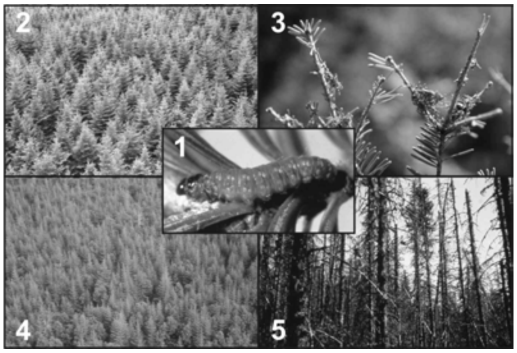
PMRA ARLA

Integrated Pest Management

Principles of Spruce Budworm Integrated Pest Management

Health Canada Santé Canada

Canada



Cover Page

Photograph Captions and Credits

1. Spruce budworm larva
   (Source: Canadian Forest Service - Atlantic)
2. Healthy balsam fir trees
   (Source: New Brunswick Department of Natural Resources)
3. Balsam fir shoots severely defoliated by spruce budworm
   (Source: New Brunswick Department of Natural Resources)
4. Balsam fir trees severely defoliated by spruce budworm
   (Source: Canadian Forest Service - Atlantic)
5. Tree mortality caused by repeated defoliation by spruce budworm
   (Source: New Brunswick Department of Natural Resources)

This document outlines, in general terms, the principles that form the basis of IPM for spruce budworm in Canada along with information about available methods, limitations and future needs.

The mission of the Pest Management Regulatory Agency is to protect human health and the environment by minimizing the risks associated with pest control products in an open and transparent manner, while enabling access to pest management tools, namely, these products and sustainable pest management strategies.

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This publication is also available on the Internet at the following address:
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Foreword

This document was prepared by the Forest Pest Management Caucus in collaboration with the Pest Management Regulatory Agency (PMRA) as part of the PMRA Integrated Pest Management Partnership Projects. The PMRA is committed to promoting sustainable pest management, and is pleased to have acted as Co-chair and Secretariat for the project, and to publish this document on behalf of both groups.

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Introduction

Spruce budworm (*Choristoneura fumiferana* (Clem.)) is a major defoliator of spruce and fir forests across Canada and parts of the northern United States. Its behaviour and impact vary in different regions, and because each jurisdiction has unique circumstances, management decisions and actions are tailored to local conditions. Although these decisions affect individuals, woodlot owners, communities, and local business, the main focus of action is often to protect forest industries whose existence is predicated on long-term sustainable supplies of wood. In the past, protection against spruce budworm was seldom applied to achieve non-timber objectives, but this could become an important issue in the future. Wood supply shortages and other factors that adversely influence costs are critical to maintaining competitiveness in local or global markets. Potential economic impacts are enormous, as are concurrent environmental and public concerns. Nonetheless, many principles and actions are common to all spruce budworm management programs; yet these are not well known or understood by the general public.

Integrated Pest Management (IPM) is basic to managing forests and related resources to help protect against the impact of spruce budworm. The reality of IPM, however, is not easy to grasp, first in terms of its definition and hence its meaning, and consequently in its implementation. IPM is variously defined and, subsequently, approached. Consequently, the former federal Pest Management Alternatives Office, which existed in the early 1990s, polled government, industry, and other stakeholders, and considered 29 suggested definitions of IPM. As a result, they chose to incorporate those diverse views into the following definition[1], which we adopted for this document because of the large stakeholder cross-section it represents:

> "Integrated Pest Management (IPM) is a broadly based method that uses all suitable control measures to reduce pest-related losses to an acceptable level with the goal of respecting genetic diversity and reducing risks to human health and the environment.
>
> The elements of an IPM program include the following:
>
> (a) Planning and managing production systems to prevent organisms from becoming pests
>
> (b) Identification of potential pests
>
> (c) Monitoring populations of pests, beneficial organisms, and all other relevant environmental factors
>
> (d) Establishment of economic, damage, and action thresholds

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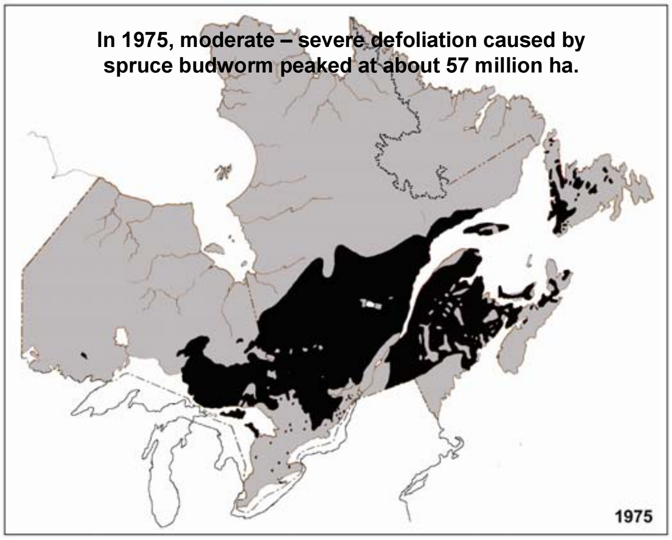
[1] Anon. 1995. The quest to define IPM is complete. Agriculture and Agri-Food Canada. Pest Management Alternatives Office. *Ecopest.2* (1):1. ISSN 1198-1512.

(e) Application of cultural, physical, biological, behavioural, and chemical control measures to maintain pest populations below threshold levels

(f) Evaluation of the effects and efficacy of pest control measures used."

Research and Development (R&D) are critical elements of IPM that are not explicit in this list, but they must not be forgotten. Greater understanding of insect population dynamics and ecological interrelationships within forest ecosystems is always possible. Feedback from R&D and operational experience make IPM an adaptive process. Meanwhile, we must apply the knowledge we already have. Also, there are issues about public input into decision making and subsequent response to enquiries once decisions are made. Those are matters to be developed by the agency responsible for implementing the various decisions.



Kettela, EG. 1983. A cartographic history of spruce budworm defoliation from 1967 to 1981 in eastern North America. Information Report. DPC-X-14. Canadian Forest Service. Environment Canada.

Purpose

This document outlines, in general terms, the principles that form the basis of IPM for spruce budworm in Canada along with information about available methods, limitations and future needs. It is organized to follow the main elements of IPM set out above. Ultimately, the use of IPM techniques for the management of spruce budworm involves an understanding of the insect and the tree species upon which it feeds. In recognizing the need to control spruce budworm to preserve tree health, controversial decisions involving the use of insecticides may be required. Under an IPM program, these decisions are taken within a larger context of pest management, the integration of non-timber forest resources, and sustainable forest production. An IPM approach ensures that insecticide use is not the basis for pest management but is only one tool among many, used only when needed.

Primer on Spruce Budworm

General

Spruce budworm is indigenous to North America, occurring across the northern part of the continent in association with its host spruce and fir forests. Research has revealed periodic large-scale outbreaks back to the 1700s. Undoubtedly, spruce budworm has been part of the evolutionary cycle of North American forests. Hence, historic outbreaks were part of natural ecosystem processes and were not influenced by forest practices. Likewise, recent outbreaks were also natural occurrences. Forest management practices were not the cause of the outbreaks. Nonetheless, outbreak severity in some areas might have been influenced by contemporaneous forest practices, including the combined effects of harvesting, reforestation, fire control, and insect control.

Host species

Spruce budworm larvae feed primarily on balsam fir, subalpine fir, white spruce, red spruce, black spruce (including red-black hybrids) and Engelmann spruce. Hemlock, larch, and white pine can be attacked, but these are regarded as incidental host species.

Susceptibility

Susceptibility refers to the probability that a forest stand will be attacked, and budworm larvae will successfully develop. This happens on the host conifer tree species noted above—the susceptible hosts. Larvae are occasionally found on hardwood trees, but these trees do not provide appropriate food for spruce budworm to survive; thus hardwoods are not regarded as susceptible hosts.

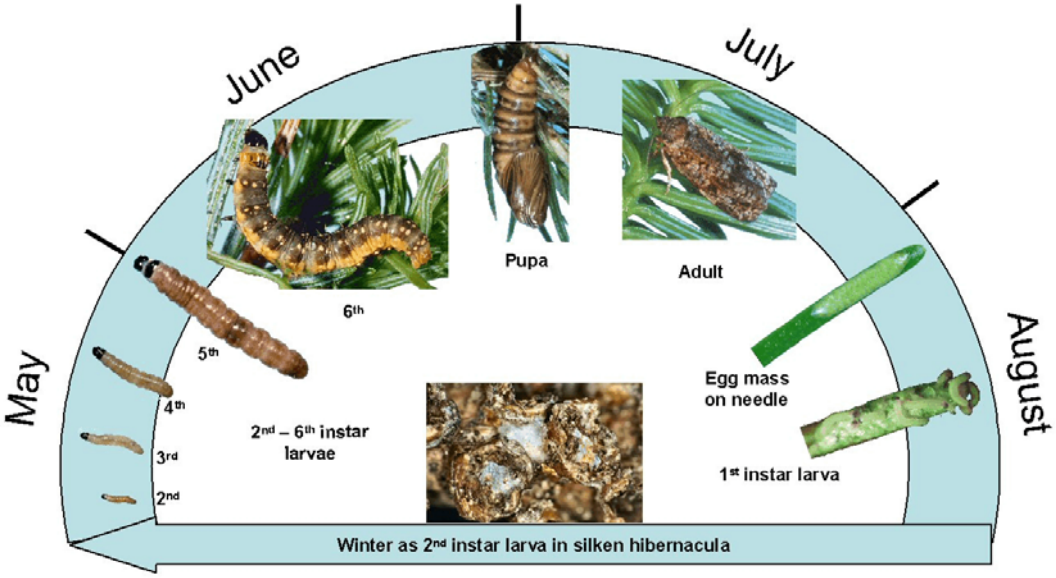
Vulnerability

Vulnerability refers to the probability that a forest stand will suffer mortality once an outbreak occurs. Vulnerability is influenced by stand age, composition, and site conditions, as well as severity of outbreak (i.e., population density and duration). Young forest stands growing on fertile sites are less vulnerable than old stands growing on less fertile, poor quality sites. Balsam fir sustains the most mortality, and hence is the most vulnerable. White spruce and red spruce are intermediate in decreasing order, and black spruce is the least vulnerable. Nonetheless, black spruce can be predisposed to other pests after budworm attack. For instance, a severe outbreak of four-eyed spruce bark beetle occurred on black spruce resulting in the combined loss of millions of cubic metres of wood following severe defoliation by spruce budworm in Newfoundland in the 1970s and 1980s.

Minor outbreaks of short duration can cause light, moderate, or severe defoliation over relatively small areas and yet cause little tree growth loss or mortality (see section on Establishment of Thresholds: Damage thresholds). Conversely, major outbreaks can significantly reduce growth (especially on balsam fir) in the current year of attack, and cause tree mortality to begin within three to seven years depending on tree species, age, site, and related factors. Mortality, especially of older trees, can continue for several years after an outbreak has subsided, due to root die back and reduced tree vigour. Although surveys can provide population forecasts for the ensuing year, the duration and severity of outbreaks cannot be predicted. Nonetheless, historic patterns indicate that outbreaks will occur at irregular intervals with varying duration and intensity. These pose a significant challenge for long-term sustainable forest management.

Biology

Knowledge of the insect’s biology and the damage it can cause are key elements for monitoring and forecasting, as well as for planning and implementing various control actions. The budworm life cycle consists of the following stages: egg, larva, pupa, and adult. Eggs are laid in July and August, and hatch in about two weeks. After hatching, the larvae grow, then shed their skin and become progressively larger larvae called “instars”. There are six larval instars before the pupal stage in which the transformation to the adult moth takes place. The first instar budworm larvae emerge and disperse in late summer (sometimes on silk threads much as spiders disperse by hanging on silk threads that are caught in air currents). These larvae (whose feeding habits have recently been demonstrated) seek places to hide, such as in old flower cups, on branches, in bark crevices, or in other suitable sites on host trees, moult into second instars, and spend the winter in these protective shelters.



Pictures courtesy of Natural Resources Canada, Canadian Forest Service

Generalized Spruce Budworm Life Cycle

In April and May, the second instar larvae (which can also be dispersed on silk strands by the wind) emerge and burrow into (mine) old needles before moving about the branches for a very brief time. Then, they spin silken webs at the base of developing buds and mine them along with male flowers when they are present. Feeding continues as flowers and buds open and the current-year shoots and needles expand and grow. These needles contribute much of the energy required for the trees to grow. If all current-year needles are eaten, larvae may continue to feed on older foliage (referred to as back feeding). The sixth instar eats about 90% of all the foliage each larva will consume before turning into a pupa in mid- to late-June.

In July and August moths emerge, mate, and disperse by active and passive flight, resulting in emigration over short and long distances (up to several hundred kilometres under certain weather conditions). These dispersal mechanisms have significant implications in epidemiology and control. Each mated female budworm moth can lay about 200 eggs that have a male to female sex ratio of approximately 1:1. Hence, populations can remain relatively stable even if 99% of the larvae fail to make it to the adult stage—another fact that must be considered in any applied population control strategy.

Budworm populations fluctuate over time and are regulated by complex interactions with predators, parasitoids, diseases, weather, and host species. Despite popular belief, birds are not efficient regulators of budworm populations at epidemic levels, though they play an important role at low densities. Likewise, spiders are not significant regulators at high density. There are about 90 species of parasitoids that attack budworm, but only about 15 species are common. These parasitoids are most evident at the end of outbreaks and contribute to their collapse.

Various diseases also affect the budworm, including fungi, bacteria, microsporidan protozoa, and viruses. Again, these seldom cause high rates of budworm mortality, but they often cause sub-lethal infection, reduced vigour, and possibly reduced mating success. Population reductions due to adverse weather are not significant, except for occasional extremes that tend to be localized (e.g., late spring frosts). Natural control by adverse weather can not be predicted and, thus, is not a substitute for a protection strategy.

Population cycles result from complex interactions between the budworm, natural bio-controls, weather, and host trees. The mechanisms of how these function have been debated in scientific circles. Despite changes in abundance during an outbreak cycle, no single factor is solely responsible for regulating populations.

Impact

General

The impact of budworm outbreaks on tree volume and mortality has been extensively studied. The last outbreak significantly affected forests over tens of millions of hectares in the 1970s and 1980s in eastern Canada and continued into the 1990s and later in western Canada. Hundreds of millions of cubic metres of wood were lost due to tree mortality, reduced volume increment, and top kill. To use some of this wood before decay set in, road-building was accelerated, and many large clear-cut pre-salvage and salvage harvests were conducted where smaller-size regulated harvests could have normally been conducted. Vast areas of dead forests and salvage harvesting resulted in changes to the landscape and altered habitats for many plants and animals, with dead forests increasing the forest fire hazard for several years after the trees were killed.

Wood supply impacts

Decades of data have proven that uncontrolled spruce budworm outbreaks can significantly reduce wood supplies from spruce and fir. Protection is therefore essential to economic investment. Analyses of wood supplies are key to determining the long-term sustained yield that is the cornerstone of major investment in forest-based industries. To be competitive and economically viable, the assurance of sustainable supply is critical, and threats to severely reduce supplies have to be assessed. Computer models, based on empirical data, have been developed to examine wood supplies with and without protection during an outbreak.

Non-timber impacts

In recent years, there has been increased desire to more actively identify and manage non-timber values within forest management plans. Some examples include the establishment of 'reserve' areas (where little or no human intervention is permitted), ecologically sensitive areas (e.g., rare species, natural vistas), and wildlife habitats (e.g., mature coniferous forest habitat, deer wintering areas). These particular management objectives pose another dilemma (i.e., whether to protect or not) when the selected areas contain spruce-fir forests threatened by spruce budworm outbreaks. Additional values, less often identified for impact and protection, could include increased risk of fire, water quantity and quality, soil erosion (on steep slopes), aesthetics, as well as recreational and property values.

Economic impacts

For private woodlot owners, the magnitude of economic loss is related to the size of their property, the amount of vulnerable budworm host material present, and the intensity with which the property is being managed. Even individual landowners with vulnerable ornamental trees have values at risk.

Economic values at risk can be dominated by potential losses to the forest industry, which can be a major portion of provincial or regional resource-based industries. The threat of a budworm outbreak usually results in cost/benefit analyses that reflect local resources and values. Individual circumstances would determine relative economic importance that could be summarized with indicators such as the following:

- Number of direct and indirect jobs that could be affected
- Value of wages and salaries
- Silvicultural investments at risk
- Regional or local importance (e.g., number of forest-dependent communities)
- Proportion of all goods produced in the province
- Proportion of exports
- Gross value of production
- Proportion of Gross Domestic Product

Planning and Managing Production Systems to Prevent Organisms From Becoming Pests

General

Planning and managing are essential to good forest husbandry. However, producing a crop in which no organism will become a problem, or reach pest status, is seldom achieved by proper management alone, except perhaps on a limited scale. Unlike farms, where significant changes can be made annually, forests are vastly different settings. Forests are composed of production systems with long-lived softwood and mixed-wood forest ecosystems, and spruce budworm is only one of a complex of pests of concern. The principal hosts of spruce budworm constitute extensive parts of the forest landscape of Canada; hence, they are part of the generalized "budworm equation", i.e.,

Outbreak Potential = Budworm ± Hosts ± Natural Biocontrols ± Favourable Weather

Ways to alter natural biocontrols are limited and there is no way to control the weather. Consequently, mitigating the impact of a spruce budworm outbreak means taking actions against the insect itself, or its hosts, or both.

In reality, factors beyond the control of any one Province or agency limit the degree to which planning and management can prevent spruce budworm from becoming a pest. This is reinforced in the following description of the distribution of spruce budworm and its hosts:

> "The spruce budworm is the only eastern representative of the Abietoideae-feeding species. It is associated mostly with the Boreal forest, but also with the Great Lakes–St. Lawrence and Acadian regions... wherever balsam fir and white spruce are found... It is the most widespread of all the group as it extends from the shores of the Atlantic provinces and states westward to the foothills of the Rocky Mountains in Alberta and northward to the Arctic Circle in the Mackenzie River valley and the Yukon. It is probably the most important economically as it develops periodic outbreaks and causes considerable tree mortality of its two principal hosts, balsam fir and white spruce... It also causes significant damage to black spruce, red spruce, and subalpine fir."[2]

Forest management

Forest management is comprised of short- and long-term practices that alter forest conditions. Changed conditions can be more, or less, favourable to a pest. For protection against pests, actions that make conditions less favourable for attack or reduce potential losses are favoured.

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[2] Harvey, G.T. 1984. The taxonomy of the coniferagous *Choristoneura* (Lepidoptera: Tortricidae): A review. Pg. 21 In Sanders, C.J., R.W. Stark, E.J. Mullins and J. Murphy, Eds. Recent advances in spruce budworms research. Proceedings of the CANUSA spruce budworms research symposium. Can. For. Serv., Ottawa, Ont. ISBN 0-662-14202-0.

Generally this is achieved through harvesting practices, silviculture, and protection (see also section on Application of Control Measures to Maintain Pest Populations Below Threshold Levels).

Harvesting practices

Harvesting practices can reduce forest vulnerability. One method is to remove older host trees that have attained their maximum volume, or other specified objective. If this is done by a clear-cut operation and the site is left to develop naturally, these areas often regenerate to similar even-aged forests that ultimately become vulnerable to spruce budworm. The cut-over area can also be a candidate for planting, and hence possible alteration of species mix, or species conversion (raising the question of what species to choose) (see following section on Silviculture).

Another harvest method is selective cutting. In mixed-age spruce/fir stands, selective cutting of the oldest trees will reduce average stand age and, therefore, its vulnerability, but not necessarily remove the stand from the threat of attack and loss. In mixed-wood stands, selective removal of spruce and fir could convert the remaining stand to predominantly hardwood and hence make it non-susceptible. This might also increase natural budworm control by parasitoids from alternative insect hosts, though interrelationships are not well known and prescriptions remain undefined. Both these selective harvesting practices can be incorporated in operations depending on specific circumstances and management priorities.

Harvesting practices also spatially alter the forest at the landscape level through limitations of cut-block size and distribution. Although breaking the continuity of even-aged forests helps to reduce vulnerability and increase dispersal losses of early instar larvae, adult budworm females are capable fliers and can re-invade stands the following year. Changing age-class structure over vast areas is a long-term endeavour.

Silviculture

Silvicultural practices may include: (1) planting non-susceptible or less-vulnerable species (see section on Application of Control Measures to Maintain Pest Populations Below Threshold Levels: Cultural), (2) thinning stands to increase tree vigour, and (3) thinning stands to favour non-susceptible or less-vulnerable species by selectively reducing the number of host trees. The choice of species to plant is usually made in favour of species that are closely related to the climax forests that naturally dominate our landscape. Planting introduced species or changing species composition to reduce vulnerability is tantamount to altering natural biodiversity. Plantations or thinned stands create conditions conducive to their own unique set of pest problems. Thus, the merit of attempting to address the budworm problem solely by silviculture brings with it other implications. Like other management methods, silviculture is only one part of an IPM program that keeps in mind the large-scale and long-term focus. It is necessary to plan reforestation programs that use ecologically based, site-specific soil and plant information while not forgetting the possibility of future protection needs (see also section on Application of Control Measures to Maintain Pest Populations Below Threshold Levels: Cultural).

Identification of Potential Pests

There are many pests of concern in the forest other than spruce budworm (e.g., hemlock looper, tussock moths, tent caterpillars, sawflies, bark beetles, as well as various diseases of the foliage, roots, and stems), and each has its own set of conditions that dictate how it could be managed. Efforts to change forest conditions to the detriment of spruce budworm could create conditions appropriate for the irruption of other pests. The biology and related management issues of most of these are often less understood than those of the budworm.

Additionally, there are threats associated with accidental introductions of foreign pests that can have major significance (e.g., tree mortality, changes to natural biodiversity) under favourable conditions, especially when immediate control is not initiated or possible. Some examples from the past include: balsam woolly adelgid, gypsy moth, Dutch elm disease, white pine blister rust, and beech bark disease. In recent years, concerns have increased over the introduction of Asian gypsy moth, Asian longhorn beetle, brown spruce longhorn beetle[3], emerald ash borer, pine shoot beetle, various other bark beetles, and butternut canker. These and countless other threats are potentially carried on ships from around the world as incidental travellers in or on packaging material and dunnage, and by various other means of transportation and commerce.

On occasion, minor pests can generate heightened awareness when they attack high-value plantations or thinned stands created to offset wood supply shortages, or natural stands managed for non-timber purposes, such as parks or wildlife habitat. In these cases, control actions can be warranted. Sometimes manual techniques and small-scale habitat destruction (including burning) can be effective and sufficient without the use of insecticide. In some instances, the ground application of insecticide is practical, and even small-scale aerial applications can be efficient.

Availability of a suitable insecticide is a complicating issue associated with an outbreak of a minor pest. Often, the only insecticide registered is a chemical product because biological alternatives have not been developed. Lack of registered and/or effective alternatives is also a concern for forest managers and others having to cope with major pest outbreaks.

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[3] Anecdotally, the confirmation of the brown spruce longhorn beetle in Nova Scotia in 2000 might have severe long-term consequences (i.e., impact on weakened spruce trees) following another spruce budworm outbreak should efforts to eradicate the beetle not succeed.

Monitoring Populations of Pests, Beneficial Organisms, and All Other Relevant Environmental Factors

Pest surveys

Monitoring

Surveys are used to determine and monitor budworm population levels (see following section on Forecasting) and annual forest conditions, as well as to track long-term trends (e.g., egg or larval counts, aerial surveys of defoliation). Aerial and ground surveys provide ways to identify areas of dead or dying stands. Aerial surveys of defoliation are best conducted during a brief period, possibly two weeks, after feeding has stopped and damage is evident as a reddish-brown colour on infested trees. For best visibility, trained observers conduct mapping flights using high-winged aircraft or helicopters. When possible, defoliation is generally classified as Light (≤30%), Moderate (31–70%), or Severe (>70%), and boundaries of affected areas are sketched on maps of convenient scale from the aircraft. These areas are later transferred to other base maps and the size of the outbreak is calculated. These maps are used in determining areas in need of protection. Surveys of tree mortality can be conducted during the survey for defoliation or at some other convenient time. Some jurisdictions have recently started using laptop computers and special software that allow observers on the aircraft to directly record information in Geographic Information System (GIS) databases.

Navigation of aircraft was historically done using maps, careful observation, and communication between observer and pilot. In the 1980s, this was improved by using Loran-C equipment to augment map-reading. Greater accuracy is now achieved using Global Positioning Systems (GPS).

Research has been conducted with satellite imagery and high-level aerial photography to rate and map defoliation, but, to date, a suitably accurate, timely, and affordable system has not been developed. Theoretically, this could be linked to GIS databases and used in stand-specific growth and yield models to improve wood supply analyses, harvest plans, and protection planning.

Forecasting

Surveys are well established for predicting the extent and severity of outbreaks for the ensuing year during epidemics (see also section on Establishment of Thresholds: Damage thresholds). The traditional method is an egg mass survey conducted in late summer after moth flights have occurred and mated females have deposited their eggs. In the early 1980s, some provinces and states (e.g., Maine) replaced this with a survey of overwintering second instar (L2) larvae. Population categories relating egg mass or L2 numbers to expected defoliation have been developed. The L2 survey requires a specialized laboratory and use of sodium hydroxide to extract larvae from the branches. A more time-consuming technique can be used in the spring by collecting branches and forcing larvae to emerge under laboratory conditions. This can provide information on larval numbers, overwinter survival, and parasitism but the latter two factors seldom greatly influence populations. Furthermore, the use of this technique is impractical in large-scale control programs because spring is too late for forecasting and planning operations.

When populations are extremely low or at endemic levels, it is less practical to monitor density using egg mass or L2 surveys without greatly increasing the number of trees sampled per location. In recent years, some jurisdictions have adopted the use of special insect traps baited with synthetic female sex pheromone to capture male budworm moths to detect and forecast population changes. Although advances have been made in some jurisdictions, relationships between trap catches, population change or defoliation are still being developed. Nevertheless, trends revealed by increases in trap catches could signal increasing populations and lead to egg mass or L2 surveys that have associated predictive damage levels. Whether results from pheromone trap surveys can be used to define areas for an early intervention strategy remains to be determined.

A fairly recent development in association with pheromone trap surveys is the use of a method of analysis known as “Kriging”. This is a geo-statistical procedure applied to plots of related data (e.g., number of budworm moths per trap) to interpolate or estimate values between sample points over varying distances between them (somewhat similar to making a weather map of temperatures from readings taken at different locations). Class limits can also be set and the data displayed as landscape maps showing zones of specified populations, thus removing the subjectivity in making hand-contour maps based on sample point data. Changes in population densities between years can also be calculated and plotted.

Monitoring beneficial organisms

Years of monitoring beneficial organisms (i.e., parasitoids, predators, and disease) in operational surveys and research led to the realization that this is of limited operational benefit. This is because interactions between these organisms are so complex in population dynamics that they are difficult to study, but, more importantly, there is no single factor that regulates budworm outbreaks (see also sections on Primer on Spruce Budworm: Biology; and Monitoring Populations of Pests: Pest surveys).

Monitoring environmental factors

Environmental factors can be physical (e.g., host trees), biological (e.g., bio-controls), chemical (e.g., nutrition), and meteorological (i.e., weather). Studies have revealed much about how these interact in complex ways to affect the life cycle of spruce budworm and influence its damage. Also revealed are the concomitant implications and operational limitations to monitoring local-level interrelations (especially including weather) over vast geographic areas. Consequently, the proxy measurement for environmental factors is the annual change in population density and severity of damage, rather than individual measurements. Factors that are measured, however, are indicated throughout this report. Long-term implications from global weather changes would only be speculative at this time. During control programs using insecticide, weather monitoring is essential for optimizing treatment applications (e.g., aircraft use and biological treatment window) (see also section on Establishment of Thresholds: Action thresholds).

Establishment of Thresholds

Economic thresholds

There is no standard economic threshold because each situation has unique circumstances that the individual forest manager has to evaluate in the context of his or her short- and long-term objectives. Whereas the principles could be common, the magnitude of scale is vastly different for a small private woodlot compared with large industry or government (see also section on Primer on Spruce Budworm: Impact).

Cost of protection

Protection programs using insecticide incur various costs that reflect their size and complexity (e.g., number and type of aircraft, number of loading sites and airstrips), as well as the cost and type of product. The principle of economy of scale applies, and optimization of costs is a fiscally responsible role of resource management, as it could affect other socio-economic programs.

When protection programs are small, certain cost differentials on a per-hectare basis may seem negligible, or at least deemed to be acceptable. The cost differential is magnified in a large program. For instance, at $20/ha *v.* $30/ha, the difference in cost of a 100 000-ha program, at $2 million *v.* $3 million, respectively, might be acceptable. On the other hand, a one million-ha program with a $10 million cost difference would most likely be scrutinized more closely, especially when money comes from provincial coffers (where public funds are needed for health care, education, social programs, etc.). In either case, the salient objective is to obtain a desired level of protection in a responsible, cost-efficient manner, in terms of the options available. Hence the selection of products most likely to be successful is a major consideration, and it is therefore highly preferable that a range of options be available within an IPM strategy. Whereas aerial insecticide control programs in the 1980s could be conducted for under $20/ha, current-day costs range from $30 to more than $50/ha, depending on product, application rates, number of applications, aircraft, and logistics. There are significant implications if large programs are needed in the future.

Damage thresholds

According to the number of budworm found in the forecast survey, thresholds are used to establish and delineate on maps zones of Low, Moderate, High, or Extreme populations. These categories refer to levels of defoliation expected from larvae feeding on the current-year needles that will be produced the following summer. Generally, Low = ≤30% current defoliation, Moderate = 31–70%, Severe = >70%, and Extreme = complete loss of current-year foliage plus some feeding on previous years' foliage. Repeated moderate and severe defoliation lead to volume loss and tree mortality (see also section on Primer on Spruce Budworm: Impact).

Light defoliation caused by Low populations, even for several years, is unlikely to cause tree mortality, and generally does not cause significant reduction in annual volume increment. Consequently, in designing control programs aimed at foliage protection, candidate areas would be selected from zones with Moderate or higher populations. If the objective were population reduction or maximum protection of growth, even Low populations might be candidates for control (if areas had already been predisposed by severe defoliation). Volume loss and tree mortality estimates based on empirical data have been incorporated into computer decision support models to project potential losses according to specified input parameters (e.g., outbreak severity, forest type, annual defoliation, and population forecast).

Action thresholds

Planning

During an outbreak, it is seldom possible to consider applying an insecticide to the whole infested area, primarily because costs become prohibitive (e.g., Establishment of Thresholds: Economic thresholds). Methods have been devised to prioritize areas.

In eastern Canada, one of the oldest methods was a Hazard Rating system incorporating plot-specific data about current defoliation, previous damage (or loss of old needles), tree vigour, and budworm egg mass density (i.e., population forecast for the ensuing year). In the early 1980s, that was replaced in some jurisdictions by a system using information from aerial surveys of defoliation and fall L2 forecast surveys. Hazard areas were considered to be susceptible stands that had moderate or severe defoliation in either or both of the previous two years *and* were predicted to have moderate to extreme populations in the ensuing year. Lower thresholds (e.g., based only egg or larval counts) were often considered for high-value seed orchards, plantations or thinned stands. Maps traditionally used for large-scale protection planning were based on forest inventories and aerial photographs at various scales. There are variations in how planning criteria are used between jurisdictions for local needs.

A newer tool used to identify areas for protection is computer-based GIS databases that contain specific attributes (e.g., species, density) for all forest stands, as well as non-forest areas or areas managed for non-timber purposes. Using GIS technology, specific criteria can be selected and used to identify stands to be included or excluded from protection. Buffer zones, for instance, are areas between treatment areas and specified areas where the presence of insecticide is undesired, thus minimizing exposure to insecticide in these locations (e.g., around human habitation, intakes to water supplies, ecological reserves, blueberry fields, bodies of water, rivers, lakes and streams).

Buffer zones are set by appropriate federal and provincial departments and can be determined according to many parameters (e.g., wind speed, type of insecticide, type of aircraft, and spray equipment). Buffer zones have been set using empirical data from laboratory and field studies, and/or models, or social considerations. Provincial environment departments issue permits for operational programs before a program can take place. These also specify restrictions such as maximum wind speed (and possibly direction) and safety precautions. Only pesticides that have been approved by the Federal registration system under the *Pest Control Products Act* can be used operationally (see also section on Application of Control Measures to Maintain Pest Populations Below Threshold Levels: Insecticide registration – Role of the PMRA).

If a decision is made to conduct an aerial insecticide control program, many actions are necessary from the determination of the amount of product, aircraft, and logistical support, to the designation of treatment areas and subsequent applications and evaluation. Complex computer-based Decision Support Systems (DSS) have been developed to assist in protection planning by calculating stand priorities (PROPS) based on outbreak scenarios and various timber and non-timber parameters. Composite models such as BioSIM can make site-specific and landscape projections of larval development, based on temperature and geo-referenced weather data, and predict possible defoliation and larval mortality, based on spray deposit measurements and larval counts. Optimal applications can be determined by using: software to design spray blocks and lines (SprayAdvisor); aerially collected real-time weather data (AIMMS-10, AIMMS-20); models to simulate spray deposit to determine the best way to minimize off-target drift (AGDRIFT); Differential Global Positioning Systems (DGPS) to improve aircraft navigation over the spray block; and automated spray boom control devices. Efforts are being made to further refine these, develop newer ones, and bring these technologies to fully integrated use.

Timing thresholds

Not all larvae emerge at the same time nor do buds on all trees flush at the same rate. Therefore, to achieve best efficacy, both must be closely monitored to ensure the insecticide is not applied too early or too late. Monitoring is done using degree-day projections and field collections of larvae and tree shoots, which are put in classes of larval or shoot ‘index of development’. At least one jurisdiction has used low-level aerial reconnaissance to conduct landscape evaluations of shoot flushing on balsam fir and other closely occurring tree phenology (e.g., some hardwood flowering).

Protection of current-year foliage requires that the insecticide be applied at an optimal time after larval emergence and before large amounts of foliage are eaten (i.e., before larvae reach the sixth instar). Insecticide should therefore be applied during that window. If budworm populations are extremely high, the sheer number of larvae can significantly deplete foliage at the bud-mining stage before current-year needles grow. This creates difficult conditions for protection, though there is a narrow window when larvae move about on the needles and spin silk shelters outside the buds before the shoots and needles expand. This presents a control opportunity better suited to a contact insecticide than one that has to be eaten. In some jurisdictions, different timing is used (especially on white spruce) to maximize larval mortality and reduce feeding in the ensuing years. Annual monitoring determines when treatment might be needed again.

Monitoring the development of foliage on host trees is critical because this is the main target for the insecticide—especially to facilitate feeding inhibition or cause mortality by a product that must be ingested to be effective, as opposed to one that acts by contact. Differences between the rate of flushing of different host species (i.e., balsam fir; white, red, and black spruce) must be considered for optimal timing. The occurrence of mixed species over large geographic areas and different topographical features makes a double application of insecticide a virtual necessity (albeit more costly than a single application), especially if the product being used is only effective by ingestion or has a short period of activity. In fact, that was the normal prescription for chemical insecticides. Two applications also help to offset the likelihood of poor results due to uneven insecticide deposit, and adverse spring weather (i.e., cool and wet conditions), which tends to slow insect movement and feeding.

Application of Control Measures to Maintain Pest Populations Below Threshold Levels

Cultural

In silvicultural programs (see also section on Planning and Managing Production Systems to Prevent Organisms From Becoming Pests), reforestation includes the balanced use of natural regeneration and the planting of sites that have insufficient regeneration. To reduce the vulnerability of future stands, alternative tree species can be planted (raising the question of natural biodiversity). In some instances, prescribed burning might be possible to convert the site to less vulnerable tree species. Increased growth for greater vigour and reduced vulnerability as well as greater volume yield can be achieved using genetically improved seedlings, and by keeping crop trees in a free-to-grow condition through vegetation management to suppress plants that compete for nutrients and retard growth. In stand-thinning operations, less-vulnerable species can be favoured whenever possible. NOTE: although lowering vulnerability should reduce losses, it does not imply there is no need for protection.

A novel method of long-term protection might be the use of spruce or fir planting stock genetically modified to contain the bacterium *Bacillus thuringiensis* (*Bt*) that is toxic to spruce budworm (see also section on Application of Control Measures to Maintain Pest Populations Below Threshold Levels: Biological). Methods involving genetic engineering are presently in the research phase, hence should be viewed in this context. Although the introduction of *Bt* genes into spruce seedlings has been done, long-term testing is required before further steps should be undertaken. Concern for resistance being developed by the insect is a significant factor, and therefore the development of techniques to limit the expression of the gene is important. Adding another defensive attribute at the same time would be highly desirable, as it is more difficult for insects to develop resistance to multiple factors. Moreover, other pests (diseases or insects) that are not affected by *Bt* could still be a problem necessitating other types of protection (including the increased use of other chemical pesticides that otherwise might not be needed). Sterility of modified plants is also being considered because of the concern for introduced genes migrating into native tree populations. In addition to questions of cost and practicality, public acceptance of genetically modified organisms will be an important consideration before using this biotechnology.

Another novel idea stems from research directed at isolating and identifying naturally-occurring insect toxins and other bioactive agents from endophytic fungi (i.e., fungi that live within the needles) associated with coniferous trees. Several new fungal metabolites toxic to spruce budworm have been discovered and the inoculation of conifer seedlings with some of these toxin-producing endophytes is under study. If successful, this could have implications for long-term reforestation.

Physical

Except for the techniques noted above, there is no practical physical method that can be implemented to reduce the chances of a budworm outbreak occurring, nor to reduce the impact once an outbreak begins.

Biological

Conserving natural biocontrols

Conserving natural biocontrols is especially important when protection programs include ground or aerial applications of insecticide. This can be addressed in several ways: (1) the use of a narrow spectrum insecticide (i.e., one that affects only a single pest or has little effect on a limited range of other organisms); (2) the cautious use of broader spectrum products using lowest effective dosages to limit adverse effects on non-target organisms; (3) the identification of the minimal area in need of protection (hazard-rating systems originally developed to minimize cost and protection priority models can be used to identify minimal target areas); and (4) the use of buffer zones (see also section on Establishment of Thresholds: Action thresholds) is another, though indirect, way in which natural biocontrols are conserved in local areas.

By combining all these criteria, it is common to develop protection programs to target only a small part of an outbreak, thus conserving natural biocontrols, so the overall infestation generally runs its natural course. These risk-reduction actions minimize undesired environmental contamination and side effects of insecticide applications.

Use of predators and parasitoids

Natural biological factors that operate during the spruce budworm's life cycle are complex within and between years. Despite decades of research, however, much remains to be learned (see also section on Primer on Spruce Budworm: Biology). In the past, trials with the artificial manipulation or application of some of these as well as introduced parasitoids generally proved to be ineffective or had such severe practical limitations that they were regarded as being "not available". A microscopic parasitoid called *Trichogramma minutum*, which kills spruce budworm eggs, gave positive results in small-scale trials. Despite commercialization, however, it never became operationally competitive for use against spruce budworm. This parasitoid has a large host range, so it could also affect populations of many other insects.

Use of diseases

Fungi, bacteria, microsporidan protozoa, and viruses infect spruce budworm. Many have been studied and found to have very limited potential for control or will require much more research and development, such as genetic modifications (see also section on Application of Control Measures to Maintain Pest Populations Below Threshold Levels: Cultural). Genetically modified virus is under development, but that, too, has initiated discussion about public acceptance.

One success story is a biological insecticide based on the naturally occurring soil bacterium *Bacillus thuringiensis* var. *kurstaki* (commonly referred to as *Bt* or sometimes *Btk*). Research throughout the 1970s and 1980s brought *Bt* to commercial production and operational use in forestry.

The environmental benefit of *Bt* is that it has a narrow spectrum of activity because it only affects larvae of Lepidoptera (i.e., butterflies and moths) if they are feeding at the time of application *and* ingest a lethal dose. Although *Bt* has much lower impact than chemical insecticides, it is also still negatively perceived by some people. *Bt* tends to be less persistent than chemicals and is degraded by sunlight. *Bt* has no contact toxicity and must be ingested in sufficient quantity to be effective. Larval death is caused by septicemia and toxemia facilitated by their naturally high internal *pH*. Some larvae can recover and still cause unwanted defoliation if they only ingest a sub-lethal dose.

To increase the chance of success, *Bt* is usually not applied until much of the current-year foliage has flushed from beneath the bud caps (see also section on Establishment of Thresholds: Action thresholds). This means a narrower window of application (as much as 3–10 days less) for *Bt* compared to chemical insecticides, and this must be considered when the logistics of a control program are developed. Concern is elevated when dealing with forests consisting of mixtures of host species that flush at different rates over complex topography. This could substantially increase the number of aircraft required and significantly increase costs. Other costs associated with *Bt* have been reduced by the development of more concentrated formulations making shipping and application costs potentially similar to those incurred with chemical insecticide, depending on circumstances (see also section on Establishment of Thresholds: Economic thresholds).

Much information on the use of *Bt* was collected from the mid-1980s to the mid-1990s when budworm populations were declining. During that time, *Bt* efficacy was often much less than chemical insecticide at moderate and high populations. This was frequently associated with lower rates of budworm larval mortality with *Bt* than with chemicals, thus leaving greater numbers of larvae that caused greater levels of defoliation. A concern for the future is whether *Bt* will give acceptable effectiveness when populations again reach epidemic levels. Recent small-scale trials are being conducted to assist in making future prescriptions, such as higher application rates, repeat applications, and improved products (which all have cost implications). Finally, much needs to be learned about the use of *Bt* to achieve adequate protection on various species of spruce.

Behavioural

Research has been done to investigate products that can alter spruce budworm behaviour (e.g., anti-feedants), but results did not lead to an efficacious product. The only material still under consideration is synthetic sex pheromone for use in mating disruption. Natural pheromones are odours emitted by female moths to attract males for mating. Thus, the theory is to permeate the air with synthetic pheromone so that male moths will be confused and unable to find females for mating, thereby reducing the number of viable eggs laid. Research indicates that in high-density populations other factors come into play and make this strategy less likely to work. Whether it could be used to suppress increasing populations or to hasten the collapse of declining populations is uncertain. One concept is to first reduce larval populations by applying *Bt* or other insecticide and then apply pheromone to disrupt mating. Considering debatable results from aerial trials in the 1970s, as well as some positive results from ground trials in the 1980s, further work is needed to determine whether a pheromone formulation and definitive prescription can be developed for effective and affordable operational use. Some positive small-scale aerial trials were done since the late 1990s, but progress is hampered by high costs and uncertain industrial pheromone supply, even for research. Criteria for when and where to intervene are not defined.

Chemical

From the early 1950s to the mid-1960s, the infamous insecticide DDT was extensively used until less-persistent replacements were developed. Despite the testing and use of several products (including some with agricultural and domestic uses), the organophosphate fenitrothion became the principally used insecticide. This was closely followed by the carbamate aminocarb, which was voluntarily withdrawn from the market by the manufacturer in 1987 because of insufficient sales (its use was almost solely in forestry). Registration (see also section on Application of Control Measures to Maintain Pest Populations Below Threshold Levels: Insecticide registration – Role of the PMRA) for large-scale aerial use of fenitrothion was terminated in 1998.

Many of the few remaining older registered products will probably be unacceptable for future large-scale use because of smaller and outdated toxicological databases, known adverse environmental side effects, low efficacy, and high cost. Federal re-evaluations (see also section on Application of Control Measures to Maintain Pest Populations Below Threshold Levels: Insecticide registration – Role of the PMRA) of the registrations of organophosphate and carbamate insecticides are under way. The only alternative to *Bt* is the synthetic insect growth regulator called tebufenozide (Mimic®), often referred to as a 'bio-rational insecticide'. This product, when ingested in sufficient quantity, interferes with the normal moulting process, leading to the insect's death. Like *Bt*, it is narrow spectrum (also affects larvae of butterflies and moths), and offers similar environmental protection. It, too, could have non-target effects on other Lepidoptera, though less severe than traditional chemical insecticides. The efficacy of tebufenozide continues to be studied, including the possible direct or indirect targeting of first instar larvae to reduce the following generation. This may open a wider window of application and an unproven strategy for budworm control.

Insecticide registration – Role of the PMRA

Any insecticides – or other pesticide – that may be developed in the future for use against the spruce budworm or any other pests will have to be registered by the Pest Management Regulatory Agency (PMRA) of Health Canada. Pesticides in Canada are regulated under the *Pest Control Products Act* (PCPA) and Regulations. Companies that wish to sell a pest control product in Canada must submit detailed information and data for evaluation by the PMRA. These companies provide all the scientific studies needed to determine if the product is acceptable in terms of safety, merit and value. Before making a registration decision on a new pest control product, the PMRA conducts a comprehensive assessment of the risk and value specific to the proposed use. The evaluation determines whether the product is granted registration and allowed for sale and use in Canada, or is rejected. Pest control products are registered only if the human health and environmental risks are acceptable and the product is efficacious.

Only pesticides that are registered for use under the PCPA may be imported into, or sold or used in Canada. The provinces and territories regulate the sale, use, storage, transportation, and disposal of registered pesticides in their jurisdictions as long as the measures they adopt are consistent with any conditions, directions, and limitations imposed under the PCPA and other federal legislation.

Evaluation of Pest Control Measures Used

Effects of control measures

Whenever there is intervention in natural processes, there are effects on the target organism, non-target organisms, and the environment. This not only applies to insecticides, but is also true for forest management and silvicultural options. Ideally, one would like to have control measures that affect only the pest organism. Unfortunately, very few such options exist, especially for forest pests. During the registration process for all types of pesticides, PMRA conducts a comprehensive assessment of human and environmental risks and value. Companies that wish to sell a pest control product in Canada must submit detailed information and data for evaluation by the PMRA. The rigour and costs of these studies, and the small and uncertain forest market (compared to agriculture), are the main reasons why very few insecticides are registered for use against spruce budworm and other forest insects. In many instances, post-registration studies are conducted to add data to the research studies and make adjustments as necessary (e.g., refinement of dosage rates, buffer zones).

Efficacy of control measures

It is necessary to state program objectives or target levels of protection, such as foliage retention (e.g., to retain a certain percent of the current year's foliage) or insect mortality (i.e., specified percent population reduction). Efficacy is a measure of the degree to which treatments achieve their objectives (see also section on Establishment of Thresholds: Action thresholds). If there is no measure of comparison between treated and untreated check areas, it is impossible to confirm how much protection was provided, and difficult to determine whether future changes are needed. Thus, efforts must be made to monitor pre-spray and post-spray conditions in comparable areas. A relationship between larval mortality and foliage protection does not always occur because mortality might not happen until well into the sixth instar of larval development, especially if the insecticide application was late. Consequently, larval mortality can be high but foliage protection low.

The objective of insect mortality could be to reduce populations so that the numbers of larvae the next year will only cause light defoliation and not require treatment. In that case, objectives would relate to the target levels of tolerable populations and the proportion of the outbreak area to which this prescription is applied. Measures of efficacy can be determined and expressed in different ways.

Research for the Future

Some issues of future R&D have been alluded to in various parts of this document.

Research of protection options based on forest management and silviculture can be constrained by the amount of area potentially at risk to budworm outbreak and the time it takes to make significant changes. Furthermore, the list of possible options is short (e.g., changing species composition and forest structure, planting non-native species, using genetically modified trees containing insecticidal genes), though techniques to achieve these might warrant research. They are also very expensive, and introduce their own set of unknown, though anticipated, future complex research issues. For instance, if the forest is managed differently or for another purpose, how does one cope with possible unknown future pest problems. One might even wonder about effects on biodiversity and implications to the carbon budget. The forests of today are different from those of the past, and will continue to change due to humans and nature.

During the epidemic phase from the 1950s to the 1980s, scientists gathered massive amounts of data about spruce budworm. Conversely, much less is known or understood about the endemic phase. It has only been within the past 10–15 years that scientists have had the opportunity to investigate biological functions that interact during this phase. Investigations and analyses are ongoing to enable the interpretation of these relationships. Studies of population dynamics should be continued to gain greater understanding of natural processes that might result in the identification of control opportunities not presently known.

Applied control using insecticides will probably continue to be necessary. Because of the paucity of acceptable alternatives, there will be heavy dependence on products with as narrow a spectrum of non-target side effects as possible. At present, this implies using biological insecticides based on the bacterium *Bt*, and the ‘bio-rational’ insect growth regulator, tebufenozide. How efficacious these will be during rising budworm populations remains to be seen, though current research shows some promise on balsam fir and white spruce. Protection of red spruce (or red-black hybrids) needs to be investigated. One might expect an increased demand for additional information on the direct and indirect environmental side effects of these materials, especially if they become used perennially over vast areas as was common with chemical insecticides in the past. The possibility of other known controls (e.g., pheromones, viruses, fungi) or novel materials being developed will require similar verification and validation.

Likewise, new prescriptions for insecticide uses such as “early intervention” and “maintenance of volume increment”, or spraying in alternate years need to be examined to determine their feasibility and whether they would be more advantageous than past prescriptions, based mostly on keeping trees alive. In this case, there are opportunities for further use, development, and verification of computer-based decision support systems as well as to investigate, compare and contrast different scenarios.

In the final analysis, it is very likely that insecticides will be part of future integrated protection programs. And, because of the magnitude of spruce budworm outbreaks, this will necessitate aerial applications. Thus, it is necessary to continue to develop aerial application technology to ensure that systems are most efficient, safe, and effective (e.g., navigation, weather monitoring, application equipment, models to improve delivery to the designated area and reduce off-target drift).

Conclusion

The management of any natural resource is not an easy task, especially when stakeholders constitute not only those directly involved but also the general public. The challenge is increased when the resource is actually a multitude of interdependent systems. Moreover, the simple notion that proper management guarantees there will be no problem is far from being true. For years, there have been suggestions that budworm outbreaks should be left to run their natural course. When the information is assessed in terms of the social and economic implications of trying to manage forests and related resources without protection, the results speak for themselves. The following quotations illustrate this point:

> *"To manage the fir–spruce forest, it must be protected — no renewable resource can be managed if it cannot be protected."*[4]
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> *"The Commission perceives no technical reason, either on the grounds of public safety or functional effectiveness, why bacterial insecticides should be preferred to synthetic chemical insecticides, and therefore recommends contingency planning to protect 400 000 ha (1 000 000 acres) of forest annually against insect depletions and, on the basis of benefit/risk principles recommends the use of synthetic chemical insecticides sprayed by aerial means from fixed or rotary wing aircraft, subject only to operating within the rules and regulations prescribed by the federal authorities in Canada."*[5]
>
> *"Unless there is a commitment by the Provincial Government to an effective forest pest protection policy, then all silvicultural activities such as pre-commercial thinning and reforestation should be terminated. This would indicate the abandonment of any long-term management programme for the provincial forest resource."*[6]

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[4] Baskerville, G. 1976. Report of the Task Force for Evaluation of Budworm Control Alternatives. New Brunswick. pgs. 192-193.

[5] Connor, J. 1984. FORESTRY. Report of the Nova Scotia Royal Commission on Forestry. Nova Scotia. pg. 82.

[6] Poole, C.F. 1981. Report of the Royal Commission on Forest Protection and Management. Part 1. Newfoundland. pg. 98.

> *"The major loss of forest which will arise if the current budworm epidemic continues unchecked will have major socio-economic consequences, including increased unemployment. This is a major threat to the health of the Newfoundland population. In light of this, the postulated health hazards from the current short-term spraying program with aminocarb in Newfoundland are deemed to be insignificant."*[7]

Uncontrolled outbreaks of spruce budworm can cripple forest industries and create unemployment, with associated adverse social and economic consequences. Because the use and management of Canada's forests have far-reaching economic and social implications, ranging from local to international, it is only natural that difficult issues will bring public, political, industrial, scientific, and even academic debate.

There is no single prescription for managing forests and related resources against the impacts of spruce budworm outbreaks. This document has outlined, in general terms, the principles that form the basis of IPM for spruce budworm in Canada along with information about available methods, limitations, and future needs. Every province, jurisdiction, industry, agency, or even private woodlot owner, having to manage forests threatened by spruce budworm, has to judge for themselves which actions and components of the IPM strategy best suit their own situation and use them in an appropriate adaptive manner.

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[7] Patey, P. 1980. Supplemental Report (1980) of the Newfoundland Medical Association Committee Formed to Review the Medical Aspects of the Spruce Budworm Epidemic and Control Programme. Newfoundland.