See appendix 1 for habitat-type groupings for the northern U.S. Rocky Mountains.)

Habitat group	*Index value*
Cold subalpine fir, timberline types	0
Cool, moist spruce; cool, moist subalpine fir types	0.6
Warm, wet grand fir; western redcedar, western hemlock; warm, wet subalpine fir types	1.0
Cold Douglas-fir; cold grand fir; cool, dry spruce; cool, dry subalpine fir types	1.2

Habitat group	*Index value*
Moist grand fir; warm, moist spruce; warm, moist subalpine fir types	1.3
Mesic Douglas-fir; dry grand fir; warm mesic spruce; warm, dry subalpine fir types	1.4
Warm, dry Douglas-fir types	1.5

7. Regional climate

Variable:

National Forest or Forest Service Region location with respect to maritime climatic influences. Interior British Columbia would probably have an index value of 1.0 or 1.1.

National Forest or Region	*Index value*
R-6 (west of the Cascades)	0
Idaho Panhandle (exclusive of the St. Joe), Kootenai	0.2
St. Joe, Clearwater, Lolo (west-side), Nezperce (Selway District only), Colville	1.0
Flathead, Nezperce (exclusive of the Selway District), Wallowa-Whitman, Umatilla, Malheur, Ochoco, Okanogan, Wenatchee, Boise, Payette	1.1
Bitterroot, Lolo (eastside), Beaverhead, Custer, Deerlodge, Gallatin, Helena, Lewis and Clark, R-4 (exclusive of the Boise and Payette), R-2, R-3	1.2

8. Surrounding host-type continuity

Variable:

The percentage host type of the surrounding 1,000 acres (400 ha) and the preponderance of host-type stands immediately adjacent to the subject stand.

Stands are considered "host type" if they are dominated by primary host species (GF, WF, DF, SAF, ES). Even-aged regeneration stands and stands occupying the cold subalpine fir series are not considered host type regardless of their species composition.

Percent host type in the surrounding 1,000 acres (ca. 400 ha)	*Character of adjacent stands*	*Index value*
0–15	Nonhost	0.6
0–15	Host	0.8
16–25	Nonhost	1.0
16–25	Host	1.2
26–75	Nonhost	1.4
26–75	Host	1.5
76–100	Nonhost	1.6
76–100	Host	1.7

As examples, susceptibility indexes have been calculated for a slightly susceptible stand (A) and a stand (B) that is moderately susceptible (table 6-8).

To derive the susceptibility index (SUIN):

Stand A

SUIN = 0.3 * 0.6 * 1.3 * 1.1 * 1.1 * 1.1 * 1.0 * 1.0 * 1.2 = 0.37

Stand B

SUIN = 1.8 * 2.0 * 1.5 * 1.6 * 1. 2 * 1.7 * 1.2 * 1.2 * 1.7 = 43

The susceptibility index is a quantitative expression of the relative quality of habitat for budworm. The variables used are part of the stand-examination files of Forest Service Region 1 and can be obtained from that data base; other Regions have similar data bases. Thus, for most stands previously inventoried and entered into the data base, the susceptibility index can be calculated.

Classifying susceptibility indexes into hazard groups may be useful. For convenience, the following grouping is suggested:

Susceptibility index	*Hazard*
0–20	Low
21–50	Moderate
51–100	High

Table 6-8—Hazard ratings of two hypothetical stands: A, slightly susceptible; B, moderately susceptible to budworm

Factor	Criterion variable	Stand A		Stand B	
		Actual value	Index value	Actual value	Index value
Composition	A. Percent host crown cover	15	0.3	72	1.8
	B. Percent climax host crown cover	5	.6	54	2.0
Density	Percent crown cover	54	1.3	95	1.5
Vigor	Relative stand density	44	1.1	84	1.6
Maturity	Mean host age	54	1.1	115	1.2
Height structure	Coefficient of variation	15	1.1	65	1.7
Site climate	Habitat type group	Moist SAF	1.0	Cold DF	1.2
Regional climate	National Forest	Clearwater	1.0	Helena	1.2
Surrounding forest	Percent host in surrounding 1,000 acres	22	1.2	78	1.7

6.7 Using the Models

Models of stand susceptibility will allow managers to map hazard to budworm by drainage, ranger district, forest, or other geographic area, and can be used to locate and select areas for silvicultural treatment to reduce stand susceptibility.

Foresters interested in rating their stands for hazard to budworm should test all of the models presented in this chapter—and view the results critically. One caution is that some factors in the ground-survey models and the generalized indexing model seem contradictory and would suggest opposite silvicultural treatments. Because more data and validation are required to increase the predictive ability of the models, those who require more precise information must await further analyses.

Chapter 7
Tactics for Managing Trees and Stands

David G. Fellin

Forest managers have two general options for dealing with budworm in western forests—direct application of a chemical or biological insecticide or indirect manipulation of the budworm habitat, the forest.

Decisions are complicated by several factors: the diversity of geography and climate; the variety of tree species that serve as hosts, growing in many habitats over several forest series; and variations in the insect—its behavior and complex relations with host trees. Land ownership and physiography are also complications: nearly 75 percent of the land is federally owned; in many parts of the West, budworm outbreaks are scattered and discontinuous, and the forests separated by wide expanses of nonforested land.

In this chapter, alternatives for managing budworm populations—both directly and indirectly—are discussed. First, we describe chemical insecticides, their efficacy, and the rationale for using them. We review and appraise biological agents, including viruses, bacteria, sex pheromones, insect hormones, and growth regulators. The option of indirect management of budworm through silviculture is discussed. Finally, the concept of integrated pest management (IPM) is briefly introduced in the context of future management of budworm.

7.1 Chemical Insecticides

Patrick J. Shea and David G. Fellin

7.1.1 Past Insecticide Use

When either large- or small-scale insecticide spray programs are directed at any major forest pest, resource managers are faced with complex and difficult judgments. Decisions are often hampered because information on impacts of the pest on timber production may be limited or unavailable, and data on other resource values are often fragmentary or difficult to assess. Treatment responses and their longevity are difficult to predict, and the effectiveness of alternatives to insecticides are often not well described or verified.

At the beginning of western budworm outbreaks in the late 1940's and early 1950's, resource managers had two options: do nothing and hope the budworm would go away or take some action. Most managers realized, or at least strongly suspected, that the budworm would continue to infest these coniferous forests; the option of doing nothing seemed unacceptable. The only alternative under the second option was direct application of some chemical. Most managers selected this second option because DDT was available, cheap, and could be applied aerially (fig. 7-1). Chemical insecticides were first applied against western budworm in about 1930 on the Shoshone National Forest in Wyoming (fig. 7-2).

Figure 7-1—Aerial spraying of DDT over budworm-infested forests in Montana, 1955.

Figure 7-2—Ground spraying of lead arsenate and fish oil on budworm-infested trees with high-pressure equipment, Shoshone National Forest, WY, about 1930.

The first major aerial application of an insecticide to suppress western budworm took place in eastern Oregon in 1949, when 267,000 acres (108 000 ha) were treated with DDT. From then until 1966, more than 11 million acres (4.5 million ha) were aerially treated with insecticides—mainly DDT. Although most of the operational programs were centered in eastern Oregon and the northern Rockies (Idaho and Montana), significant budworm-infested acreage was also treated in Colorado, Wyoming, and New Mexico.

Discovery of undesirable and long-lasting environmental side effects of DDT during the 1960's eventually caused a reduction in its use against all forest insect pests. Forestry uses of DDT were cancelled by the Environmental Protection Agency (EPA) in December 1972 for all but strictly limited uses. Following a recommendation by the

President's Science Advisory Committee in 1963 that safer and less persistent insecticides should be sought, the Forest Service, Forest Insect Research, began testing insecticides belonging to the organophosphorous and carbamate groups to find suitable substitutes for DDT. This effort has led to EPA registration of several compounds for use against budworm.

The primary objective of the early insecticide applications against budworm was to reduce target populations as much as possible, thereby reducing growth loss and tree mortality. The hypothesis was that once populations were low, they would remain suppressed, alleviating the need for more applications or reducing the number of subsequent applications. During those early years, two different concepts of treatment were used, "entomological units" and "partial-unit control." Treating an entomological unit meant that an entire infestation or infested drainage would be treated to effect maximum population reduction. Under partial-unit control, the object was to treat only those infested host types where the probability of tree mortality appeared high.

From the late 1960's to the present, the use of chemical insecticides has become increasingly controversial, partly because of the changing value of the resource and concern about the use of toxic substances, but also because assessing effects of outbreaks has been difficult. Managers decide whether to intervene directly with chemical insecticides based on three primary considerations: whether the infestation is likely to disrupt short-term use of timber or long-term productivity—including recreation, wildlife, range, timber, and water; economic analysis, such as benefit-cost or net present value; and evaluation of the potential environmental effects of the insecticides being considered.

The results and effectiveness (at least as expressed by the percentage of population reduction) of many of the materials tested, or even those used operationally since testing, have been disappointing and often unsatisfactory. Although many of these materials seemed promising during laboratory testing, various logistical, meteorological, and biological problems reduced their effectiveness in actual use. The main problems appear to have been the relatively short-lived nature of the chemicals, intricate problems with timing and method of application, and adverse weather during or after application.

7.1.2 Chemical Insecticides Registered for Suppression of Western Budworm

The three major groups of insecticides now in use are the chlorinated hydrocarbons, organophosphorous compounds, and the carbamates. The chlorinated hydrocarbons, which include DDT, have long residual activity but are generally not acutely toxic to human beings. They accumulate in the fatty tissues of animals, however, and can build up through the food chain. Most organophosphorous compounds have high acute toxicity to human beings and other animals and are implicated in more pesticide poisonings than any other group. Organophosphorous compounds do not accumulate through the food chain; they tend to break down fairly rapidly so the potential for long-term environmental effects is minimal. The carbamates are a large group of insecticides that are only moderately persistent and vary greatly in their acute toxicity to human beings and other animals. Four chemical insecticides—acephate (Orthene), carbaryl (Sevin-4-oil), malathion, and mexacarbate (Zectran)—are currently registered for operational aerial application against the western budworm in the United States. Naled (Dibrom), resmethrin, and methomyl (Lannate) are also registered for ground application. In Canada, five chemical compounds are registered against western budworm: acephate, aminocarb (Matacil), carbaryl, fenitrothion, and trichlorfon (Dylox). Although only four insecticides are currently registered by EPA for use against western budworm, six are registered for use in the United States against eastern budworm and seven are registered by Agriculture Canada. Efforts are being made for joint registration in both countries to give forest managers greater latitude in the selection of environmentally acceptable and efficacious insecticides.

Acephate, formulated and marketed as Orthene (75 or 95 percent), is registered for use against western budworm and several other forest and agricultural pests. Acephate is an organophosphorous insecticide with only moderate acute toxicity to warm-blooded animals and a very low toxicity to fish and other aquatic organisms. Thus it is attractive for use near streams and lakes. Like all organophosphorous insecticides, acephate is a cholinesterase inhibitor of moderate persistence. Residues degrade fairly rapidly (4 to 15 days) and are not accumulated in the food chain. Acephate is manufactured as a soluble powder and thus is easily mixed, but it has an unpleasant odor.

Although field experiments and pilot projects at 1/2 lb/acre (560 g/ha) showed that acephate was effective in reducing budworm populations in Idaho and Montana, results from recent operational programs in Idaho and Oregon were less than desired. Unsatisfactory treatments may be explained in part by the fact that acephate is applied in water-based formulations, which makes careful selection of aircraft and specific procedures necessary to achieve an acceptable population reduction.

Carbaryl is a carbamate insecticide. Seven-4-oil is the most often used formulation. It is a fairly broad-spectrum insecticide that has been in use for over 20 years for suppression of numerous agricultural and forest-insect pests. Relatively nonpersistent, it acts by inhibiting cholinesterase activity. Like many carbamates, it is only moderately toxic to warm-blooded animals and presents little hazard to mammals and birds when used at the registered rate. In contrast, carbaryl is extremely toxic to fish, aquatic insects, and insect pollinators (wild and domestic).

Recently, carbaryl has become the insecticide of choice for budworm suppression. Several large operational programs have been conducted in Idaho, Oregon, Washington, and New Mexico over the last several years, most of which have been described as highly successful.

Mexacarbate is a carbamate insecticide recently reregistered for western budworm suppression and formulated as Zectran DB. Zectran was tested extensively in the late 1960's as a substitute for DDT. Economic considerations forced the original registrant to withdraw it from the marketplace. The compound has recently become available again, and it was used operationally in Oregon in 1983. It is highly toxic to western budworm, especially to sixth instars. Although toxic to bees, Zectran has a very low dermal toxicity to mammals and is nonpersistent, lasting only a few hours in full sunlight. It is further degraded by biological systems. Because it is so highly toxic to western budworm, Zectran can be used in very small amounts.

Malathion is an organophorous compound registered for suppression of budworm and many other insects. Although malathion is a cholinesterase inhibitor, it is less toxic to warm-blooded animals than most other organphosphorous compounds. The last major budworm project where malathion was used was in eastern Washington in 1976. Over 300,000 acres (121 000 ha) were treated at ultralow volume (ULV) 13 fl oz/acre (0.95 l/ha). Results were unsatisfactory, and malathion has not been used again in an operational program; further use is unlikely without additional testing.

Methomyl (Lannate) and naled (Dibrom) are organophosphorous compounds registered for ground use against western spruce budworm. They are toxic to fish, wildlife, and bees.

Aminocarb, an oil-soluble carbamate insecticide marketed as Matacil, is registered in Canada for eastern and western spruce budworm. Matacil has been extensively used in Eastern Canada since 1973, but only one field experiment has been conducted in the Western United States. It is considered very effective by Canadian users, is relatively inexpensive, and easy to formulate. Because the formulation is oil based, evaporation after release is of little consequence.

Trichlorfon, marketed as Dylox, is an organophosphorous insecticide registered for budworm suppression in Canada. It is extensively used in agriculture in both Canada and the United States. Field experiments and pilot tests of Dylox against the western budworm in the United States gave unsatisfactory population reduction.

Fenitrothion is a carbamate insecticide registered for budworm control in Canada; it is marketed as Accothion, Sumithion, Folithion, and Novathion. Used extensively for control of eastern budworm, fenitrothion can be formulated as either water emulsion or oil solution. A pilot test of fenitrothion conducted in Oregon against western budworm produced very poor results. If used correctly, fenitrothion has a fairly low toxicity to nontarget organisms, but errors in application—especially in the overlapping of swaths—can kill songbirds.

Recent tests in Montana have indicated that some insecticides showed promise for ground application, particularly for protecting seeds and cones. Early laboratory work showed that some insecticides can move systemically through plant tissues and might offer protection against early instars feeding in buds, developing shoots, and cones. Ground-spray techniques have been described (Stipe 1984, Stipe and Green 1981).

Ground tests of acephate and carbaryl showed that a single treatment after flowering would be effective if the primary objective were foliage protection. A single application increased seed production slightly. Tests in 1980 showed that double and triple applications not only provided excellent foliage protection but seed production significantly increased.

Systemic insecticides have been tested by implantation into tree trunks before budburst. Tests using Orthene Medicaps showed high population reduction and high foliage protection. An orthene implant is currently registered. Injection and implantation techniques have been described (Reardon 1984). Implantation is appealing because the toxic materials are introduced directly into the tree.

7.1.3 Project Planning, Evaluation, and Environmental Monitoring

Planning an aerial application program is a complex undertaking with no set guidelines. Each agency or region has its own planning procedure and organizational structure, but many common biological considerations must be addressed when suppression projects are contemplated.

Monitoring of budworm populations precedes insecticide application. Aerial surveys are conducted to delineate potential treatment areas by mapping defoliation. Defoliation is usually characterized as light, medium, or heavy. Egg-mass sampling is conducted to obtain additional information on populations in the defoliated areas mapped by aerial surveys. The information is used to determine whether the current budworm population warrants treatment and to establish the boundaries of the outbreak.

As time for application nears, monitoring of target populations has a different objective—to assure that application of the insecticide coincides with the most vulnerable larval stage. Insecticides are applied when most of the larvae are in the fourth or fifth instar. Postspray evaluations are conducted to evaluate the effectiveness of the application; they usually estimate population reduction (percent mortality or survival) and degree of foliage protection. Foliage protection can be evaluated by branch sampling and counting destroyed versus viable buds. More often, however, postspray aerial surveys are used for a subjective judgment on whether significant foliage was saved.

Because most registered insecticides have undergone rigorous and extensive safety testing, environmental monitoring for nontarget effects in operational programs is done only as a safeguard against unexpected events. Selection of nontarget faunal groups to monitor depends on the chemical and physical properties of the insecticide used, assessment of hazard in previous studies, and laboratory evaluation of potential acute and chronic effects.

Environmental monitoring efforts must be an integral part of the overall operational program. The success of the spray treatments for suppression of the target insect can be weighed against effects on nontarget fauna.

Safe use of pesticides is of paramount importance. Safety and spill-contingency plans are required for every project, and mitigation procedures are included in environmental documents and work plans. Several safety manuals specific to pesticide use and management are available (Singer 1978, Stimmon 1977).

7.2 Biological Agents

David G. Fellin and Patrick J. Shea

Interest in biological insecticides has increased greatly in recent years, stimulated largely by some undesirable side effects of chemical sprays and a public concern about the use of chemicals in general. Biological agents that have received attention in the laboratory and field are bacteria (principally *Bacillus thuringiensis* Berliner), viruses, pheromones, growth regulators, antifeedants, nematodes, protozoa, and entomopathogenic fungi.

7.2.1 *Bacillus thuringiensis*

Bacillus thuringiensis (B.t.) is a naturally occurring aerobic, spore- and crystal-forming pathogen. Once a larva ingests B.t. the interaction of digestive juices with the crystals and spores ruptures the gut wall. Action is fairly quick in that feeding ceases within a few hours after ingestion, although affected insects may not die for several days.

Smirnoff's (1983) biochemical analyses have shown that B.t. treatments had a detrimental effect on the vigor of eastern spruce budworm after treatment. Conversely, he found that chemical insecticides (organophosphates and carbamates) encouraged the resurgence of vigorous populations, as a result of stimulation of the budworm by sublethal dosages.

Several formulations of B.t.—Bactospeine, Dipel, Futura, Sok–Bt, and Thuricide—have been registered for use against budworm in Canada and the United States. The popularity of B.t. has varied because the results of past tests have been inconsistent and costs have been high compared to chemical insecticides. Costs have dropped, however, and recent tests have shown that B.t. can be effective at higher dosages.

B.t. is especially useful in and around sensitive areas and where off-target drift is unacceptable, where other pesticides are restricted, and where no treatment would be the only other alternative. An important attribute of registered formulations of B.t. is that their mode of action on the target insect is like a chemical insecticide—that is, they are effective when applied, but infections do not continue from one generation to the next. A large pilot test was conducted in northern New Mexico in 1981, using Dipel 4L and Thuricide 16B. This test resulted in conclusions and recommendations for improving mixing, aerial application, and postspray-sampling procedures (Ragenovich 1983):

> B.t. provided sufficient control to keep budworm populations at a low level for two years. Timing and weather can affect the results of B.t.; however, under controlled conditions, the material gives acceptable results and should be considered for use in conjunction with a chemical pesticide in operational projects.

7.2.2 Viruses

Viruses have the desirable characteristics of being host specific and remaining infectious long after being introduced into the ecosystem. Two types of virus found in budworm populations—nucleopolyhedrosis virus (NPV) and granulosis virus (GV)—have been investigated. Both kill budworm in the laboratory, but their performance in field tests has been inconsistent. Some degree of foliage protection has been obtained in the field, but population reduction has been well below operational goals.

Research on improving efficacy of virus will likely continue, but prospects for an effective formulation soon are dim. Production of virus is labor intensive and costly. For example, 7,500 larvae were required to produce the dosage used to treat 2.5 acres (1 ha) in a Canadian spray test. Also, the virulence of current strains is less than desirable.

7.2.3 Pheromones

Female budworms produce a pheromone that attracts males. The pheromone has been synthesized for both eastern and western budworm and presents opportunities for population assessment and manipulation. Heavy concentrations of the pheromone in the atmosphere could disrupt the ability of males to find females. This phenomenon could, in turn, affect numbers in the next generation. Preliminary tests have shown enough promise to encourage further testing.

7.2.4 Insect Growth Regulators

Insect growth regulators (IGR's) are hormones or hormonal mimics that disrupt the metamorphosis of insects. Juvenile hormone analogues and molt inhibitors have been tested, and research in Canada and the United States suggests such compounds have potential in budworm management. Nevertheless, several problems remain to be investigated. Although they are more target-specific than chemical insecticides, a serious shortcoming of the IGR's is that they are not specific to the target species; they could adversely affect nontarget arthropods, including budworm predators and parasites. They would thus be less acceptable than the host-specific bacteria, viruses, and sex attractants.

7.2.5 Future of Biological Agents

B.t. is receiving considerable research attention and will likely become more reliable and widely used. Besides its recently improved efficacy, it is commercially available in large quantities, fairly cheap, and environmentally safe. Because of environmental concerns about chemical insecticides, research on the biologicals will doubtless continue; pheromones are currently being studied extensively. Availability of the others is unlikely for operational use within the next decade. Even when efficacy is established, testing for safety requires considerable time before registration.

7.3 Effectiveness of Direct Suppression

After any direct treatment, knowing whether the treatment was effective is essential; so is some indication of how long the effects can be expected to last. Many past spray programs are believed to have brought outbreaks to a close, but success for others has been short lived.

Effectiveness of treatment has often varied by forest and site conditions. In western Montana, the best results of spraying—where efforts appeared to have a more persistent effect—were on good growing sites and in mixed stands that generally are not inherently very susceptible to western budworm. Poorest results were achieved in areas of dry sites and marginal timber—usually south and east exposures—where defoliation was heaviest and the incidence of tree mortality was greatest.

Resource managers in Oregon and Washington consider the large-scale aerial spray programs between 1949 and 1962 highly successful. Over that period, larval populations were reduced from 96 to 99 percent and damage to the forest resource was minimized. More important, and in contrast to experience over about the same years in the northern U.S. Rocky Mountains, less than 1 percent of the areas sprayed between 1946 and 1956 had to be retreated. No retreatment was necessary in areas treated between 1958 and 1962.

In New Mexico, several programs have been conducted since 1977, the most recent in 1983. Part of the plan in 1977 called for monitoring budworm populations for several years after spray applications to obtain information on how long the treated population would stay low. Each year since, egg-mass and defoliation samples have been obtained from treated and adjacent untreated areas. Results indicate that the budworm populations in the treated areas remain significantly lower than the untreated ones.

A 1/2-million-acre (0.2-million-ha) spray program in 1964 in Idaho was reported to be responsible for sudden reductions in both intensity of defoliation and size of infested area. One year later, however, budworm populations had built up rapidly.

In the northern Rocky Mountains of the United States, managers realized early that repeat treatments were often necessary to keep budworm populations at tolerable levels. Of 22 entomological units on 9 National Forests treated between 1952 and 1957, half were entirely or partially resprayed during that period despite high mortality from spray programs. Repeat treatments were necessary because treated areas became reinfested, either from unsprayed infested forests, from areas missed, or from resurgence of survivors in treated areas. By 1965, the entire outbreak area, including the areas treated in the mid-1950's, was reinfested to outbreak densities.

DDT was never used against western budworm in Western Canada; moreover, no suppression programs have used DDT or any other insecticide against the Modoc, 2-year-cycle, or other (non-*occidentalis*) budworm species in the West. All outbreaks of these species have subsided naturally before significant damage occurred.

Operational spraying to suppress western budworm has increased markedly since 1974. In the last several years, resource managers have treated more than 1 million acres (400 000 ha), mostly in Oregon, Washington, and New Mexico, with lesser amounts in Idaho. Carbaryl has performed most consistently and achieved significantly high population reductions. Successful operational programs, primarily using carbaryl, were conducted in Oregon and Washington in 1976, 1977, 1982, and 1983. Area sprayed in the 1983 program approached 500,000 acres (200 000 ha).

Susceptible forests can sometimes be protected by direct suppression treatment, but such treatment will not change their susceptibility; forest managers are therefore interested in conditions that cause susceptibility and management strategies that can lessen it.

7.4 Silvicultural Treatment

Clinton E. Carlson, Wyman C. Schmidt, and N. William Wulf

7.4.1 Introduction

From analyses of historical records of conditions in forests where outbreaks have occurred, studies of the factors affecting budworm development and survival, new research on ecological relations of budworm and its habitat, and our experience, we believe that prescribed silvicultural treatment can reduce stand and forest susceptibility to western budworm. Mortality of dispersing larvae can be increased, foliage quality can be rendered less favorable to budworm, sites for egg deposition can be reduced, and habitat for predators can be increased. Less hospitable habitat for budworm can be created by altering species composition, changing stand density and vertical structure, and regulating the pattern of harvest.

The expected effectiveness of silvicultural remedies needs to be viewed relative to time and space. Treatment of a given stand may provide immediate protection for that stand, but will have little influence on a forestwide outbreak. Over time, enough stands can be treated over an extensive land base and forest susceptibility can be reduced such that a budworm outbreak might not be supported. We discuss silvicultural practices that we believe will reduce susceptibility in mature and immature forests.

In this discussion, the new stand after a regeneration cut is composed of seedlings and saplings, immature stands have pole-sized trees, and mature stands have fully mature dominant and codominant trees.

7.4.2 Treatments for Mature Stands

Mature stands should be rated for susceptibility (see chapter 6). Ranking the stands will give the silviculturist a starting point for setting treatment priority. Inspecting the data used to rate susceptibility of a stand quickly indicates which factors contribute most to the rating; appropriate treatment can then be logically prescribed.

7.4.2.1 Even-Aged Silvicultural Methods—Even-aged regeneration methods—so called because the primary objective is to establish a new, even-aged stand of conifers—are particularly effective for reducing forest and stand susceptibility to budworm. The methods used—clearcut, seed-tree, and shelterwood—are differentiated by the amount of residual stand left after the initial harvest (fig. 7-3). Clearcutting (fig. 7-4, top) leaves no residual stand, seed-tree (fig. 7-4, bottom) leaves about 1 to 10 percent of stand basal area, and shelterwood, 25 to 75 percent. Those trees left after initial cutting in the seed-tree

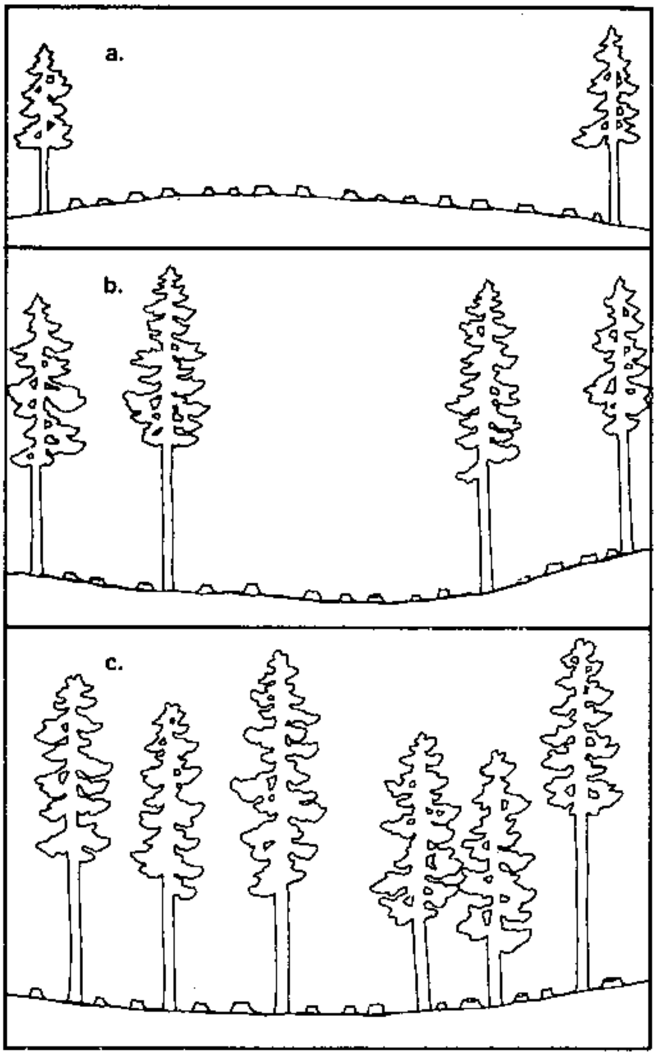

Figure 7-3—Comparison of clearcut (a), seed-tree (b), and shelterwood (c) harvest regeneration methods.

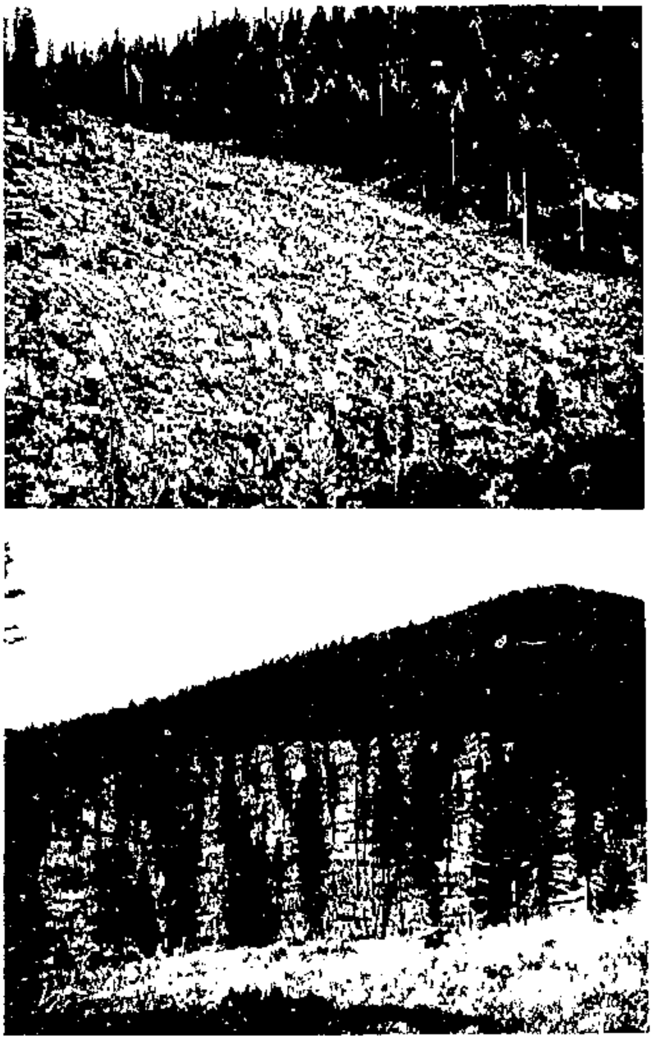

Figure 7-4—Even-aged methods such as clearcuts (top) and seed-tree cuts (bottom) create conditions unsuitable for budworm. Mortality of dispersing larvae is increased, predation of larvae on small trees is enhanced, and seral species not favored by budworm usually are established after the harvest.

and shelterwood methods are removed once regeneration is established.

The choice of which type of regeneration method to apply depends first on the physical and ecological factors peculiar to the site. For example, a clearcut (fig. 7-4, top) may be a good choice for a relatively moist, cool site—such as a stand with north aspect in the subalpine fir forest climax series—but a shelterwood would be more appropriate for a south-facing stand in the dry, Douglas-fir series.

Within these ecological constraints, considerable latitude is available to minimize future stand susceptibility to budworm and to optimize stand growth. Current research conducted in the northern Rocky Mountains of the United States strongly suggests silvicultural treatment is a superior tool for dealing with the budworm. Detailed measurements were made in 166 stands 5 to 20 years old regenerated through silvicultural systems appropriate to specific site and stand conditions. The adjacent, mature, uncut stands were susceptible to the budworm. Defoliation of host regeneration (budworm hosts) within the cutting units was low and seldom exceeded 25 percent of the current year's growth. The regeneration was usually composed of fast-growing, shade-intolerant, even-aged, seral, conifer species. Current-leader growth and 5-year periodic height growth of small trees were seldom affected by the minor amount of budworm feeding, even though the surrounding mature forest was highly susceptible and budworms fed heavily on it.

Several factors can be regulated to reduce stand susceptibility to budworm. Species composition; density and height-class structure of the residual and new stands; and size, shape, topographic position, and spatial relation of the cutting units all can be manipulated. Suggestions for regulating these factors and reducing budworm susceptibility associated with the three types of regeneration cuts apply equally to the clearcut, seed tree, and shelterwood systems and are discussed together below.

Residual Stand—Overstory remaining the first 10 years after a seed-tree or a shelterwood cut will generally not be a liability to newly developing seedlings. Budworm will infest residual host trees and larval dispersal will occur, but most of the dispersing larvae will be lost. After 10 years or so, the overstory can be a significant factor in distributing budworm larvae to the new stand. Studies in Idaho showed that defoliation in the advanced regeneration decreased as additional overstory was removed.

Choice of overstory tree species remaining will influence species composition in the new stand. The overstory should be removed promptly once the silvicultural objectives have been met, at least within 10 years after the original cut. New seedlings—the subsequent regeneration—should have been established by this time and will be large enough that they are a better target (that is, more susceptible to dispersing larvae). Overstory removal to some extent will reduce numbers of dispersing larvae and will encourage rapid, vigorous growth of the new stand.

New Stand (Seedlings and Saplings)—Susceptibility of the new stand can be reduced by manipulating the following attributes:

• Species composition—Regulating species composition can change stand susceptibility. In most stands, at least two and, in many, up to eight conifer species may be adapted to a site. A good mix of seral species should be established soon after cutting. We believe that climax budworm-host species should comprise not more than about one-third of the stand.

Fast-growing seral host species in a given habitat type usually are the least susceptible to budworm (fig. 7-5).

Figure 7-5—Thrifty, seral Douglas-fir established after a clearcut on a grand fir habitat type are not seriously affected by budworm.

The least shade-tolerant species suited for a particular habitat type are apparently the least susceptible to budworm. Relative shade tolerance is difficult to determine, may differ geographically and by successional status, and be influenced by various ecological factors. Our ranking of budworm hosts (from least to most shade tolerant), however, is in the same order we have observed in budworm feeding preference: western larch, interior Douglas-fir, Engelmann spruce, grand or white fir, and subalpine fir. Pines are seldom injured by budworm; they are also relatively shade intolerant.

• Stand density—Density of the developing stand should be maintained such that the small trees receive optimal light and are subjected to minimal water stress. High densities of host species offer a larger target area for larval interception during dispersal, which will benefit the insect, not the stand. High tree densities can produce water stress and increase the biochemical susceptibility of Douglas-fir in older stands; similar relations may operate for small trees. Depending on site conditions and seedling distribution, optimal density would be from 300 to 600 seedlings per acre (740 to 1,480/ha) at a stand age of 10 years.

• Planting may be required to establish the new stand because budworm can reduce natural regeneration significantly if the harvest is scheduled for the drier Douglas-fir habitat types during a budworm outbreak. Probability of adequate stocking with natural seedlings may be significantly reduced because the budworm feeds not only on foliage but also on the cone and seed crop needed for natural regeneration. The probability of inadequate natural regeneration is not as likely in the moist grand fir, cedar, and subalpine fir habitat types, however, because nonhost species contribute a much greater proportion of seed for the new stand.

• Stand height-class structure—In stands 20 years old, some vertical structure has developed. The lower strata are usually composed of shade-tolerant species. This canopy stratification provides secondary feeding sites for larvae that disperse from adjacent mature stands or the tallest stratum of the new stand. Stand susceptibility can be reduced by removing hosts from the lower shade-tolerant, susceptible strata. Structure in these younger stands is less important than in pole-sized stands.

• Unit size, configuration, and spatial relations—Stand susceptibility to budworm decreases with increasing size of the cutting unit. Meager information is available on dispersal distance of small larvae, but some information indicates that larval densities decrease with increasing distance from the stand boundary. Adult male budworms were caught more frequently at the edges of cut units than near the center. Thus, the area of a cutting unit should be maximized relative to the stand perimeter, recognizing other management constraints.

Mosaics of varying stand conditions may be appropriate to reduce drainagewide susceptibility. This may also protect watershed values, provide adequate stand diversity for birds and other budworm predators, and enhance habitat for big game.

A regeneration harvest immediately reduces susceptibility on the acreage treated but probably has little effect on a general budworm outbreak. The general outbreak presumably can be weakened by developing drainagewide mosaics of thrifty stands with low susceptibility to budworm. This process will take at least a rotation to implement. Some short-term effects may be gained by concentrating harvest in drainages with large, contiguous areas of a climax host type.

Planning to reduce forest susceptibility should place priority on harvesting stands most susceptible to the budworm and regenerating those sites to thrifty, fast-growing, relatively shade-intolerant species. Available stand inventories can be used to classify stands into budworm-susceptibility groups such as high, medium, and low, based on the susceptibility rating mentioned earlier, and harvest schedules should at least consider the rankings.

7.4.2.2 Uneven-Aged Silvicultural Methods—Uneven-aged management in host cover or habitat types can increase stand susceptibility to the budworm. Group selection or single-tree selection in the absence of ground fire tends to promote development of multistoried, laddered stands with shade-tolerant, budworm-susceptible understory species. Group selection, however, provides more opportunity to control species composition than does single-tree selection. Shade-tolerant species in a multilayered canopy usually grow slower than shade-intolerant seral species would under even-aged conditions on the same site. Also, most of these stands are overstocked, stressed, and of low vigor, further increasing their susceptibility.

Selection harvesting combined with judicious use of fire could be compatible with sound budworm management on some habitat types. Light ground fire after a selection harvest on sites where Douglas-fir is climax may prepare the site for seral species and eliminate unwanted advance shade-tolerant regeneration. Proper fire intensity will prepare the seedbed for shade-intolerant species such as ponderosa pine or western larch. Provided that harvesting was heavy enough to allow nearly full sunlight to the forest floor, the seral species should develop well. This procedure mimics the role of natural fire in the Douglas-fir series. Uneven-aged, relatively open stands of ponderosa pine with scattered Douglas-fir would be relatively nonsusceptible to budworm and may satisfy other management objectives.

7.4.2.3 Salvage Cutting in Mature Stands—Salvage cutting of dead or badly damaged host trees may be appropriate for reducing some stand-volume losses. Because budworm damage and mortality often is greatest in the smaller suppressed and intermediate crown classes, however, loss recovery may not be economically feasible. Also, highly vulnerable stands may occur on arid, rocky, south-facing exposures where timber values are marginal even without budworm; and salvage may be a questionable option. Salvage cutting will not reduce stand susceptibility to budworm, and future losses in susceptible mature stands can be expected until final harvest.

Figure 7-6—Thinning second-growth stands 20 to 80 years old will reduce stand susceptibility to western spruce budworm. Radial growth rate in this stand doubled after thinning, and defoliation of host trees was reduced from 60 percent before thinning to 25 percent after treatment.

7.4.3 Treatments of Pole-Sized, Immature Stands

Intermediate cuttings, such as thinning or removing undesirable trees (weeding), represent an opportunity to regulate composition and growth of a stand as it matures (fig. 7-6). The sequence and design of these intermediate treatments should be planned to maintain high individual-tree vigor and seral composition of the stand. The residual stand density prescribed for each cutting must be contingent on planned subsequent cuttings, so that intertree competition does not become severe for an extended period. Maximizing the growth rate of individual trees at the expense of stand growth is inadvisable because the reduction of budworm impact is not likely to be worthwhile.

Release and precommercial thinning treatments should retain the seral, more rapidly growing trees at a density that will not allow mean annual increment to decline before the next harvest. Density of young stands of western larch has been shown to influence feeding on budworm. At low budworm populations, a higher percentage of crop trees were injured at low stand densities than in unthinned stands. At high budworm densities, however, no difference occurred in the percentage of trees damaged in relation to stand density; later the recovery of height growth was more rapid in the low-density stands.

Thinning can affect budworm populations and damage. An eastern study compared budworm on stands thinned from above to two densities with similar untreated stands. In general, as residual density decreased, so did defoliation. In another study, a combination of thinning and fertilizing increased stand susceptibility to eastern budworm. Larvae developed faster in the treated stand; because the treatment can increase canopy temperatures, survival of large larvae is favored and new foliage biomass is increased, prompting more egg laying.

Thinnings allow more sunlight into the canopy, which favors survival of larvae. The more open stand, however, should increase mortality during dispersal of small larvae. A subsequent increase in tree vigor should also become detrimental to all larvae. Thinning from above is not usually advisable and, of any thinning method, would be the most likely to fail to prevent budworm damage. Unless understory stocking is altered, dispersal mortality may not be strongly affected. The trees in the lower crown classes are more shade tolerant, less likely to respond to release, and inherently more susceptible. Thinning from below has the advantage of minimizing increases in canopy temperature while maximizing subsequent tree vigor and mortality of small larvae. Free thinnings—favoring only the trees considered most suitable to form the final crop, in whatever layer of the canopy they may be found, and leaving the rest of the forest crop unthinned—can also be used to maintain an even canopy structure.

Implementation of silvicultural strategies for managing forests with budworm problems is highly desirable. Priorities should be set according to economic criteria; correct silvicultural procedures can then be prescribed. Systematic reduction of the susceptibility of stands can reduce the likelihood of large-scale outbreaks, and should be incorporated into forest planning. With the use of insecticides for selected resource protection, these silvicultural strategies form the basis for a truly integrated plan for budworm.

7.4.4 Demonstration Areas

Four demonstration areas have been established in the West for evaluating effects of silvicultural techniques on budworm defoliation:

Region	*National Forest*	*Ranger District*
Northern	Lolo	Ninemile
Northern	Gallatin	Bozeman
Southwest	Carson	Taos
Intermountain	Payette	McCall

The areas will be used by both researchers and forest managers to test and illustrate silvicultural practices in various forest types.

One demonstration area in the Carson National Forest in New Mexico will compare these silvicultural treatments: clearcutting with planting, shelterwood seed-step cutting with protection of advance regeneration, and shelterwood final-removal cutting. One untreated area has been left as a check unit.

Budworm will be sampled annually, and stands will be examined at 2-year intervals. Silvicultural treatments will be evaluated by comparing species composition, stand structure, growth rate, and incidence of budworm damage between treatment units. Future observations will provide insight into the feasibility of applying recommended silvicultural strategies for budworm management on mixed-conifer sites in the Southwest.

7.5 Integrated Pest Management

David G. Fellin and Patrick J. Shea

Integrated pest management (IPM) has been accepted as Forest Service policy for coping with destructive forest insects (Forest Service Manual 3400). It has been defined (USDA Forest Service 1982) as

> A process for selecting strategies to regulate forest pests in which all aspects of a pest-host system are studied and weighed. The information considered in selecting appropriate strategies includes the impact of the unregulated pest population on various resource values, alternative regulatory tactics and strategies, and benefit/cost estimates for these alternative strategies. Regulatory strategies are based on sound silvicultural practices and ecology of the pest-host system and consist of a combination of tactics such as timber stand improvement plus selected use of pesticides. A basic principle in the choice of strategy is that it be ecologically compatible or acceptable.

Forest managers will soon have several treatment alternatives to chemical insecticides for managing budworm. Operational treatments with biological agents are desirable because most pathogenic microorganisms are highly specific and environmentally acceptable. Although one, B.t., is already being applied, many merely show promise.

Silvicultural treatment can be used effectively to reduce forest and stand susceptibility to the budworm. The value of this approach is that most commercial forests will be subjected to some silvicultural manipulations to meet management objectives and deal with other pests—even without budworm outbreaks. Thus, managers can select the combinations of silvicultural treatments that are best ecologically and least favorable to the budworm to lessen the chance of an outbreak.

For mature budworm-susceptible forests, even-aged management may be appropriate, but other strategies should also be assessed. Specific site conditions, alternative resource values, economics, and other factors must be considered by the managers before decisions are made. Even-aged strategies do appear to be particularly effective against the budworm, although they may not be best in all stands or under all conditions.

To counteract the budworm, clearcut, seed-tree, and shelterwood systems should be favored. Planting should provide optimal mixes of species; no more than one-third of the total number of trees should be shade-tolerant species on a given site. Stands should be thinned periodically to maintain vigor and desirable species composition. Practices that encourage establishment and development of shade-tolerant conifers almost surely will lead to a stand susceptible to budworm. Valid techniques include creating buffer zones of nonhost species and increasing the size of cutting units.

Although not addressed directly, fire, both wild and prescribed, will undoubtedly play an increasingly important role in budworm management. Recent let-burn policies and prescribed burning of the understory—although not currently done specifically to reduce budworm—may effectively reduce the tolerant understory-tree component of the forest and, consequently, some of the host material for the budworm.

Integrated pest management is the most desirable approach. In the short term, new-generation insecticides, perhaps in combination with conventional materials, can be applied to limited areas to help meet specific management goals by reducing populations and subsequent impact, and the forests can be treated silviculturally at the same time to create a more favorable environment for trees, predators, and parasites, and a less favorable environment for the budworm in the long term.

Chapter 8
Selecting Management Tactics

Albert R. Stage, Ralph Johnson, and J. J. Colbert

The result of the process of picking and choosing among forest-management alternatives is one product for which forest land managers are paid. Raw materials for this product are resource data, values, and ideas. The manager's production tools are models of the ecosystem being managed and procedures for comparing alternatives available for choice. This chapter suggests how managers might use these tools to make decisions about treatments of trees and stands where budworm management considerations may influence that choice.

8.1 Decisions

Decisions may be expressed either as policies or as prescriptions. Policies specify what will be done when and if some condition arises. Prescriptions for treatment, on the other hand, specify time, place, and method. For example, a policy for stand-density control might specify thinning Douglas-fir stands in *Abies grandis/Pachistima* habitats whenever density exceeds 140 ft^2/acre (32 m^2/ha) of basal area. By contrast, a density prescription would designate stand number 519-3-6 for removal of the marked trees in the fall of 1987. A pest-suppression policy might specify reducing budworm density in young sawtimber stands on high site-quality land whenever density exceeds 20 larvae per 100 buds. The consequent prescription might call for application of *Bacillus thuringiensis* at 8 BIU/acre (20 BIU/ha) at the fourth instar during 1984.

Assume that policies for management have already been decided. Here we will discuss how to choose prescriptions within the context of a set of policies. The scope of the prescription covers treatments of individual trees or stands through their period of development or of groups of stands that will be treated together.

Decisionmakers who should find these procedures useful might range from the owner of a valued residential shade tree threatened by budworm to the forester prescribing for regeneration of a stand to be harvested for timber production.

8.2 Steps in the Decisionmaking Process

Decisionmaking is a highly personal process with as many approaches as there are managers who decide. For the kinds of decisions that are strongly guided by experience with similar situations, a structure for the process can be provided. Tools for objectively evaluating many, but not all, facets of the problem may be a part of this structure. Using the structure set forth should assist the decisionmaker, but will not designate one "best" course of action. Indeed, were it possible to do so would mean that no decision was required—only data processing.

The decisionmaking process includes the following steps:

- Sense that a problem exists or may develop;
- Describe what the land is to be used for (that is, what are you trying to produce);
- Find alternative ways to alleviate the problem;
- Collect or assemble data necessary for predicting the consequences to the production objectives of doing each of those alternatives;
- Predict the consequences of doing the alternatives;
- Compare the consequences and choose the "best" alternative; and
- See if your predictions come true.

8.2.1 Sense the Problem

The first step is to detect that a problem exists or can develop and that some action may be required if the management goals are to be met. Problem detection may be as simple as knowing the local history of the budworm as it relates to something you plan to do. For example, suppose you wish to install a Douglas-fir seed orchard and have a choice between two drainages. One drainage has historically been infested with budworms, but the other has been free of budworms. By perceiving that history of the budworm is relevant to the choice of location, you have sensed the problem.

Monitoring systems may range from simple, unplanned observation to formal pest surveys. In either case, the problem should be detected with sufficient lead time to solve it efficiently.

8.2.2 Describe Land Use

After a possible problem related to the budworms is detected, the next step is to describe the values and uses of the property that might be affected by budworm damage. If timber values are at stake, we need to know the role of these stands in the long-range timber production plan. At the other end of the spectrum, the trees in jeopardy may be valued for their esthetic attributes in a campground or homesite.

8.2.3 Assemble Relevant Options

Gathering ideas about actions to alleviate the problem is the next step. Staff specialists in the manager's organization, books of this series, and related CANUSA publications should be consulted as guides to possible alternatives. At this step, all possible options should be considered, including the option of doing nothing. Dropping an option from further consideration should be avoided unless that option is clearly inferior to another in all relevant respects. What is relevant, of course, depends on the values previously identified.

8.2.4 Define Data Needs and Conduct Inventory

Two steps remain before an option is to be chosen. Forecasts will be required of how the several options will each change the values of the resources. These forecasts may require additional information. If timber-yield forecasts are appropriate, is a stand inventory available on which to base the forecast? What additional data about the budworm population are needed? If a seed orchard is at risk, the relevant data would describe whether or not current reproductive buds are present that need to be protected.

8.2.5 Forecast Outcomes

Forecasting the consequences of proposed management actions is the most technically demanding step of the process. At this step, we need to use all the scientific information and technical experience that are relevant. Qualitative expectations about effects as well as quantitative forecasts of future consequences will be needed. Times spanned by the forecasts should be long enough to demonstrate the full effects of proposed actions.

The decision-support system for western spruce budworm includes a series of simulation models that can be used to project the course of a budworm infestation and the impact of defoliation on forest stands over time. Economic models translate these projections into units appropriate to the resource desired. The Budworm Model simulates the dynamics of a population, beginning at the stage sampled, for that generation, and then estimates the size and dynamics of succeeding generations. Host-foliage growth is also projected; the amount of defoliation over time depends on changes in population density (see chapter 2). Similar models are available for the Douglas-fir tussock moth and the mountain pine beetle. For information, contact the nearest USDA Forest Service Forest Pest Management (FPM) Unit or Intermountain Forest and Range Experiment Station, Moscow, ID 83843, or State FPM specialists.

The Budworm Model is linked to the Prognosis Model, which simulates forest growth. The Prognosis Model produces growth and yield tables and forecasts stand development in the presence of budworm by simulating growth and mortality of individual tree samples. It is based on standard inventory data routinely gathered from the forests where it is to be used. This model was developed explicitly for forest planning. Although developed before CANUSA, the program has contributed to its refinement and applications.

The linkage of budworm population and defoliation models with the Prognosis Model permits estimation and forecasting of the effect of budworm defoliation on growth loss, top-kill, and stand mortality in mature stands; regeneration establishment; and the effect on growth and structure of immature stands. Routines have been developed that permit combining stand projections for providing forestwide or watershedwide coverage.

8.2.6 Choosing the Best Course of Action

Choosing the best of the alternatives is where the decisionmakers earn their keep. Future effects are seldom forecast in comparable units. Timber yields may be affected differently than are wildlife or watershed values. Although economic analysis may help evaluate incommensurate outcomes, the final decision is usually a matter of judgment rather than arithmetic.

If all outcomes could be evaluated with certainty and in the same units—whether in money, boards, or foliage—then simple enumeration of the value of each course of action would suffice. Not only is that seldom true, but we find that each major decision may entail several related, dependent decisions. For example, selecting a silvicultural prescription may, in turn, generate the need to decide on the size of the sample and the tree attributes to be recorded in the stand.

To assist in evaluation of sequential actions with uncertain outcomes, decision trees have been found useful (Stage 1975, Talerico and others 1978). Each alternative action is represented by a branch coming from a decision node. The node will have a branch for each discrete alternative. Consecutive decisions are represented by a branch coming into a node from which several new branches emanate.

Figure 8-1 shows a decision tree for a sequence of three typical pest-management decisions.

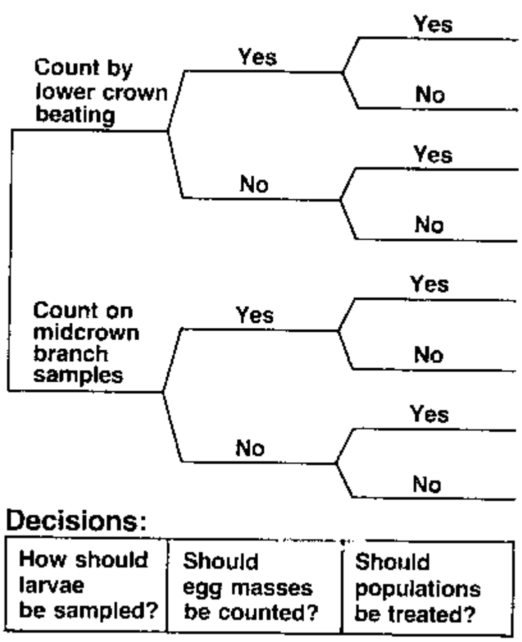

Figure 8-1—Decision tree for sampling and treating budworm populations.

In the decision tree, alternative intensities of budworm inventory are followed by a direct-suppression decision. In this example, the initial detection of a high pest population in turn triggers a subsequent examination of proposed treatment areas to verify the pest status as close as possible to the time of treatment.

This example decision tree is incomplete because it does not show responses of the opponent in this management game—nature. For each management action, the ecosystem may respond in one of several ways. When the considered action is sampling, the responses are the sample means and variances. When the considered action is a treatment, the responses are the actual outcomes—the true effects on the population. These true effects may, of course, differ from the intended effects because of natural variation in efficacy. Recognizing and dealing with the fact that natural systems do not respond exactly as predicted is a crucial part of natural-resource decisionmaking. To complete the decision tree, additional nodes are inserted between pairs of management decisions (fig. 8-2). These nodes are the origin of branches representing the range of variation of expected responses by the ecosystem. They are, in effect, nature's decision nodes.

The last node of the decision tree represents the forecast of the consequences of all the managerial decisions represented by the branches leading up to this node. Branches from this node represent differing forecasts of forest conditions. A probability value is associated with each forecast branch. This probability represents the likelihood that the presumed conditions are indeed true. Weighted averages of the forecasts for each sequence of decisions are calculated next, by using the probabilities as weights. These averages can be calculated for decision trees describing both silvicultural and budworm treatments by using the Parallel-Processing Extension of the Prognosis Model. The result is a list of alternative decision paths associated with an average outcome in terms of benefits and costs accrued by following that decision path.

The decisionmaker can review this list to choose the most appropriate action sequence. The review should also consider each of the individual outcomes, however, to determine the degree of risk associated with the average forecasts. Some outcomes may be so undesirable that they should be avoided even though their probabilities are not very high. Differing attitudes toward taking risks can lead managers to choose different sets of actions for the same situation.

8.2.7 Monitoring

The final step is to monitor execution of the selected actions. Was the chosen path through the decision tree followed? And were the outcomes as expected? The first question establishes a basis for managerial accountability. The second question establishes nature's responses at its nodes in the decision tree. Outcomes should be objectively described and recorded—both in terms of what was done and the environmental events that actually transpired. Only then can we learn from both successes and mistakes—and refine the next decision.

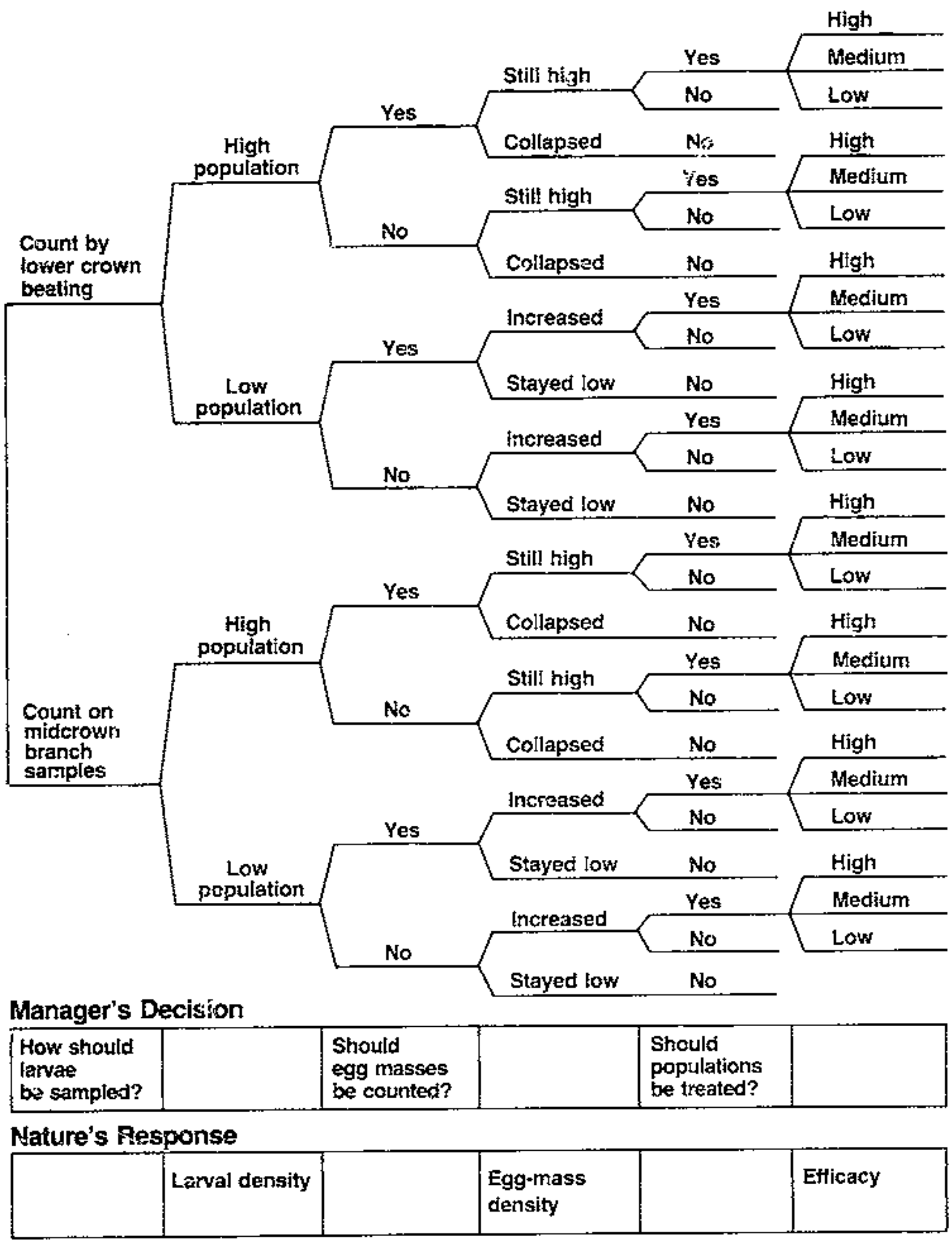

Figure 8-2—Same decision tree as figure 8-1, but including nature's random responses.

8.3 Case Study Examples

These steps will be illustrated in the following case examples chosen to include the use of various tools in the decision-support system of CANUSA-West.

8.3.1 Example One

For our first example, suppose we are in the Spider Creek drainage in southwest Montana. The stand we have to manage is composed of overmature Douglas-fir on a Douglas-fir/ninebark habitat. The aspect is southwest. The long-range plan for the area indicates we are to harvest this stand and regenerate it within 10 years. The site is such that newly established seedlings will need some protection, perhaps from a shelterwood. Besides being old, the stand is moderately infected with dwarf mistletoe.

The first step in the decision process is to establish that a problem exists. In this example, historical maps show Spider Creek was defoliated in past outbreaks with intervals of 10 to 15 years between episodes. Hazard calculated for this stand rates it highly susceptible. Although neither the historical maps nor the hazard rating is a perfect indicator that a problem exists, they serve to alert the manager to that possibility.

The second step is to define what we are to produce from the site. Once again the long-range plan is consulted. Spider Creek is designated for intensive timber management, so far as it is consistent with big game summer range. Spider Creek provides background scenery to Highway 93. Because our stand was selected for harvest, meeting future forage-cover ratios in Spider Creek may depend on meeting regeneration targets in a timely fashion. The outputs from this stand are linked with the future harvest of other stands because harvest of adjacent stands must wait until regeneration of this stand is well established.

Step three is to assemble relevant options for meeting the management objectives, given we have a budworm problem. A full range of options must be considered. For this stand, they might include the following:

- Use a shelterwood regeneration method, holding the removal cut until the seedlings are established, ignoring the budworm;
- Use a shelterwood regeneration method, spraying with chemicals to protect cones and reproductive buds;
- Use a shelterwood regeneration method, spraying with B.t.;
- Underplant the shelterwood with ponderosa pine, taking what Douglas-fir seeding you can get without direct suppression of budworms;
- Underplant the shelterwood with Douglas-fir;
- Clearcut, planting with Douglas-fir, with seedling shade;
- Clearcut, planting with ponderosa pine.

Timing of the steps in the shelterwood method is always an important part of the decision. The budworm problem adds even more emphasis to proper timing. Prolonging the period between the regeneration cut and overstory removal will not only decrease the vigor of the regeneration but will also subject it to greater defoliation from budworm dispersal out of the overstory.

The fourth step in the decision process is to assemble available data and collect additional data necessary in forecasting outcomes and making subsequent decisions. Because the stand is to be harvested soon, a presale cruise will be needed to write the prescription and estimate the value of the material to be removed. The ability to forecast outcomes depends on the amount and kind of detail collected in the presale cruise. Sufficient detail is needed to forecast stand establishment. What kind of site preparation will be used? How effective will it be? Which sample trees will likely be left in the shelterwood (although this may be a variable in the options considered)? If these data do not exist for the stand selected, data may be inferred from a similar stand in the vicinity.

For the fifth step—forecasting the outcomes for each option—the decision tree is simple. A branch takes off from the "now" node for each of the seven options. When the keywords representing each of the options are used by the Prognosis-Budworm Model, the output represents nature's expected response.

The outcome is forecast for all the commodities the stand is to produce. This means making yield projections for each of the six prescriptions and for several densities of budworm populations. Not all outcomes are equally likely, so each yield forecast has a probability attached to it. Probabilities are estimated from past experience or subjectively from knowledge of the ecosystem.

For our example, suppose spraying has a 50-percent probability of reducing budworms enough to permit sufficient seeds to be produced in a year of good cone crops. Cone years are not completely predictable. Suppose the probability of obtaining a good cone crop is 1 in 5; then we have a 1 in 10 probability of getting seed. In short, all of the ending points in the decision tree are possible, some more probable than others. The decisionmaker will use those odds in combination with differences in production to calculate the weighted average production for each of the proposed schemes of management.

Once a decision is made, a plan for monitoring whether the outcomes are as expected is essential. Monitoring plans should state the variables to be observed and the intensity of the sampling. Will surveys of damage suffice, or will egg-mass surveys be required? If the best alternative called for spraying, prespray and postspray surveys are essential to evaluate treatment. Monitoring continues until the desired result is achieved or it becomes obvious that the problem still exists.

8.3.2 Example Two

In our second hypothetical case history, let's be the manager of a 100-acre (40-ha) cutover stand near McCall in central Idaho. This stand is on a north aspect and is mixed Douglas-fir and grand fir with about 25 residual, cull, overmature trees per acre (62/ha). The stand is well stocked with grand fir and Douglas-fir regeneration to 20 years old. This particular stand is surrounded by 2,000 acres (810 ha) of mature and overmature sawtimber. The surrounding stands are typically two storied with suppressed Douglas-fir and grand fir in the understory and mostly Douglas-fir in the overstory. We also manage the surrounding land; however, according to the long-range plan, it is not scheduled for cutting for several decades and, even then, not until this stand ceases to look like an opening.

Once again the decision process will follow the previously outlined steps to arrive at a "best" way to manage this stand. In this example, we will address the complexity of looking at options that involve the adjacent stands as well as our example stand.

We start out with the following question: Do we have a problem? Hazard rating indicates we do. Nearby egg-mass surveys lead entomologists to believe a rise in budworm populations is likely within a year or two. Our stand is suitable host, so the answer is: Yes, we have, or can have, a problem.

What are the products this stand is to generate? A look at the long-range plan shows a sawtimber harvest in the decade starting 2060 for stands like ours. An average harvest of 2,300 ft^3 (65 m^3) is anticipated at rotation with one commercial thinning. Our stand is to start producing hiding cover for big game in about 10 years and will produce thermal cover starting in about 50 years. Other resource production is assumed not to be affected by any timber harvest. These outputs are summarized in table 8-1.

We know that

- Egg-mass surveys are routinely conducted in adjacent stands;
- A stocking survey is available, but is 15 years old for this stand;
- Stand exams are available for samples of the adjacent stands; and
- These stands have been hazard rated.

Expert pest-management advice defines several options for this case study:

- Kill or fell overstory;
- Let the stand develop naturally;
- Reduce the insect population only in this stand; or
- Spray this and adjacent stands to reduce budworm populations and avoid significant defoliation and mortality.

Yield forecasts for any of the listed products will require some form of modeling—in this geographical area, the Prognosis-Budworm Model (Sheehan and others 1985,

Table 8-1—Resource production on hypothetical stand near McCall, ID

	Production goals by decade								
	1	2	3	4	5	6	7	8	9
Approx. age of regeneration	20	30	40	50	60	70	80	90	100
Year	1980	1990	2000	2010	2020	2030	2040	2050	2060
Wood production	—	—	—	—	500	—	—	—	2300
Hiding cover	no	yes	yes	yes	yes	no	no	no	no
Thermal cover	yes	no	no	no	yes	yes	yes	yes	yes
Considered to be an opening	no	yes	no	no	no	no	no	no	no

Wykoff and others 1982) with the Parallel-Processing Extension (Crookston 1983 unpubl.). Because we have no current stand examination for this particular stand, one will be required. Data necessary to use the tree model include location, slope, aspect, elevation, habitat type, inventory design, and a sample of individual trees—giving species, d.b.h., tree history, height, diameter growth for the large trees, and height growth for the smaller trees. We will need to assemble the stand examination and egg-mass inventories for the adjacent stands because they will provide a source of contagion. For purposes of forecasting yields, some information on the probability of budworm infestation in this particular area will be helpful. We will need local data on cost and effectiveness of spraying, as well as the cost of sanitation work.

A yield forecast is produced for each of the branches of the decision tree. The outcomes are ranked by the extent to which the goals are met and the cost of meeting the goals. We select the "best" alternative, weighing all these items, as well as the importance of meeting each goal. Radical departures to meeting the specified goals must be fed back to the long-range plan for sensitivity analysis. If this is the only stand that does not meet the target, the impact may be small. On the other hand, if many stands do not produce at expected levels, a new long-range solution may be called for.

The final step is to set up a schedule to see if what we said we were going to do has been accomplished.

8.3.3 Example Three

In this example, we will look at a collection of mature sawtimber stands that must be ranked for harvest. Any one of the stands is eligible for cutting, but not all can be harvested at the same time. A long-range plan does not generally specify a particular stand for cutting. A class of stands is targeted, leaving the final ordering and selection up to the local manager. This ordering may be the one that produces the most fiber or the one that produces the most money, or has the least risk. Not all stands are equally susceptible to budworm damage, and the budworm may be a key influence in fiber production, monetary returns, or both.

An example of a collection of stands may be as follows:

- Dense, overmature Douglas-fir with little understory;
- Dense, overmature Douglas-fir with multiple stories;
- Scattered Douglas-fir/ponderosa pine mixed (Douglas-fir understory, potentially salvageable);
- Even-aged, single-storied Douglas-fir, 120 years old.

Obviously, infinite complications can exist in such stands, such as root rot, proximity to roads, regeneration success, and archeological sites. We will assume these kinds of things are all equally affecting the stands in question. For this example, we will look only at the ways budworm enters into the decision process. All stands are the same size.

Is there a budworm problem? Hazard ratings suggest that all of the stands in this example could sustain loss of increment from budworm attacks and that numbers of budworm sufficient to cause defoliation and mortality in the understory are possible. The hazard-rating scheme gives a relative ranking but does not quantify the losses to be expected. Historical maps show that this area has had prior episodes of defoliation. For this collection of stands, we do have a problem.

Within the next five decades, all four stands may be harvested. For reasons other than timber outputs, only one stand can be regeneration-harvested per decade. The prime use of this collection of stands is to make the most revenue over the 50 years. Any of the four stands will produce equally the necessary forage, watershed, and visual outputs.

As part of planning the timber sale, stand examinations are available for all stands. The examinations are sufficiently detailed to allow use of the Prognosis-Budworm Model.

For purposes of forecasting outcomes, no additional data will be needed. For us to forecast outcomes, we must first assemble some relevant options:

- Stand 1 can be clearcut in any of the five decades or can be left uncut (six alternatives);
- Stand 2 can be clearcut in any decade, with possible direct suppression of insect population ($6 \times 2 = 12$ alternatives);
- Stand 3 can have the overstory removed with uncertain success of salvaging the understory (if the stand is held too long, budworm might destroy much of the understory) ($6 \times 2 = 12$ alternatives); and
- Stand 4 could be clearcut at any time, but because it is younger than Stand 1, we will defer cutting until age 140 (four alternatives).

Although the decision tree for this example would look complicated, the policies it represents can be simulated with the keywords in figure 8-3. Outcomes depend not only on the budworm but also on our decision to harvest certain stands at particular times. Even in this simple case—with only four stands—34 outcomes are possible. Each outcome depends on many random occurrences. Therefore, replication of the analysis, reseeding the random-number generators, is recommended. The Parallel-Processing Extension (Crookston 1983 unpubl.) of the Prognosis Model is capable of just such calculations. Converting the output from the Parallel-Processing Extension to present net value will require the subsequent economic analysis provided by the "CHEAPO" keyword.

```
ADDSTAND
STDIDENT
00000001      DENSE OVERMATURE DOUGLAS-FIR, LITTLE UNDERSTORY
STDINFO                        ___        ___        150.   Note: This statement carries
NUMCYCLE           5.                                       all 4 stands through 5 10-yr.
                                                            cycles
WSBW     Involves Budworm Model
CALLBW   with all default parameters
END
IF
         AGE    GE    140
THEN                                                        These give a branch with
THINBBA              0.          0.         1.0             clearcut and natural
ESTAB                                                       regeneration starting each cycle
RESETAGE
END
ALSOTRY  Lack of activity Keywords
ENDIF    here creates branches representing no treatment
CHEAPO
PROCESS
ADDSTAND
STDIDENT
00000002      DENSE OVERMATURE DOUGLAS-FIR, MULTISTORY
STDINFO                        ___        ___        180.
WSBW                                                        Evaluates harvest
CALLBW                                                      scheduling options
END                                                         without spray
IF
         AGE    GE    150
THEN
THINBBA              0.          0.         1.0
ESTAB
RESETAGE
END
ALSOTRY
ENDIF
CHEAPO
PROCESS
REWIND   Brings back stand 2 for simulating spray alternatives
STDIDENT
00000002      AS ABOVE, BUT WITH SPRAY
STDINFO                        ___        ___        180.
WSBW
CALLBW   Invokes Budworm Model with suppression by chemical
SPRAY    pesticide, again using default spray requirements
END      and efficacy.
IF
         AGE    GE    150
THEN                                                        Creates decision tree
THINBBA              0.          0.         1.0             shown in figure 8-3b
ESTAB
RESETAGE
END
ALSOTRY  Creates data file output
ENDIF    for later economic
CHEAPO   analyses.
PROCESS
ADDSTAND
STDIDENT
00000003      DOUGLAS-FIR/PONDEROSA PINE, DOUGLAS-FIR UNDERSTORY
STDINFO                        ___        ___        150.
    :
ADDSTAND
STDIDENT
00000004      EVEN-AGED PURE DOUGLAS FIR
STDINFO                        ___        ___        120.
    :
PROJECT
STOP
```

Repeat same as stand 1

Repeat same as stand 2

— denotes blank field - uses default values

Figure 8-3—Keywords for alternatives in example 3, *a*; decision tree for example 3, stand 2, showing possible clearcut in any decade, *b*.

Glossary[1]

Abietoideae: Subfamily of the pine family (Pinaceae) that includes all the hosts of budworm.

Adfrontals: In caterpillars, a pair of elongated, hardened plates on the front of the head extending from the base of the antennae to the top of the head where they meet, forming two sides of a triangle.

Adult: Fully grown, sexually mature stage of an insect—in budworm, the moth.

Advance regeneration: Young trees that have become established naturally before regeneration cuttings are begun.

Adventitious foliage: Shoots arising from buds produced by conversion of mature tissue into meristematic tissue.

Aggregated distribution: Clumped distribution of a population in space.

Allele: One of a pair of genes, or of multiple forms of a gene, at the same locus of paired chromosomes.

Allelochemics: Secondary compounds produced by plants that affect the behavior of organisms feeding on or associated with them. For example, many plants produce toxic compounds that deter insect feeding.

Allopatry: Geographic separation of species or races sufficient to prevent gene exchange.

Anal shield: In caterpillars, a hardened plate on the upper surface of the last body segment.

Analysis of variance: Statistical procedure typically used to separate the variation (sum of squares of differences from the mean) into portions, each attributable to a defined source.

Apical dominance: The growth of the terminal bud at the expense of lateral buds whose development is inhibited while the terminal bud is actively growing.

Arthropods: Invertebrate animals with segmented bodies and paired, jointed appendages—for example, insects and spiders.

Bark beetles: Common name applied to the family Scolytidae, a group of beetles whose adults bore through the bark of host trees to lay their eggs, and whose larvae tunnel and feed under the bark.

Basal area: The area of the cross section of a tree inclusive of bark, at breast height (4.5 ft, 1.37 m).

Benefit-cost analysis: An economic appraisal technique used to rank alternatives based on expected return on investment.

Benefit/cost ratio: A financial measure obtained by dividing the anticipated gains from a project by its anticipated costs.

Billion International Units (BIU's): The International Unit (IU) is an expression of the potency of B.t. formulations based on that of a particular strain of *Bacillus thuringiensis* used as a reference standard; strain HD-1-S-1971 is currently used as the reference standard in the United States.

Bioassay: Determination of the relative strength or specificity of a substance—for example, sex pheromone—by comparing responses of test organisms.

Biomass: Total quantity at a given time of living organisms of one or more species or tissue per unit area.

BIU's: (See Billion International Units.)

Board foot (foot board measure, fbm): Unit of measurement represented by a board 1 ft long, 1 ft wide, and 1 inch thick.

Bole: The trunk or stem of a tree.

Budburst: Opening or flushing of vegetative buds; beginning of shoot and foliage growth.

Canopy: The more or less continuous cover of branches and foliage formed collectively by the crowns of adjacent trees and other woody growth.

Canopy closure: In a stand, the progressive reduction of space between crowns as they spread laterally, increasing the canopy density.

[1]Terms are defined as used in this book.

Chemosystematic (chemotaxonomic): Pertaining to the use of chemical characteristics for the separation and classification of organisms.

Chi-square test: Test of the mathematical goodness of fit of a hypothesized frequency to an observed frequency.

Chlorogenic acid: An organic acid found in the foliage of conifers which, in high concentrations, inhibits browsing by deer.

Cholinesterase inhibitor: A chemical that interferes with the normal transmission of nerve impulses.

Clearcutting: Removal of the forest stand completely in one cut.

Climax species: Species capable of perpetuation under the prevailing climate and soil conditions; the culminating species in plant succession in a given environment.

Clinal variation: Gradation in measurable characters of a species or other group of related organisms associated with changes in environmental conditions—for example, changes in latitude, longitude, or elevation.

Cluster analysis: A statistical tool for segregating individuals into groups based on similarities of measurable characteristics.

Clypeus: In insects, a hardened plate on the lower front of the head located just above the upper lip.

Codominant: Trees with crowns at or near the top of the canopy. In silviculture, one of the four main crown classes, recognized on a basis of relative status and condition in the stand.

Cold hardiness: The ability to survive exposure to below-freezing temperatures.

Color morphs: Different colored forms of an insect species occurring in the same population.

Community: An assemblage of populations of plants and animals in a given place.

Copulation: Mating.

Covariance analysis: Statistical procedure used to separate the variation in a response variable that is systematically related to another variable (covariate) from the variation related to treatment. For example, budworm weight gain may be related to several test diets and to starting weight. The test diet is the treatment and the starting weight is the covariate.

Cover type, forest: Forest vegetation type now occupying the ground, with no implication as to whether it is seral or climax.

Crown height (base of live crown): Of a standing tree, the vertical distance from ground level to the base of the crown, measured either to the lowest live branch whorl (termed upper crown height) or to the lowest live branch (lower crown height).

Crown kill: Portion of crown with foliage killed by defoliation or secondary causes.

Crown length: The distance from the top of the tree to the base of the live crown.

Crown ratio: The ratio of crown length to tree height of a standing tree.

Damage: Any effect of insect feeding deemed deleterious to some management objective or objectives.

Decision tree: A systematic way of illustrating alternatives and their outcomes over time.

Defoliation: Reduction in the amount of foliage through actions of insects, fungi, or other agents, as distinct from natural leaf fall.

Defoliation prediction model: A model or algorithm used to predict amounts of defoliation.

Degree-day: A measure that accounts for both time and temperature during that time; 24 hours at a temperature that is 1° above a specified threshold temperature equals 1 degree-day (°D).

Dendrology: The science of the identification and systematic classification of trees.

Dependent variable: A variable whose value is determined by the value of one or more other independent variables in a function.

Detection: Procedure used to discover outbreaks of forest insects and diseases; detection surveys may be made by observations from aircraft or the ground.

Diameter breast high (d.b.h.): Diameter of a tree at 4.5 ft (1.37 m) above the ground.

Diameter inside bark (d.i.b.): Diameter of a tree less the bark thickness.

Diapause: Condition of suspended animation or arrested development during the life cycle of an organism—for example, overwintering budworm larvae undergo diapause.

Dieback: Progressive dying from the extremity of any part of a plant.

Discriminant analysis: A special case of multiple linear regression where the dependent variable is a class or group—for example, low, medium, and high.

Dispersal: The act or result of dispersing or scattering; usually refers to the distribution of adults or to the redistribution of larvae after eggs have hatched—for example, dispersal of early instars.

DNA: Deoxyribonucleic acid; hereditary material found in the chromosomes that stores and transmits genetic information.

Dominant: (1) A plant species within a community or more narrowly defined assemblage of components, that exerts the greatest influence because of its abundance or activity; (2) a tree or group of trees occupying the uppermost layers of the forest canopy and that are largely free growing.

Dormant (latent) bud: A bud in a resting state with growth and development suspended until triggered by some environmental cue.

EA: (See Environmental Assessment.)

Early larvae: Larvae that have recently issued from eggs; usually first and second instars.

Ecology: The study of plants and animals in relation to their environment.

Economic-selection cutting: Logging only of the highest value trees from a stand; exploitation cutting, often called "high grading."

Ecosystem: An assemblage of living plants and animals and their environment.

Ecotone: Transition zone between two adjoining communities—for example, a forest edge forms an ecotone between forest and meadow.

Efficacy: Effectiveness, as of an insecticide; ability of a product to control the specified target pest or to produce the specified action.

Egg mass: Eggs deposited in a group by a single female.

EIS: (See Environmental Impact Statement.)

Elastic demand: (See also Price Elasticity of Demand.) Demand is elastic if a decrease in price results in a greater than proportional increase in demand. Similarly, increase in price results in decrease in total revenue.

Electrophoresis: Movement of suspended particles through a fluid under the action of an electromotive force; compounds can be separated based on differences in the rate of movement.

Entomological unit: Portions of the susceptible host type usually defined by physical features or stand composition.

Entomopathogenic: Refers to microorganisms and viruses capable of causing disease in an insect host.

Environmental Assessment (EA): Public document providing results of environmental analysis of the impact of a proposed action; used to determine the need for an Environmental Impact Statement.

Environmental Impact Statement (EIS): Public document, required by Federal law, which documents the significant environmental effects of any major action on federally owned land that may alter the quality of the human environment.

Epicormic branching: Growth of foliage and branches long after normal laterals have elongated; originating from buds that may have been suppressed for many years.

Esterase: An enzyme that mediates or promotes synthesis and hydrolysis of an ester.

Evaluation survey: A survey in which the current or potential significance of an insect or disease outbreak is appraised.

Even-aged: The condition of a forest or stand composed of trees having no or relatively small differences in age.

Fecundity: Productivity (numbers of offspring) of an organism. The fecundity of the budworm is measured in numbers of eggs produced per female.

Fixed-size plots: Sampling method using plots of a predetermined and fixed size.

Foot board measure (fbm): Measurement of lumber (see Board Foot).

Formulation: Packaged active ingredient plus various other materials that a manufacturer of pesticides produces.

Frass: Waste product of insect digestion.

Free thinning: A thinning to favor only the trees considered most suitable to form the final crop, in whatever layer of the canopy they may be found.

Gene frequency: The proportion of individuals in a population carrying a given gene.

Genetic polymorphism: Existence in the same population of genetically different forms.

Genitalia: Sexual organs and related structures.

Genotype: Genetic constitution of an individual or a species.

Granulosis virus (GV): Virus causing disease of insects characterized by minute granular inclusions in infected cells.

Gravid: Pregnant.

Group selection: A modification of the selection system in which trees are removed in small groups.

Guild: A group of organisms that share a definable ecological trait—for example, conifer-gleaning birds or larval parasites of western spruce budworm.

Habitat: The place occupied by a plant or animal considered in relation to all the environmental influences affecting it.

Habitat series: Collection of habitat types that share a common overstory climax species.

Habitat type: The units of land capable of producing similar plant communities at climax.

Hazard: Probability of attack or damage by a pest.

Hazard rating: An index of relative likelihood of attack or damage by a pest.

Head-capsule: the hardened portions of the larval head that form a rigid compact case, which is shed with the skin at each larval molt.

Height-class structure: Stand structure expressed in terms of variation in tree heights.

Hemolymph: Body fluid of an invertebrate organism having an open circulatory system.

Hibernaculum (pl., hibernacula): Silken shelter spun by a budworm larva and in which it overwinters.

Host: Any organism on or within which another organism lives.

Host type: Forest composed primarily of tree species that are hosts for budworm.

Hybridization: Mating between members of different populations of the same species with different gene complexes, or between members of different species.

Hyperparasite: A parasite that lives in or on a primary parasite.

IGR's: (See Insect-Growth Regulators.)

Impact evaluation survey: (See Evaluation Survey.)

Implant (technique): Method used to introduce chemicals into tree tissues by drilling a hole into the woody tissue and implanting the chemical in a solid form. The chemical is slowly absorbed and translocated by the tree (see also Injection).

Independent variable: A variable whose value determines that of one or more other variables.

Inelastic demand: (See also Price Elasticity of Demand.) Demand for a product or quantity is inelastic if a change in unit price causes a change in the same direction of total revenue—that is, if unit price increases, so do total revenues and vice versa.

Infectious: Able to produce infection—that is, able to enter into a susceptible host, to multiply, and to produce disease; said of certain microorganisms and viruses.

Infestation: In budworm, presence of insects in sufficient numbers to produce visible defoliation.

Infinitely elastic demand: (See also Price Elasticity of Demand.) Demand is infinitely elastic if changes in quantity offered by producers do not affect product price.

Injection (technique): Method used to introduce chemicals into tree tissues by injecting a liquid formulation of the chemical into the wood.

Insect-growth regulator: Insect hormones, hormone mimics, or molt inhibitors that affect the ability to develop normally, survive, or reproduce.

Instar: Period or stage between molts in an insect larva.

Internal rate of return: The interest or discount rate that equates the present value of a project's benefit and costs.

Internode: The part of a stem between two adjacent nodes.

Intolerant species: A kind of plant that grows poorly or dies in competition with other plants (as for light, moisture).

Isoenzymes: Functionally like enzymes with similar amino acid sequences; may be separated electrophoretically or by chromatography.

Isomer: Chemical compound that contains the same number of atoms of the same elements as another compound, but differing in structure and properties.

Kairomone: A chemical compound produced by one species that affects other species.

Larva: The immature form of an insect that undergoes complete metamorphosis: a caterpillar, maggot, or grub.

Late (large) larvae: Mature larvae near the end of the feeding period, usually fifth and sixth instars.

Leader: Terminal, topmost shoot.

Life table: Tabulation of mortality factors acting on a population that displays the relative importance of each factor and permits estimation of survival; the information on survival, coupled with a knowledge of fecundity, allows estimation of the size of the succeeding generation.

Lignification: Hardening of the cell walls in a woody plant by conversion of cell-wall constituents to lignin.

Linear function: Any relation between variables which when graphed yields a straight line.

Linear regression: A statistical modeling technique in which a response (dependent) variable is assumed to be a linear function of independent variable(s) plus an associated normal error.

Locus (gene locus): Fixed position of a gene in a chromosome.

Loss function: Relation describing how cost of making an error changes with the size of the error.

Lower crown: That portion of the tree crown whose main branches originate from the lower third (usually) of the tree crown.

Maturity: Loose term for the stage at which a tree has attained full development, particularly height, and is in full seed production.

Meristematic tissue: Undifferentiated tissue capable of further division and specialization.

Mesic: Pertaining to relatively moist habitats.

Metamorphosis: The process of change in which an organism passes through several developmental stages: for example, budworms develop from eggs to larvae to pupae to adults.

Midcrown: Portion of the tree with branches originating from the middle third (usually) of the crown.

Model: Formal description that represents a system or process.

Molt: Shedding of the larval integument, a process that allows for growth

Molt inhibitor: Chemicals that interfere with the process of molting.

Monomorphic: Existing in only one form.

Monoterpene: A hydrocarbon in the terpene group composed of one unit of the basic terpene structure (see Terpene).

Morph, color: (See Color Morphs.)

Net present value: Value of an investment measured by discounting all future returns minus associated costs.

Node: In plants, the part of a stem where leaves and axillary buds arise; in decision trees, the point on a branch that gives rise to two or more branches.

Nomenclature: System of terms or names used to describe organisms.

Nucleopolyhedrosis virus (NPV): Virus causing disease of insects, mainly larvae of certain Lepidoptera and Hymenoptera, characterized by the formation of polyhedra in the nuclei of infected cells; usually fatal.

Operational suppression: Use of biological or chemical compounds for the large-scale suppression of insect populations.

Outbreak: Period of high insect (budworm) numbers during which conspicuous defoliation occurs.

Overstory: The portion of trees, in a forest of more than one story, forming the upper or uppermost canopy layer.

Parameter: A quantity that is considered constant for a particular situation, although it may differ in other situations.

Parasite: An organism that develops in or on a host organism at the host's expense.

Phenology: Observational science dealing with the time of appearance of periodic events in the life cycle of organisms, particularly as these events are influenced by local conditions.

Phenotype: Expression by visible characters of an organism of the interaction of genotype and environment.

Pheromone: A chemical compound produced by an organism that affects others of the same species.

Photoperiod: Variation in light and dark periods (day length), which affects plant development. For example, flowering in many plants will occur only under certain photoperiods.

Photosynthesis: Process in green plants of conversion of carbon dioxide and water to carbohydrates and oxygen by the energy of sunlight.

Phytophagous: Feeding upon plants.

Pilot test: A test of the efficacy of a pesticide against its target organism over a fairly large area before the pesticide is used operationally.

Pistillate bud: Structure that forms the female cone in conifers.

Pole: A still young tree from the time its lower branches begin to die up to the time when the rate of height growth begins to slow down and crown expansion becomes marked.

Pole pruner: Sectional pole with cutting shears and a basket on the upper end for collecting branch samples from the tree crown.

Pollen cones: In conifers, male (staminate) structures that produce only pollen.

Polymorphism: (See Genetic Polymorphism.)

Population dynamics: The study of changes and the reasons for changes in population numbers.

Predator: A free-living organism that feeds on other organisms—for example, birds and ants that feed on budworm.

Pretreatment, posttreatment: Before and after treatment with insecticide.

Price elasticity of demand: For any quantity being sold, the percentage change in quantity divided by the percentage change in price.

Primary parasite: A parasite that establishes itself in or on a host that is not a parasite.

Prothoracic shield: In caterpillars, a hardened plate on the upper surface of the first body segment behind the head.

Provenance: Original geographic source of seed, pollen, or propagules.

Pupa: The resting, intermediate stage of an insect between the larva and the adult.

Race: (See Subspecies.)

Refoliation: Regrowth of foliage after defoliation.

Regeneration cutting: Any removal of trees intended to assist regeneration already present or to make regeneration possible.

Regional climate: Long-term weather averages over an area, such as western Montana or the northern Rocky Mountains.

Reproductive isolation: The prevention of mating between potentially interbreeding organisms by physical, temporal, or behavioral mechanisms.

Residual life: Length of time that a pesticide remains effective against its target organisms after application.

Residual properties: Ability of pesticides to remain efficacious for some time after application.

Residual pupae: Budworm pupae that survive predation by predators such as ants and birds but are subject to other mortality factors such as parasites.

Risk: Probability of an undesirable event occurring within a specified interval.

Salvage cutting: Harvesting of trees that are dead, dying, or deteriorating before their timber becomes worthless.

Sapling: Loose term for a tree no longer a seedling but not yet a pole; in the United States, a tree 2 to 4 inches (5 to 10 cm) d.b.h., in Canada, one-half to 3 inches (1.3 to 7.6 cm).

Sclerotization: The hardening of the body wall of an insect.

Seed cones: In conifers, female (pistillate) structures that bear seed.

Seedling: In general, a young tree grown from seed from its germination up to the sapling stage.

Seed-tree cutting: Removal in one cut of the mature timber from an area, leaving a small number of seed bearers singly or in small groups.

Selection cutting: Periodic removal of trees (particularly mature trees), either singly or in small groups.

Sequential sampling: Sampling with a variable sample size, in contrast to conventional sampling procedures that require a fixed number of sample units.

Seral species: A plant species characteristic of a stage in the development of forest communities (see Succession); not permanent (see Climax).

Setal areas: In caterpillars, areas of attachment on the body of stiff erect hairs (setae).

Severity index: An index of the severity of previous budworm defoliation based on the magnitude of growth reduction.

Sex pheromone: Insect-produced chemical that stimulates a specific sexual attraction response by the receiving individuals.

Shade-tolerant: Said of plant species capable of growing and reproducing in shade.

Shelterwood cutting: Regeneration cutting in a mature stand designed to establish a new crop under the protection of the remaining stand.

Significance: Referred to generally as the significance level; when a statistical hypothesis is tested, it cannot be rejected if a calculated probability exceeds a given value.

Silvicultural system: A process whereby forests are tended, harvested, and replaced to result in production of crops of distinctive form; systems are classified by methods of felling that remove the mature crop with a view to regeneration.

Silviculture: Theory and practice of controlling the establishment, composition, constitution, and growth of forests.

Simulate: To use models to represent real systems.

Single-tree selection: Removal of individual, usually high-risk, mature trees from an even-aged forest to realize the yield and establish a new crop of irregular constitution.

Site climate: Regional climate modified by the slope, aspect, elevation, and edaphic characteristics at a particular site.

Site index: A measure of the relative productive capacity of a site based on the height of dominant trees in a forest stand at an arbitrarily chosen age.

Site potential: The potential productivity of a site.

Socioeconomic model: A collection of computer programs used to translate the volume of timber, water, and other factors into dollar impacts of a simulated outbreak.

Sparse population: A population at low density; sparse populations of budworms cause little or no visible defoliation.

Staminate bud: Structure that forms the male, pollen-producing cone in conifers.

Stand composition: The representation of tree species in a stand.

Stand density: Quantitative measure of tree stocking, usually expressed as number of trees, basal area, or volume per unit area.

Stand vigor: An expression, usually not quantitatively defined, of the general health of a stand.

Stereoisomer: (See Isomer.)

Stocking: In a forest, a more or less subjective indication of the number of trees as compared to the desirable number. More precisely, a measure of the proportion of the area actually occupied by trees as distinct from their stand density.

Strobilus (pl., strobili): Male or female inflorescence in most conifers; cone.

Stumpage: Harvested tree volumes, considered with reference to their quantity or marketable value.

Subclimax: The stage in plant succession immediately preceding climax.

Subspecies: Geographically defined group of populations of a species with different characteristics.

Succession: Replacement of one kind of community by another; the progressive changes in vegetation and animal life that may culminate in the climax.

Suppression: In pest management, reduction of pest populations below economically damaging levels.

Susceptibility: The probability that a stand will become infested by western spruce budworm.

Susceptibility index: A number representing the relative susceptibility of a stand to western spruce budworm.

Sustained yield: Continuous production; balance, over time, between net growth and harvest.

Sympatry: Overlap in the geographic ranges of related species.

Synonomy: A chronological list of all the scientific names assigned to a particular taxonomic group, such as a species.

Taxonomy: The orderly classification of plants and animals according to their presumed natural relationships.

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Technology transfer: Communication of research and development information to potential users that results in a change or improvement in procedure.

Terpene: General name of hydrocarbons having the formula $C_{10}H_{16}$, many of which occur in volatile oils of plants.

Thermoperiod: Effect of cyclic alternations of temperature between day and night on plant processes. For example, plant growth is increased in some species when cool night temperatures alternate with moderate daytime temperatures.

Thinning: A felling made in an immature crop or stand primarily to accelerate diameter growth; also, a selection made to improve the average form of the trees that remain.

Threshold development temperature: Critical temperature above which some biological process, such as growth, begins.

Tolerant species: A kind of tree that grows well under specific conditions, most commonly in the shade of or in competition with other trees.

Top-kill: Death or dieback of the leader and more or less of the upper part of the crown.

Toxicity: Poisonous quality, especially its degree or strength.

Toxicology: Science dealing with poisons and their effects on specific organisms.

Translocation: Movement of dissolved substances through the vascular tissue of a plant.

Tribe: A category in the Linnaean classification system between family and genus; a group of genera.

Understory: Generally small trees and woody species growing under the main tree canopy.

Uneven-aged: Said of a forest, crop, or stand composed of intermingling trees that differ markedly in age.

Unit elasticity: (See also Price Elasticity of Demand.) Demand for a quantity or product relative to its selling price is said to be of unit elasticity if a change in price is counterbalanced by a change in demand so that total revenues remain unchanged.

Variable: A quantity that may assume any one of a set of values.

Vegetative buds: Buds that give rise to roots, stems, or leaves, and not to reproductive parts such as flowers.

Virus isolate: A virus that has been isolated from contaminants and associated microorganisms.

Vulnerability: Probability that damage will occur in a stand, given an infestation of western spruce budworm.

X-ray energy spectrometry (XES): An x-ray technique whereby elements and their relative amounts in insect tissues are determined.

Xylem: Woody tissue of higher plants, which functions in support and water conduction.

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Habitat Type[1] Groups for Western Spruce Budworm Hazard Rating

1. Cold subalpine fir, timberline types
Whitebark pine, subalpine larch series

850 PIAL-ABLA
860 LALY-ABLA
870-897 PIAL TYPES

Mountain hemlock series

680-682 TSME/MEFE
710-712 TSME/XETE
840-842 TSME/LUHI

Subalpine fir series

734 ABLA/VASC/PIAL
810-812 ABLA/RIMO
820 ABLA-PIAL/VASC
830-833 ABLA/LUHI

Spruce series

497 PICEA/RIMO

2. Cool, moist spruce; cool, moist subalpine fir types
Mountain hemlock series

675-677 TSME/STAM
685-687 TSME/CLUN

Subalpine fir series

605 ABLA/CABI
635-637 ABLA/STAM
650-655 ABLA/CACA
670-674 ABLA/MEFE
740 ABLA/ALSI

Spruce series

410 PICEA/EQAR
415 PICEA/CALE
490 PICEA/CADI

[1]See Cooper and others (1984 unpubl.), Pfister and others (1977), Steele and others (1981 and 1983).

3. Warm, wet grand fir; western redcedar; western hemlock; warm, wet subalpine fir types
Subalpine fir series

610 ABLA/OPHA

Western redcedar series

530-535 THPL/CLUN
540-542 THPL/ATFI
545-548 THPL/ASCA
550 THPL/OPHO
555 THPL/GYDR
560 THPL/ADPE

Western hemlock series

565 TSME/GYDR
570-574 TSME/CLUN
575-578 TSME/ASCA
579 TSME/MEFE

Grand fir series

529 ABGR/SETR

4. Cold grand fir; cool, dry spruce; cool, dry subalpine fir types
Subalpine fir series

640 ABLA/VACA
690-694 ABLA/XETE
701 ABLA/ARLA
707 ABLA/PERA
720-723 ABLA/VAGL
730-733 ABLA/VASC
745 ABLA/JUCO
780-782 ABLA/ARCO
790-793 ABLA/CAGE
795 ABLA/CARO

Spruce series

450 PICEA/VACA
460-462 PICEA/SEST
475 PICEA/JUCO
485 PICEA/VASC
493 PICEA/HYRE
495 PICEA/ARCO

Grand fir series

580 ABGR/VACA

5. Moist grand fir; warm, moist spruce; warm, moist subalpine fir types
Subalpine fir series

601 ABLA/ACRU
603 ABLA/PHMA
609 ABLA/THOC
620-625 ABLA/CLUN
630 ABLA/GATR
645-647 ABLA/ACGL
660-663 ABLA/LIBO

Spruce series

420-422 PICEA/CLUN
430 PICEA/PHMA (SAF is a minor climax)
440 PICEA/GATR
470 PICEA/LIBO

Grand fir series

516-519 ABGR/ASCA
520-526 ABGR/CLUN (SAF is a minor climax)
525-527 ABGR/ACGL
590-593 ABGR/LIBO

6. Mesic Douglas-fir; dry grand fir; warm mesic spruce; warm, dry subalpine fir types
Subalpine fir series

607 ABLA/SYAL
638 ABLA/COOC
702-704 ABLA/BERE
705 ABLA/SPBE
750-752 ABLA/CARU
760-762 ABLA/OSCH
770 ABLA/CLPS

Spruce series

480 PICEA/SMST

Appendix 3

Grand fir series

505 ABGR/SPBE
506-508 ABGR/PHMA
510-512 ABGR/XETE
511 ABGR/COOC
515 ABGR/VAGL
585 ABGR/CARU

Douglas-fir series

260, 261, 265, 266 PSME/PHMA
280-283 PSME/VAGL
290-293 PSME/LIBO
390-393 PSME/AGGL

7. Dry Douglas-fir types
010 Scree (Douglas-fir, spruce, and subalpine fir can be climax)

Douglas-fir series

210 PSME/AGSP
220-222 PSME/FEID
230 PSME/FESC
250 PSME/VACA
262 PSME/PHMA-CARU
263 PSME/PHMA-SMST
264 PSME/PHMA-PIPO
310-315 PSME/SYAL
320-326 PSME/CARU
330-334 PSME/CAGE
340-344 PSME/SPBE
350 PSME/ARUV
360 PSME/JUCO
370-372 PSME/ARCO
375 PSME/OSCH
380 PSME/SYOR
385 PSME/CELE
395-399 PSME/BERE

Limber pine series (Douglas-fir is coclimax)

040 PIFL/AGSP (R-1 code 901)
050-052 PIFL/FEID (R-1 code 092-094)
060 PIFL/CELE
070 PIFL/JUCO (R-1 code 095)
080 PIFL/HEKI

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