The eastern hemlock looper, *Lambdina fiscellaria fiscellaria* (Guen.) (Lepidoptera:Geometridae) in Newfoundland, 1983 - 1995

J. Hudak

Newfoundland and Labrador Region • Information Report N-X-302

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Cover Photo: Balsam fir stands severely damaged by the eastern hemlock looper. Salvage harvesting in foreground.

This Canadian Forest Service publication uses recyclable paper.

The National Library of Canada has catalogued this publication as follows:

Main entry under title:

The eastern hemlock looper, *Lambdina fiscellaria fiscellaria* (Guen.) (Lepidoptera: Geometridae
in Newfoundland, 1983 - 1995

(Information report; N-X-302)
Includes an abstract in French.
ISBN 0-662-25669-7
Cat. No. Fo46-15/302E

1. Hemlock looper -- Newfoundland.
2. Balsam fir -- diseases and pests -- Newfoundland.
I. Hudak, J.
II. Canadian Forest Service. Newfoundland & Labrador Region.
III. Series: Information report (Canadian Forest Service.
Newfoundland & Labrador Region); N-X-302

SB945.H45E37 1997 634.9'6'75467 C97-980153-2

ISSN NO. 0704-7657
CAT. NO. Fo46-15/302E
ISBN NO. 0-662-25668-9

Copies of this report are available in English
at no charge from:

Natural Resources Canada
Canadian Forest Service
P.O. Box 6028
St. John's, Newfoundland
A1C 5X8

Telephone (709) 772-4117
Facsimile (709) 772-2576

OR

A microfiche edition of this publication may be purchased from:

Micromedia Inc.
240 Catherine Street, Suite 305
Ottawa, Ontario
K2P 2G8

Printed in Canada

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edited by

J. Hudak

INFORMATION REPORT N-X-302
1996

NATURAL RESOURCES CANADA
CANADIAN FOREST SERVICE
NEWFOUNDLAND AND LABRADOR REGION

Table of Contents

ABSTRACT

The eastern hemlock looper (EHL), *Lambdina fiscellaria fiscellaria* (Guen.), is a native species to Newfoundland and outbreaks of this insect have periodically caused extensive defoliation and tree mortality of balsam fir, *Abies balsamea* (L.) Mill. The EHL is distributed from Newfoundland to Alberta, but outbreaks have been more frequent and severe in Newfoundland than elsewhere in its range.

This report reviews the outbreak of the EHL in Newfoundland from 1983 to 1995 and summarizes survey and research results:

1. The outbreak started as two small infestations in eastern and central Newfoundland in 1983 and expanded to western areas in subsequent years. Moderate and severe defoliation extended over 541 000 ha in productive forests by 1995 and caused an estimated 11 300 000m^3 of tree mortality and additional growth loss in excess of 100 000m^3.
2. A sequential sampling method for overwintering eggs of EHL was developed to forecast looper populations and defoliation severity. Research on biological mortality factors indicated that native entomopathogenic fungi are important in influencing the collapse of EHL infestations.
3. The pheromone components of the EHL have been identified and application to patent the discovery filed. Artificially produced pheromone is used in pheromone bated traps to efficiently detect and monitor EHL populations to facilitate timely response to outbreaks.
4. Development of control tactics resulted in registration of *Bacillus thuringiensis* Berliner var. *kurstaki* and the growth regulator tebufenozide for use against the EHL. Experimental mass fermentation of entomopathogenic fungal spores *Emtomophaga aulicae* (Reichardt) Humber, has been patented and exotic parasitoids evaluated for control of EHL.
5. Research on biodeterioration and utilization of damaged stands indicated that secondary woodwasps and bark beetles influence the establishment of decay fungi and the rate of deterioration. Woodwasps and associated fungi are more common than bark beetles in damaged stands and permit longer salvage periods.
6. Detection and classification of insect damage including discoloration and loss of foliar biomass using satellite imagery has been successful. Anticipated advances in remote sensing may provide predictive models to facilitate integrated pest management at the landscape level.
7. The EHL is the most destructive forest defoliator of Newfoundland forests and is capable of causing severe extensive tree mortality. The widespread forest depletion has major socio-economic impacts which justify the application of control measures to facilitate sustainable development.
8. The current outbreak of the EHL is the seventh extensive outbreak recorded in Newfoundland and there is a considerable data base on population biology of the insect and its impacts on the forest and also on control alternatives. Research to consolidate all available information and knowledge into a comprehensive decision support system has been successful to improve the integrated management of the EHL.

RÉSUMÉ

Les infestations de l'arpenteuse de la pruche (AP), (*Lambdina fiscellaria fiscellaria* (Guen.)), une espèce indigène de Terre-Neuve, causent périodiquement une défoliation et une mortalité à grande échelle du sapin baumier (*Abies balsamea* (L.) Mill.). L'aire de répartition de l'arpenteuse s'étend de Terre-Neuve à l'Alberta, mais les infestations se sont révélées plus nombreuses et plus graves à Terre-Neuve que partout ailleurs.

Le présent rapport passe en revue les infestations de

l'AP à Terre-Neuve entre 1983 et 1995 et résume les résultats des relevés et des recherches concernant ce ravageur :

1. L'infestation a débuté en 1983 dans deux petits foyers à l'est et au centre de Terre-Neuve, pour s'étendre les années subséquentes à l'ouest de l'île. En 1995, plus de 541 000 ha de forêt productive avaient été de modérément à gravement défoliés, phénomène qui a provoqué la mort de quelque 11 300 000 m^3 d'arbres et une perte de croissance additionnelle de plus de 100 000 m^3.
2. Une méthode d'échantillonnage séquentiel des oeufs présents pendant l'hiver a été élaborée pour prévoir les niveaux de population de l'arpenteuse et la gravité de la défoliation. La recherche sur les facteurs biologiques de mortalité chez l'AP indique que les champignons entomopathogènes indigènes jouent un rôle important dans l'effondrement des populations de ce ravageur.
3. Les composantes des phéromones de l'arpenteuse ont été isolées et ont fait l'objet d'une demande de brevet. On a appâté des pièges sexuels avec une phéromone de synthèse pour détecter et surveiller efficacement les populations d'AP, et accélérer du même coup l'adoption de mesures de lutte.
4. L'élaboration de stratégies antiparasitaires a entraîné l'homologation du *Bacillus thuringiensis* Berliner var *kurstaki* et du tébufénozide, un régulateur de croissance, pour la lutte contre l'arpenteuse de la pruche. De plus, on a breveté un procédé expérimental de fermentation de masse de spores d'un champignon entomopathogène (*Entomophaga aulicae* (Reichardt) Humber) et on a évalué l'efficacité de parasitoïdes introduits pour la lutte contre l'AP.
5. Une recherche sur la biodétérioration et l'utilisation des peuplements ravagés a révélé que l'action de sirex et de scolytes, des déprédateurs secondaires, avait une incidence sur l'établissement de champignons de la carie et sur le rythme de détérioration des arbres. Les sirex et les champignons qui leur sont associés sont plus courants que les scolytes dans les peuplements endommagés, où on peut alors étaler sur une plus longue période les coupes de récupération.
6. Grâce à des images satellitaires, on a réussi à détecter et classer les dégâts causés par les insectes, notamment la décoloration et la perte de biomasse foliaire. Les progrès prévus dans le domaine de la télédétection pourraient déboucher sur des modèles de prévision qui facilitent la lutte intégrée contre les ravageurs au niveau du paysage.
7. L'arpenteuse de la pruche, capable de décimer les arbres d'un vaste territoire, est le plus grand défoliateur des forêts de Terre-Neuve. Le décroissement à grande échelle des forêts a des impacts socio-économiques majeurs, qui justifient l'application de mesures de lutte en vue de favoriser le développement durable.
8. La présente infestation de l'AP est la septième infestation majeure relevée à Terre-Neuve. On dispose désormais d'une base de données considérable sur la biologie des populations de ce ravageur et sur ses incidences sur la forêt, ainsi que sur les diverses mesures de lutte applicables. L'élaboration d'un système complet d'aide à la décision, fruit de la mise en commun de toutes ces informations et connaissances, a permis d'améliorer la lutte intégrée contre l'arpenteuse de la pruche.

Acknowledgments

Many individuals representing governments, universities, private forest and related industries and organizations have made significant contributions over the years to our research programs that produced the results summarized in this report. Purposefully I do not list individuals for the risk of overlooking some contributors, but I express my sincere gratitude to all those who cooperated and made this report possible. However, I wish to thank Hildegarde M. Ryan and Beverly A. Woodford individually for their perseverance and excellence in producing this report.

THE EASTERN HEMLOCK LOOPER, *Lambdina fiscellaria fiscellaria* (Guen.) (Lepidoptera: Geometridae) IN NEWFOUNDLAND, 1983 - 1995

J. Hudak, Editor
Natural Resources Canada - Canadian Forest Service

INTRODUCTION

The eastern hemlock looper (EHL), *Lambdina fiscellaria fiscellaria* (Guen.), is native to Newfoundland and outbreaks of this insect have periodically caused extensive defoliation and mortality of balsam fir, *Abies balsamea* (L.) Mill. The EHL is distributed from Newfoundland to Alberta, but outbreaks have been more frequent and severe in insular Newfoundland than elsewhere in its range (Otvos *et al.* 1979). Defoliation was severe and widely distributed throughtout the Island during the 1966 - 1972 outbreak and large scale aerial application of insecticides was required to minimize tree mortality (Otvos and Carter 1970; Otvos *et al.* 1971). The severe damage by the balsam woolly adelgid, *Adelges piceae* (Ratz.), particularly in western Newfoundland have also contributed to the severe tree mortality caused by the EHL (Hudak *et al.* 1978).

The most recent outbreak of the EHL began in 1983 (Clark and Carew 1984) and followed closely the collapse of the eastern spruce budworm (ESBW), *Choristoneura fumiferana* (Clem.), outbreak which had reached unprecedented size and severity by killing over 50 million m^3 of softwood stands (Poole *et al.* 1981; Flight and Peters 1992; Hudak 1991; Milne 1991). The widespread forest depletions caused by the ESBW and the pending outbreak of the EHL prompted the Canadian Forest Service (CFS) to enhance its forest protection research program to develop more effective, environmentally acceptable integrated pest management systems for the EHL.

This report reviews the outbreak of the EHL from 1983 to 1995 and summarizes survey and research results in: 1. Progress of defoliation and subsequent tree mortality; 2. Population dynamics including the assessment of biological mortality factors and the development of sequential sampling for overwintering eggs to forecast population levels and subsequent defoliation severity; 3. Development of a pheromone based detection and monitoring system; 4. Development of control tactics including the registration of *Bacillus thuringiensis* Berliner var. *kurstaki* and experimental mass fermentations of fungal spores, *Entomophaga aulicae* (Reichardt) Humber and the evaluation of exotic parasitoids for control of EHL populations; 5. Biodeterioration and utilization of damaged stands; 6. Detection and classification of damage with remote sensing; 7. Socio-economic assessment of the EHL and 8. Development of a comprehensive decision support system for the EHL.

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OUTBREAK HISTORY OF EASTERN HEMLOCK LOOPER IN NEWFOUNDLAND, 1983 - 1995

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and
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Department of Forestry and Agriculture - Newfoundland Forest Service

INTRODUCTION

The Forest Insect and Disease Survey (FIDS) of the Canadian Forest Service (CFS) in cooperation with government and private forest agencies have been conducting annual surveys over 50 years to detect, assess and forecast forest pest conditions (Sterner and Davidson 1982; Power 1986; Power and Williams 1987; Hall and Moody 1994). The results of such surveys have been instrumental in support of research and development programs including regional, national and international plant quarantine activities and have been used for practical ecosystem management decisions by client agencies in planning and conducting operational control programs to minimize forest depletion to facilitate sustainable forest development (Milne 1991).

Here we summarize the survey and research results that document the history of the most recent outbreak of eastern hemlock looper (EHL) from 1983 to 1995 in Newfoundland.

SURVEY AND RESEARCH RESULTS

Historically, ground and aerial surveys have been used to detect and sample various life stages of the EHL and to delineate and classify defoliation and subsequent tree mortality. Sampling methods for larvae and pupae and for collection of overwintering eggs of EHL have been described by Carroll 1956, Otvos 1974, 1975 and Otvos and Bryant 1972. Results from these surveys also provided an assessment of mortality factors and their role in the population fluctuation of the EHL (Otvos 1973).

The sampling of overwintering eggs to forecast larval populations and subsequent defoliation intensities was considered essential for the effective management of the outbreak. Intensive collection and counting of looper eggs from various substrates including balsam fir branches, crown inhabiting lichens, loose bark from paper birch and ground mosses provided the basis for the development of a sequential sampling systems for EHL eggs. Counting of eggs from a lower mid-crown branch from each of five balsam fir trees was considered adequate to forecast larval populations and defoliation classes (Dobesberger 1989). The evaluation of mortality factors in the population dynamics of the EHL is presented by Carroll in this report.

Aerial survey methods to scetch map defoliation intensity and subsequent tree mortality have been outlined by Moody 1979 and Sutton 1981. Annual defoliation maps were overlaid on forest inventory maps and digitized to determine the area and volume of affected stands and to derive forest depletion statistics (Hall and Moody 1994). More recently data from remote sensing methods including aerial photography, airborne multi-spectral scanners and from digital satellite imagery linked to geographic information systems have also been used to monitor forest pest damage (Power 1986; Power and Williams 1987; Power and D'Eon 1991; Hudak *et al.* 1993). The use of satellite remote sensing to detect and classify forest damage by the EHL is presented by Luther in this report.

The most recent outbreak of the EHL began in 1983 as two small infestations, one on the Avalon Peninsula near Markland and other near Bay d'Espoir. The area of moderate and severe defoliation totalled about 600 ha (Table 1). In addition looper larvae were common in the regular larval sampling throughout the Codroy Valley, along the North Shore of Bay of Islands in western Newfoundland and near Aspen Brook, Noel Paul's Brook and Lake Douglas in central Newfoundland indicating a general increase in looper population levels (Clarke and Carew 1994). Based on the summary of looper larval numbers the development of a new outbreak of the EHL was anticipated since 1979 but competition for food by the spruce budworm was considered to be the primary factor in slowing the progress of looper outbreak as the seasonal development of the looper follows that of the budworm by about a month (Otvos 1976; Otvos and Clarke 1979). Early detection of impending outbreaks of EHL is critical for effective management of this destructive pest. The development of a pheromone-based detection and monitoring system for the EHL is described by Bowers and West in this report.

Table 1. Eastern hemlock looper damage and salvage in productive forests[1] of Newfoundland, 1983 - 1995.

	Defoliation (ha)[2]		Volume (m^3)			
Year	Light	Mod.& Severe	Defoliated	Tree Mortality	Growth Loss	Salvage
1983	9 100	600	905 000	.	700	.
1984	42 000	53 000	8 902 000	.	67 000	.
1985	79 000	51 800	12 546 000	.	82 000	.
1986	116 000	215 500	30 211 000	3 207 000	283 000	339 000
1987	8 700	152 000	10 892 000	4 592 000	278 000	191 000
1988	4 700	12 900	1 769 200	281 600	123 000	191 000
1989	3 900	9 500	1 062 000	852 000	108 000	149 000
1990	10 600	1 900	1 665 000	95 000	93 900	165 000
1991	400	2 600	238 400	1 715 000	4 000	144 000
1992	1 600	4 000	237 300	355 000	9 800	97 000
1993	3 700	5 800	398 700		9 600	60 000
1994	1 900	9 700	326 500	32 900	5 600	29 000[3]
1995	26 900	21 400	4 532 700	158 800	28 000	20 000[3]
Total	309 100	541 200	73 685 800	11 289 300	1 093 500	1 385 000

1. Productive forest = Capable of producing ≥ 35 m^3/ha.
2. Defoliation; Light 6 - 25%, Moderate 26 - 75%, Severe 76 -100%.
3. Estimates to be reviewed.

The two infestations by the EHL on the Avalon Peninsula and near Bay d'Espoir recorded in 1983 have expanded considerably in 1984. In addition, separate areas of defoliation occurred in numerous locations in central and eastern Newfoundland. Based on the distribution of defoliation and subsequent intensive larval and egg sampling in most of the immature and mature forests of the Island the area of moderate and severe defoliation was forecast to expand in central and western Newfoundland (Clarke and Carew 1984, 1985, 1986). The distribution and severity of the outbreak peaked in 1986 when moderate and severe defoliation occurred on about 215 000 ha of productive forests (Table 1) and light defoliation on 116 000 ha (Clarke and Carew 1987). Tree mortality in severely defoliated stands exceeded 3 000 000 m^3 and growth loss caused by defoliation was estimated at 283 000 m^3 (Table 1). Research on the biodeterioration and utilization of stands damaged by EHL is presented by Warren in this report.

The distribution of the outbreak commenced to decline in 1987 when moderate and severe defoliation was recorded on about 152 000 ha of productive forest (Clarke and Carew 1988). However, tree mortality form cumulative defoliation reached 4 600 000 m^3 (Table 1, Figure 1). Generally, the outbreak continued to decline with some temporary fluctuations in subsequent years (Clarke and Carew 1989; Clarke *et al.* 1990, 1992; Raske *et al.* 1992; Bowers *et al.* 1993, 1994; Hudak *et al.* 1996).

The Department of Forestry and Agriculture of Newfoundland and Labrador in cooperation with the forest industry conducted operational control programs against the EHL beginning in 1985 with the application of chemical and biological insecticides (Table 2). The CFS cooperated by conducting concurrent experimental programs to develop improved, more effective formulations of environmentally acceptable treatments. These experimental control programs are outlined by West in this report.

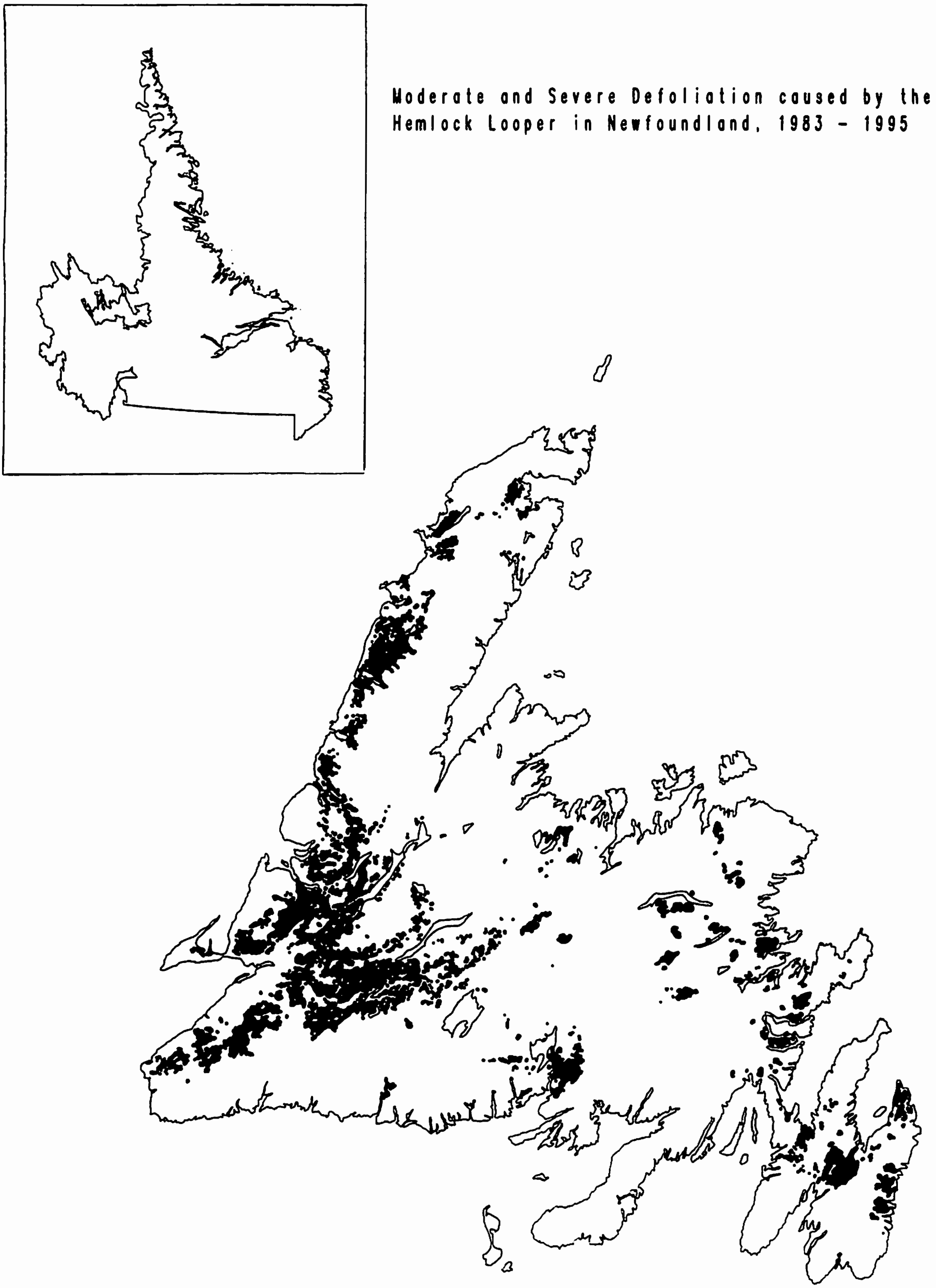

Figure 1. Moderate and Severe Defoliation caused by the Eastern Hemlock Looper in Newfoundland, 1983 - 1995.

Table 2. Area (ha) treated and insecticide used for operational control of eastern hemlock looper in Newfoundland, 1985 - 1995.

YEAR	Area Treated (ha)		
	Fenitrothion[a]	B.t.[b]	Total Area (ha)
1985	122 728	2 365	125 093
1986	79 028	5 420	84 448
1987	164 362	4 183	168 545
1988[c]	45 138	23 828	68 966
1989	-	5 362	5362
1990	-	10 616	10 616
1991	NO HEMLOCK LOOPER CONTROL PROGRAM		
1992	-	538	538
1993	-	15 424	15 424
1994	-	10 719	10 719
1995	-	47 893	47 893

[a] Chemical insecticide - fenitrothion (Folithion® or Sumithion®)

[b] Biological insecticide (*Bacillus thuringiensis*) - various products

[c] Area includes 40 ha treated with *B.t.* in three campgrounds of Gros Morne National Park.

The aerial application of chemical or biological insecticides in the integrated management of forest pests has always been controversial and subject of intense public debate (Poole *et al.* 1981). In response to the multitude of enquires from forest agencies and the general public we have reviewed the technical and scientific literature and provided current information in the form of questions and answers about the outbreak of the EHL and its control (Appendix I).

The EHL is the most destructive defoliator of Newfoundland forests and is capable of causing extensive, severe tree mortality and forest depletion. The present outbreak has caused an estimated 11 300 000 m^3 of tree mortality and an additional growth loss in excess of 1 000 000 m^3 (Table 1). Such a widespread, severe forest depletion has several significant impacts including the economic timber supply and non-timber values such as wildlife habitat, watershed management and recreation. The salvage and utilization of damaged stands by forest managers was considered critical for securing the future wood supply (VanDusen 1991). The socio-economic analysis of the EHL outbreak is presented by Wernerheim and Parsons in this report.

The current outbreak of the EHL is the seventh extensive outbreak recorded in insular Newfoundland and there is a considerable data base on the population biology of the looper and its impacts on the forests and also on control alternatives. Research to consolidate all available information and knowledge into a comprehensive decision support system to facilitate the practical integrated management of the EHL is described by Carroll in this report.

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THE DYNAMICS OF EASTERN HEMLOCK LOOPER POPULATIONS

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INTRODUCTION

The eastern hemlock looper (EHL), *Lambdina fiscellaria fiscellaria* (Guen.), is the major disturbance agent of the balsam fir forests of insular Newfoundland (Poole et al. 1981). During the past century, seven distinct outbreaks have culminated in the defoliation and subsequent mortality of more than 1.5 million hectares of forest (Carroll et al. 1995). EHL populations are characterized by extreme temporal fluctuations. During periods when populations are locally abundant, several hundreds of larvae can be found on a single branch of a mature balsam fir tree. By contrast, when populations are low, it is often difficult to find a single larva among many trees.

Despite drastic temporal fluctuations, the frequency and ubiquity of outbreaks suggests that EHL populations persist within the balsam fir forests of Newfoundland. For populations to persist, however, their numbers must be regulated such that the probability of extinction is minimal (Varley *et al.* 1973; Hassell *et al.* 1989; Crowley 1992; Royama 1992). Given that population fluctuations can be decomposed into two major components - trend and deviations from it - a persistent population must have associated with it the mechanism(s) to check its trend and regulate its deviations about the trend (Royama 1992). If either of the two requirements are violated, population densities will fluctuate without bounds and inevitably approach extinction (Hassell *et al.* 1989; Royama 1992; but see Den Boer 1991).

Ecological factors that dictate population fluctuations are traditionally classified into density-dependent and density-independent types (e.g., Varley *et al.* 1973; Southwood 1978; Price 1984). A density-dependent factor is one whose measure or parameter, is influenced by the population density of the animal, whereas the measure of a density-independent factor is unaffected by population density (*sensu* Royama 1992). Generally, patterns of population fluctuations reflect the combined influence of intrinsic density-dependent processes and random, exogenous density-independent perturbations (e.g., Royama 1981a, 1984, 1992; May 1986; Hassell 1987). For forest insect populations, density-independent factors are most commonly thought to comprise climatic variables (e.g., temperature and precipitation), whereas density-dependent factors are thought to manifest as components of the natural enemy assemblage (e.g., predators, parasites and pathogens). Robust population regulation, and hence persistence, can only be achieved by density-dependent processes that ensure an equilibrium state of a population within a suitable range of density-independent environmental conditions (Royama 1977, 1992), i.e., processes that check a population's trend and limit deviations about the trend.

Over the past several decades, significant efforts have been directed toward minimizing the impact of EHL outbreaks. Among these efforts have been a number of studies that have either directly or indirectly focused on the ecology of EHL populations (references in Raske *et al.* 1996). The primary objective of this chapter was to review and consolidate the state of knowledge regarding the ecological factors that affect EHL population fluctuations. The secondary objective was to contextualize this knowledge within the current framework of population dynamics theory. For clarity, this review is structured using the conventional division of density-independent (e.g., climate) versus density-dependent (e.g., natural enemies) factors. For convenience, potential density-dependent natural enemies will be presented according to their broad taxonomic groups: vertebrate predators, invertebrate predators and parasitoids, and pathogens. Insofar as the data will allow, the potential for each factor to interact with a population as either a density-independent random perturbation or a density-dependent regulatory process is discussed.

DENSITY-INDEPENDENT FACTORS

For decades, climatic conditions have been considered to have a major influence on EHL population levels through impacts to overwintering eggs and/or developing larvae (Watson 1934; Otvos 1977a,b). The impact of low temperature on the survival of diapausing eggs was assessed by Otvos (1977a). Over four generations, mortality of eggs from three field sites ranged from 1.9 to 65.3%. When compared with the deviation in temperature from a 30-year average for the months of October to May for each year and site, a close correspondence between egg mortality and unusually cold conditions was apparent (Otvos 1977a). It was concluded that, although the lethal low temperature for overwintering eggs was unknown, low winter temperatures were the major factor responsible for egg mortality.

In a similar study, Otvos (1977b) explored the relationship between EHL larval abundance (i.e., the average number of larvae per tree) and both temperature and precipitation for the years 1941 to 1970, inclusive. Using the average deviation from the 30-year (1941-70) normal for precipitation and temperature during the period from May to August, collected from three Atmospheric Environment Service (Environment Canada) weather stations across insular Newfoundland, larval numbers were compared with deviations from normal conditions. Otvos (1977b) concluded that the three EHL outbreaks recorded during the period in question (i.e., 1947-54, 1959-63, and 1966-71), were preceded by two years of above-normal temperature and below-normal precipitation - conditions that enhanced larval development and facilitated a rapid increase in population levels. Interestingly, a similar conclusion was reached in two related studies (McNamee *et al.* 1990; Carroll *et al.* 1995) that incorporated more detailed climatic data (five versus three weather stations) and a longer temporal window (i.e., 1950-87) involving a fourth EHL outbreak (i.e., 1983-87).

Not unexpectedly, climatic factors appear to have significant impacts upon EHL populations - deviations from normal conditions affect survival of most, if not all, life stages. Consequently, optimal conditions (i.e., low precipitation and high temperatures) likely lead to a rapid increase in EHL population levels. However, as outlined above, climatic conditions represent pure density-independent factors in that their measure is uninfluenced by EHL abundance. Thus, precipitation and temperature comprise random (albeit substantial) deviations about the potential population trend as dictated by intrinsic density-dependent processes.

DENSITY-DEPENDENT FACTORS

Vertebrate Predators

Given the predominantly arboreal habits of each life stage of the hemlock looper [i.e., larvae on foliage, eggs and pupae on tree stems (Carroll 1956)], and the relatively depauperate small mammal community over insular Newfoundland (Buckner 1966), insectivorous birds are the only significant vertebrate predators of the hemlock looper. Passerines that prey upon the hemlock looper in Newfoundland have been censused in some detail (Otvos and Taylor 1970; Otvos 1973). During the peak and decline of an outbreak, Otvos (1973) found 19 species with evidence of hemlock looper in their guts. For eight of the 19 species, looper comprised the major prey item [(i.e., 50% of the diet in at least one of the census years (Table 1)].

The overall tendency for predation by birds to decrease as the hemlock looper population declined (Table 1) prompted Otvos (1973) to suggest that bird populations may respond to changes in looper abundance in a density-dependent manner. Notwithstanding the tenuous nature of a conclusion based upon such a short time series (i.e., 3 years), passerine populations are incapable of density-dependent responses because they cannot increase/decrease in step with their prey populations (Royama 1992). No matter how numerous the hemlock looper becomes, it is only available to birds for a relatively short period each year. Once the looper life cycle is finished, birds must find sufficient food to maintain their populations through the winter; both for resident species

Table 1. Major avian predators of the eastern hemlock looper in Newfoundland (i.e., species for which the hemlock looper comprised 50% of the diet in one or more census years). Birds were collected from 23 locations during the declining phase of a hemlock looper outbreak. [Adapted from Otvos (1973)].

	Hemlock looper in diet (%)		
Species	1969	1970	1971
Yellow-bellied flycatcher	25	54	30
Black-capped chickadee	71	11	41
Hermit thrush	59	-	14
Black and white warbler	68	6	48
Tennessee warbler	84	-	-
Black-throated green warbler	91	44	-
Blackpoll warbler	80	29	-
Pine Grosbeak	65	49	-

(i.e., black-capped chickadee and pine grosbeak) and migrants (i.e., yellow-bellied flycatcher, hermit thrush, and the warblers). Thus, by the beginning of the next breeding season, bird population densities would reflect little, if any, impact of the previous year's looper abundance.

Invertebrate Predators/Parasitoids

Invertebrate predators and parasitoids are generally considered to have significant potential for population regulation because of their capacity to respond rapidly to changes in prey/host abundance. Despite a diverse assemblage of invertebrate predators in Newfoundland, none have been observed feeding on the hemlock looper (Otvos 1973). Hence, their potential importance in the population processes of the looper has not been assessed. By contrast, the parasitoid assemblage associated with the hemlock looper in Newfoundland has been studied in some detail (Carroll 1956; Otvos 1973).

Parasitoids are generally distinguished by the life stage of the host they parasitize (i.e., eggs vs. larvae and pupae). One species of egg parasitoid and 20 species of primary larval and pupal parasitoids have been reported to attack the hemlock looper in Newfoundland (Carroll 1956; Otvos 1973). During the declining phase of an outbreak, egg parasitism by *Telenomus* sp. (Hymenoptera: Scelionidae) was reported to average 1.5 to 15.5%, reaching as high as 48% at individual sites (Otvos 1973). During the same period, larval and pupal parasitism ranged from ca. 15 to 66%, the vast majority by dipteran parasitoids (Table 2). Interestingly, hyperparasitoids (secondary parasites of primary larval/pupal parasitoids that can potentially reduce the effectiveness of primary parasitoids) are uncommon in Newfoundland (Otvos 1973).

Among the larval and pupal parasitoids of the hemlock looper, the most commonly collected were *Winthemia occidentis* Rnd. (Diptera: Tachinidae), *Itoplectis conquisitor* (Say) and *Apechthis ontario* (Cress.) (Hymenoptera: Ichneumonidae) (Otvos 1973). Surprisingly, each of these parasitoids were introduced to insular Newfoundland (McGugan and Coppel 1962; Clark *et al.* 1973). The fact that introduced species have become the dominant parasitoids of the hemlock looper suggests that they may have i) displaced vulnerable indigenous species, and/or ii) occupied vacant niches that exist as a result of a depauperate parasitoid community - a possible consequence of the biogeographic isolation of insular Newfoundland (MacArthur and Wilson 1967).

Based upon the levels of egg, larval and pupal parasitism outlined above, Otvos (1973) suggested that parasitoids may be, in part, responsible for the collapse of hemlock looper populations following an outbreak. However, conclusions based upon these data are suspect for two reasons. First, although parasitism rates appear to be significant during the decline of an outbreak, particularly by larval and pupal parasitoids (Table 2), single yearly estimates of impacts grouped by parasitoid order or complex can be misleading (Van Driesche 1983; Royama 1992). Each parasitoid species will have its own phenological window of attack, development and emergence. Unless sampling corresponds with the peak level of parasitism for individual species, considerable underestimation of total parasitism will result (Van Driesche 1983; Royama 1992). Second, potentially high rates of parasitism during the decline of the looper population may simply reflect a spurious correlation (Royama 1992) - a compelling criticism given that parasitism was only examined for 4 consecutive years. Unfortunately, to date none of the studies of looper parasitoids (Carroll 1956; Otvos 1973) provide seasonal breakdowns of parasitism rates by individual species nor attempt to establish a causal relationship between parasitism and population decline. Hence, the impacts of parasitoids on hemlock looper populations requires much further study.

Pathogens

Due to their rapid rate of increase, entomopathogenic organisms also have considerable potential to respond to fluctuations in the density of their hosts. Accordingly, a variety of authors have censused the pathogen complex associated with the hemlock looper (Angus 1952; Carroll 1956; Hughes 1957; Cunningham 1970; Otvos 1973; Otvos *et al.* 1973). Presently, a nuclear polyhedrosis virus and two entomopathogenic fungi, *Entomophaga aulicae* (Reich.) Sorok. (= *Entomophthora egressa* Mcleod and Tyrell; Humber 1984) and *Erynia radicans* (Bref.) Humber (= *Entomophthora sphaerosperma* Fres.), are known to be pathogenic to the looper in Newfoundland (Otvos 1973). However, only the fungal pathogens have been isolated with regularity (Otvos 1973; Otvos *et al.* 1973, 1979).

In Newfoundland, fungal pathogens periodically manifest as intense, localized epizootics. Larval infection rates have been reported in excess of 80-90% (Table 3). Not surprisingly, most authors have attributed the decline of looper populations to the action of entomopathogenic fungi (Otvos 1973, 1977b; Otvos *et al.* 1971, 1973, 1979). Given a review of the data collected from the two most-recent EHL outbreaks (1967-71 and 1983-88), there is clearly a significant fungal infection rate among late-instar larvae as outbreaks progress (Table 3). Unfortunately, lack of consistency in sampling and reporting among years precludes

Table 2. Percentage of eastern hemlock looper larvae and pupae parasitized by dipteran and hymenopteran parasitoids in Newfoundland. Parasitoids were collected from 10 locations during the declining phase of a hemlock looper outbreak. [Adapted from Otvos (1973)].

	% Parasitism by year			
Order	1969	1970	1971	1972
Diptera	13.5	16.8	39.3	65.8
Hymenoptera	1.0	0.6	1.0	0.4
Total	14.5	17.4	40.3	66.2

Table 3. Average yearly infection rate of eastern hemlock looper larvae and pupae by entomopathogenic fungi during the declining phases of two eastern hemlock looper outbreaks (i.e., 1969-71 and 1986-88) in Newfoundland.

Year	Mean % infected larvae / pupae[a]	Sites sampled	Authors
1969	53.3 (20-90) / -	3	Otvos 1973; Otvos *et al.* 1973
1970	36.7 (5-80) / 20 (-)	3	Otvos 1973; Otvos *et al.* 1973
1971	57.0 (7-90) / -	3	Otvos 1973; Otvos *et al.* 1973
1986	4.5 (2-20) / -	3	Clark and Carew 1987
1987	1-25 (-)[b] / 2 (-)	22	Clark and Carew 1988
1988	1-33 (-) / 4 (-)	17	Clark and Carew 1989

[a] Means followed by ranges in parantheses. A dash indicates where data were unavailable.

[b] Means reported for "young" and "old" portions of EHL outbreak.

conclusions regarding the potential of entomopathogenic fungi to regulate hemlock looper populations. Indeed, some authors (Royama 1984, 1992) have questioned the potential for fungal pathogens to respond to changes in their host populations in a density-dependent manner due to the inconsistent and non-persistent nature of epizootics. Nonetheless, the frequent association of fungal pathogens with declining EHL populations across insular Newfoundland (see references in Raske 1996) suggests an important role for entomopathogenic fungi in the dynamics of hemlock looper populations.

CONCLUSIONS

Significant efforts have been devoted to censusing the biotic and abiotic mortality factors associated with EHL populations. Clearly, the density-independent actions of temperature and precipitation play a critical role in dictating year to year fluctuations in EHL abundance - frequently facilitating an increase in populations to outbreak levels. Less clear, however, is the potential for the various biological mortality agents to regulate the EHL population trends and limit deviations about the trend. Correlational evidence from two outbreaks suggests that entomopathogenic fungi may well be important to the decline of EHL populations although much more study is required.

Population processes are density-dependent stochastic processes (Royama 1981a; 1992). The rate of change in density from natality through mortality, and immigration and emigration, is in general reliant upon population density during past periods (Royama 1981a). To ascertain the density-dependent structure of populations of a univoltine animal such as EHL (the essential component to understanding population change) a long-term detailed life-table study is required (Royama 1981b) - one designed to assess stage-specific mortality and the agent(s) responsible over a number of generations during the endemic and epidemic phases of a population.

ACKNOWLEDGEMENTS

B.J. Hearn, I.S. Otvos and J. Hudak provided critical reviews of an earlier version of this manuscript.

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DEVELOPMENT OF A PHEROMONE-BASED DETECTION AND MONITORING SYSTEM FOR EASTERN HEMLOCK LOOPER

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INTRODUCTION

The eastern hemlock looper (EHL), *Lambdina fiscellaria fiscellaria* (Guen.), is a phytophagous insect found in Canada from Newfoundland to Alberta and from the Great Lakes to the eastern seaboard in the United States (Raske *et al.* 1995). The insect is a major pest of balsam fir, *Abies balsamea* (L.) Mill., and eastern hemlock, *Tsuga canadensis* (L.) Carriere (Carroll 1956; Otvos *et al.* 1979). The extent and severity of EHL outbreaks in Newfoundland and a review of control options for the pest are reported elsewhere in this report. A comprehensive review of hemlock looper literature is presented by Raske *et al.* (1996). The insect remains the most important forest insect pest in Newfoundland.

Over 100 years ago the great French naturalist Jean Henri Fabré observed that male Emperor moths were attracted to a virgin female in a cage. In an elegant series of experiments, he demonstrated that male moths use their sense of smell to locate potential mates. Since these early experiments, semiochemicals have been investigated for many Lepidoptera (Birch 1974; Mayer and McLaughlin 1991) and multicomponent sex pheromones appear to be the rule for most moths (Silverstein and Young 1976). Despite much progress, our understanding of geometrid responses to pheromones is still in its infancy. While it is known that male moths generally find their mates by following the females' pheromone plume to its source (Cardé 1995), the role of semiochemicals in mediating the dispersal and mating behaviour of geometrids remains largely unknown.

It is generally recognized that long-range attraction of male moths is usually elicited by a blend of chemicals released by calling females. Sex pheromones, comprised mainly of tetraene, triene or polyenic hydrocarbons, monoene or diene monoepoxides alone or in combination with corresponding hydrocarbons, have been isolated and chemically characterized for several geometrid species in Canadian forests including winter moth, *Operophtera brumata* (L.); Bruce spanworm, *Operophtera bruceata* (Hulst), fall cankerworm, *Alsophila pometaria* (Harr.); spruce-fir looper, *Semiothisa signaria dispuncta* (Wlk); and jack pine looper, *Semiothisa bicolorata* (F.). The sex pheromone of the winter moth has been successfully used to monitor moth populations in Germany and Scotland and synthetic components of the fall cankerworm have been shown to disrupt orientation behaviour. Herein, we summarize EHL behaviour and report on current trends in the development of a pheromone-based monitoring system for the insect.

INVESTIGATIONS

Studies to investigate EHL semiochemicals, calling behaviour, mating behaviour and reproductive biology commenced in 1989. Identification of the EHL sex pheromone was a collaborative effort involving the collective expertise of scientists at the Canadian Forest Service (CFS), Simon Fraser University, and the National Research Council. The first objective of the research was to provide knowledge concerning reproductive behaviour of the EHL. Such knowledge was an important prerequisite to meeting the second objective aimed at elucidating the chemical components responsible for moth attraction.

Studies to investigate EHL attraction, flight and calling behaviour, mating behaviour and reproductive biology were initiated by entomologists in Newfoundland in cooperation with Dr. Jobin, of CFS - Quebec an entomologist familiar with looper behaviour. This component of the research was designed to demonstrate the existence of pheromone activity, establish peak calling activity, and investigate other pheromone-related behaviour including the effects of photoperiod, temperature, feeding and mating status on female calling. The flight response of the looper to newly-developed light traps was also investigated. Dr. Jobin designed and developed a portable light trap for EHL and other nocturnal flying insects that alone or in combination with a pheromone lure could act as an effective monitoring tool. Traps were improved by several new features: interchangeable bulbs, warning lights to indicate battery condition and light timers (Jobin and Coulombe 1992).

Since Silverstein and his coworkers developed an elaborate protocol for insect pheromone research in 1967, semiochemical research has been greatly advanced. Recent investigations have benefited from novel approaches using coupled gas chromatographic-electroantennographic detectors (GC-EAD), coupled GC-mass spectroscopy (MS), and chemical derivation of chiral compounds. Laboratory and field experiments leading to the discovery of EHL pheromone components were conducted in Newfoundland and at Simon Fraser University, British Columbia and are described by Gries *et al.* (1991), Li *et al.* (1993) and West and Bowers (1994). A rearing program at the Newfoundland Forestry Centre provided looper moths for laboratory research outlined above.

Lepidopteran species produce a wide variety of semiochemicals that serve a critical sexual function. Exploitation of these chemical compounds by forest managers offers a number of detection and monitoring strategies for more effective insect pest management (Shepherd 1994). Evidence for the sex pheromone for EHL was first provided using "sticky" traps baited with virgin females (Otvos 1972). Field attraction studies in Quebec also indicated males are attracted to virgin females. Ostaff *et al.* (1974) noted the presence of a pheromone gland and reported field evidence for pheromone production by western hemlock looper (WHL) in British Columbia.

The sex pheromone components of EHL were reported by Gries *et al.* (1991). Two previously unknown lepidopteran hydrocarbon components, 5,11-dimethylheptadecane and 2,5-dimethylheptadecane, were identified, synthesized and field tested. Responses to a minor component, 7-methylheptadecane was observed but was always smaller. A fourth compound, 5-methylheptadecane was detected but was not consistently present in extracts of female pheromone glands. Field tests in Newfoundland confirmed that the two dimethylheptadecanes were biologically active. This finding was the first report of methyl-branched hydrocarbons serving as a pheromone for geometrids.

Species specificity in pheromone production is probably achieved by species-specific metabolic processes giving rise to pheromone chemicals with different functional groups, geometrical isomers or release rates. Studies in British Columbia indicated that the WHL, *L. fiscellaria lugubrosa* Hulst, produced 3 major pheromone components including 5,11-dimethylheptadecane (Gries *et al.* 1993). In contrast to EHL, addition of the minor component 7-methylheptadecane significantly enhanced attraction of WHL males. The latter finding supports taxonomic separation of the two species as suggested by McGuffin (1987). Subsequently, the chirality and behavioural activity of the four stereoisomers of this major component was elucidated (Li *et al.* 1993). Only one stereoisomer, (5R,11S)-5,11-Dime-17Hy, elicited a common response from both the eastern and western species, indicating that the isomer (5R,11S)-5,11-Dime-17Hy is indeed the major sex pheromone component of both species.

The remarkable olfactory acuity of EHL was investigated in the field by West and Bowers (1994) who reported factors affecting the calling behaviour of the moth. The majority of female moths aged 1 to 7 days called for a mean total of 3.3 to 6.7 hours during the night in bouts averaging 0.6 to 3 hours. Females did not call in the day and older moths called longer and in fewer bouts than younger moths. Mated moths usually did not call. Moreover, calling was observed at temperatures as low as 5 °C, indicating that males are active at relatively low temperatures.

Following chemical characterization of EHL pheromone, application was made to patent the pheromone to ensure protection of the discovery. A patent for the pheromone is pending. The Canadian Company, Phero Tech Inc. is currently the producer of commercial quantities of the pheromone.

Sampling with pheromone baited traps is a reliable approach for early detection of impending EHL outbreaks and is now used in Newfoundland to enhance planning for egg mass surveys which in turn is used to plan operational control programs against the looper. Moreover, trapping programs are an excellent means to determine the timing of looper flight in late summer or early fall. A pheromone trapping system was first established in insular Newfoundland by the Forest Insect and Disease Survey in 1993 and continued to 1996. In each year, 3 Multi-pher traps were deployed at each of 50 locations (Fig. 1) to assess male moth activity in western, central and eastern Newfoundland.

Throughout the course of these studies life-history information on looper was gathered. Stand parameters, including defoliation, stand type, age, height, basal area, elevation and aspect were also recorded. Numbers of larvae and egg masses were assessed annually at each of the 50 permanent sampling locations. Such information will be used to describe the spatial and temporal patterns of EHL and to relate looper trap catch to egg survey data and to patterns of defoliation.

Concurrent with work in Newfoundland, research to develop a pheromone-based detection system for WHL was initiated in British Columbia (Evenden and Borden 1993). Results indicated that male moths are significantly more attracted to pheromone-baited traps than to control (unbaited) traps. Relationships between male moth catches and egg counts were investigated for use in predictive models.

The Semiochemical/Pheromone Working Group of the CFS, formed to accelerate the development of operational use of semiochemicals in Canadian forestry, has recognized and supported development of a pheromone-based monitoring system for eastern and western hemlock loopers (West *et al.* 1994). The working group continues to promote standardized trapping protocols and lure types. Novel approaches using geostatistical techniques to better interpret and utilize spatial databases are under investigation by members of the Working Group and its partners. Potential to use pheromones as a mating disruption technique against EHL as described for other lepidoptera (Jutsum and Gordon 1989; Cardé and Minks 1995) is currently being investigated.

CONCLUSIONS

Current tactics to manage EHL populations are limited in number and scope. The development of a pheromone-based detection and monitoring system for EHL has greatly advanced our ability to detect and respond to looper outbreaks. However, it is recognized that sound ecological understanding along with increased advances in chemistry, physiology and genetics are needed before such a system can be fully integrated into forest pest management strategies. Particularly, there is a strong need for forest managers to embrace pheromone monitoring systems and to refine, validate and integrate pheromone-trapping systems into their ecosystem management regimes. Moreover, efforts should be made to collect and interpret spatial data in all its manifestations. Novel statistical tools such as those offered by geostatistics should be applied to enhance qualitative and quantitative analyses. Such action will provide new insights into insect distributions and attack patterns, and increase the predictive capability of decision support systems. Mating disruption by inundating areas with pheromone may be a useful control strategy to combat small isolated outbreaks in high value stands.

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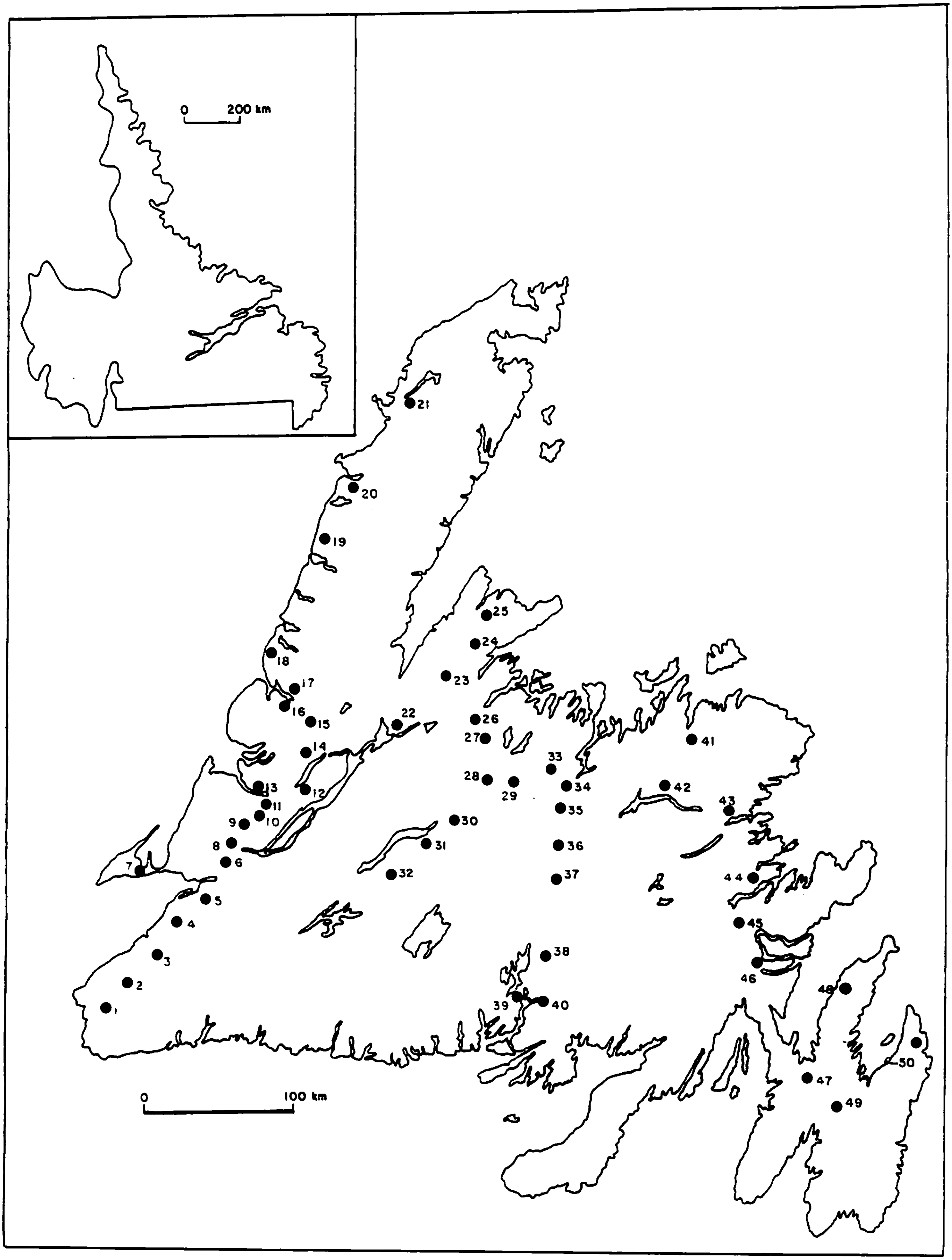

Figure 1. Locations of pheromone traps deployed to detect eastern hemlock looper moths in Newfoundland.

DEVELOPMENT OF CONTROL TACTICS AGAINST THE EASTERN HEMLOCK LOOPER

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INTRODUCTION

Inundative and inoculative control tactics to manage populations of the eastern hemlock looper (EHL) have been under development for the past five decades. Inundative tactics involve application of a mass-produced product and generally are intended for employment during outbreaks to prevent damage over the short-term. Inoculative tactics involve the importation and introduction of a known or potential natural enemy of the pest insect and represent a long-term approach. Successful establishment of the introduced natural enemy augments the existing complex of natural enemies, permanently suppressing the pest densities to less damaging levels, and perhaps reducing the frequency of outbreaks. There is also the potential for non-lethal forms of control, including disruption of mating by application of pheromone, and modifying silvicultural and harvesting schedules to reduce the impact of the looper. This paper provides a review of investigations conducted to develop improved control tactics against the EHL.

INVESTIGATIONS

Inundative Control Tactics

A. Experimental Spray Programs against the EHL (1985-1996)

Various formulations and dosages of *Bacillus thuringiensis* Berliner var. *kurstaki (B.t.),* fenitrothion, diflubenzuron, aminocarb and tebufenozide were evaluated for efficacy in experimental spray programs conducted during 1985, 1986, 1987, 1988, 1995 and 1996 (Table 1). Formulations of *B.t.* persist only for a few days and are lethal to a narrow range of species, affecting mainly lepidopterous larvae. Fenitrothion is an organophosphorous insecticide, and is toxic to a wide range of invertebrates and is somewhat toxic to small birds at operational doses. Aminocarb is a carbamate insecticide and like fenitrothion is broadly toxic to invertebrates, however, it has little impact on birds. Diflubenzuron is an insect growth regulator and is toxic to immature insects and some aquatic invertebrates. Tebufenozide is a synthetic biochemical insecticide that precipitates a premature moult resulting in larval starvation and death. Tebufenozide persists for several weeks on foliage but, other than larval lepidoptera, negatively affects few species.

1985: Water-based formulations of *B.t.* (Thuricide 48 LV, Thuricide 64B, Futura), fenitrothion (Sumithion technical grade, Sumithion 20F), diflubenzuron (Dimilin) and aminocarb (Matacil 180F) were tested for efficacy. Double applications of Thuricide 64B at 30 BIU/ha, double applications of Dimilin at 70 g.a.i./ha and double applications of technical grade Sumithion at 210 g.a.i./ha resulted in population reduction, however, foliage protection was not demonstrated (Raske *et al.* 1986, West *et al.* 1987).

1986: Water-based formulations of diflubenzuron (Dimilin 25WP) and fenitrothion (Sumithion technical grade, Sumithion 20F) were tested. All formulations tested resulted in population reduction, however, only the fenitrothion formulations provided foliage protection (Raske and Retnakaran 1987).

1987: Oil-based formulations of *B.t.* (Dipel 132, Dipel 176 and Dipel 264), water-based formulations of diflubenzuron (Dimilin 25 WP and Dimilin Flowable), and oil-based formulations of fenitrothion (Sumithion technical grade and Folithion technical grade) were tested. Single and double applications of the *B.t.* formulations and early applications of fenitrothion targeted against first-instar larvae resulted in excellent foliage protection (West *et al.* 1989, Raske *et al.* 1992). Double applications of Dimilin 25 WP provided good foliage protection, however, Dimilin Flowable was ineffective (Raske *et al.* 1992, Retnakaran *et al.* 1988). Deposit characteristics of the formulations tested were determined (Raske *et al.* 1989, Sundaram *et al.* 1988, Sundaram A. *et al.* 1987, Sundaram K.M.S. *et al.* 1987).

1988: Oil-based formulations of *B.t.* (Dipel 176 and Dipel 264), a water-based *B.t.* formulation (Futura XLV), and an oil-based formulation of diflubenzuron (Dimilin ODC) were tested. Early application of Dipel 176 and 264 provided excellent foliage protection whereas the applications of Futura XLV and Dimilin ODC provided inadequate foliage protection (West *et al.* 1992).

1995: Aqueous formulations of *B.t.* (ABG6387 and ABG6414), and the biochemical tebufenozide (MIMIC 240LV) were tested against light-to-moderate infestations. The formulations of *B.t.* were applied twice at rates of 19.3-24.1 BIU in 1.54-1.93 L/ha for ABG6387 and 33.2-36.0 BIU in 1.67-1.80 L/ha for ABG6414. Tebufenozide was

Table 1. Experimental insecticide trials against the hemlock looper in Newfoundland, 1985-1996.

Year	Insecticide	Formulation	Base	Application Rate
1985	*B.t.*	Thuricide 48LV	Water	2 x 30 BIU in 2.36 L/ha
	B.t.	Thuricide 64B	Water	2 x 30 BIU in 1.78 L/ha
	B.t.	Futura XLV	Water	2 x 20 BIU in 1.4 L/ha
	B.t.	Futura XLV	Water	2 x 30 BIU in 2.1 L/ha
	Fenitrothion	Sumithion technical grade	Water	2 x 210 g.a.i. in 1.5 L/ha
	Fenitrothion	Sumithion 20F	Water	2 x 140 g.a.i. in 1.5 L/ha
	Fenitrothion	Sumithion 20F	Water	2 x 210 g.a.i. in 1.5 L/ha
	Diflubenzuron	Dimilin 25WP	Water	2 x 70 g.a.i. in 4.7 L/ha
	Diflubenzuron	Dimilin 25WP	Water	1 x 30 g.a.i. in 2.0 L/ha
	Diflubenzuron	Dimilin 25WP	Water	1 x 35 g.a.i. in 4.7 L/ha
	Diflubenzuron	Dimilin 25WP	Water	1 x 70 g.a.i. in 4.7 L/ha
	Aminocarb	Matacil 180F	Water	2 x 90 g.a.i. in 1.5 L/ha
	Aminocarb	Matacil 180F	Water	2 x 135 g.a.i. in 1.5 L/ha
	Aminocarb	Matacil 180F	Water	2 x 180 g.a.i. in 1.5 L/ha
1986	Diflubenzuron	Dimilin 25WP	Water	2 x 70 g.a.i. in 2.5 L/ha
	Diflubenzuron	Dimilin 25WP	Water	2 x 70 g.a.i. in 4.7 L/ha
	Fenitrothion	Folithion technical grade	Oil	2 x 210 g.a.i. in 1.5 L/ha
	Fenitrothion	Sumithion 20F	Water	2 x 180 g.a.i. in 0.9 L/ha
1987	*B.t.*	Dipel 132	Oil	2 x 30 BIU in 2.4 L/ha
	B.t.	Dipel 176	Oil	2 x 30 BIU in 1.8 L/ha
	B.t.	Dipel 176	Oil	1 x 40 BIU in 2.4 L/ha
	B.t.	Dipel 264	Oil	1 x 40 BIU in 1.6 L/ha
	B.t.	Dipel 264	Oil	2 x 30 BIU in 1.2 L/ha
	Diflubenzuron	Dimilin 25WP	Water	2 x 70 g.a.i. in 5.0 L/ha
	Diflubenzuron	Dimilin 25WP	Water	2 x 70 g.a.i. in 2.5 L/ha
	Diflubenzuron	Dimilin 25WP	Water	1 x 70 g.a.i. in 5.0 L/ha
	Diflubenzuron	Dimilin 25WP	Water	1 x 70 g.a.i. in 2.5 L/ha
	Diflubenzuron	Dimilin Flowable	Water	1 x 70 g.a.i. in 5.0 L/ha
	Fenitrothion	Sumithion technical grade	Oil	2 x 210 g.a.i. in 0.4 L/ha
	Fenitrothion	Sumithion technical grade	Oil	2 x 210 g.a.i. in 0.4 L/ha
	Fenitrothion	Folethion technical grade	Oil	2 x 210 g.a.i. in 1.5 L/ha
1988	*B.t.*	Dipel 176	Oil	1 x 30 BIU in 1.8 L/ha
	B.t.	Dipel 176	Oil	1 x 40 BIU in 2.4 L/ha
	B.t.	Dipel 264	Oil	1 x 30 BIU in 1.2 L/ha
	B.t.	Dipel 264	Oil	1 x 40 BIU in 1.6 L/ha
	B.t.	Futura XLV	Water	1 x 30 BIU in 2.1 L/ha
	Diflubenzuron	Dimilin ODC	Oil	1 x 70 g.a.i. in 2.5 L/ha
	Diflubenzuron	Dimilin ODC	Oil	1 x 120 g.a.i. in 2.5 L/ha
1995	*B.t.*	ABG 6387	Water	2 x 19.3 - 24.1 BIU in 1.5 - 1.9 L/ha
	B.t.	ABG 6414	Water	2 x 33.2 - 36 BIU in 1.7 - 1.8 L/ha
	Tebufenozide	MIMIC 240 LV	Water	1 x 65.1 g.a.i. in 1.9 L/ha
	Tebufenozide	MIMIC 240 LV	Water	2 x 35 g.a.i. in 2 L/ha
1996	*B.t.*	ABG 6414	Water	2 x 35 BIU in 2 L/ha
	B.t.	ABG 6432	Water	2 x 35 BIU in 2 L/ha
	Tebufenozide	MIMIC 240 LV	Water	1 x 70 g.a.i. in 2L/ha (during larval hatch)
	Tebufenozide	MIMIC 240 LV	Water	1 x 70 g.a.i. in 2 L/ha

applied once at rate of 65.1 g.a.i. in 1.86 L/ha and twice at a rate of 33.4-35.4 in 1.91-2.02 L/ha. MIMIC 240LV and ABG6387, ABG6414 reduced larval numbers and reduced defoliation, despite rainfall within 4-18 h of application (West *et al. In press).*

1996: Aqueous formulations of *B.t.* (ABG6414 and ABG6432) and tebufenozide (MIMIC 240 LV) were applied at a rate of 2 L/ha against moderate to high populations. ABG6414 and ABG6432 were applied at a rate of 35 BIU/ha against second-instar larvae and one week later against third-instar larvae. MIMIC was applied once at a rate of 70 g.a.i./ha either mid-way during larval hatch (EARLY treatment) or when larvae were in their second instar (LATE treatment). Treatments with the exception of the early MIMIC application were delayed by two weeks due to wet weather. Most of the defoliation occurred by mid-July and first and second-instar larvae caused considerable damage before the *B.t.* and LATE MIMIC treatments. The wet weather contributed to an outbreak of *Entomophaga* sp. which caused a collapse of late-stage larvae and pupae in the experimental area. ABG-6432, ABG-6414 and the EARLY and LATE treatments of MIMIC effectively reduced larval numbers and prevented defoliation. Early application of MIMIC broadens the "spray window" for the forest manager.

B. Mass-production of an Entomopathogenic Fungus

The native fungi, *Entomophaga aulicae*, (Reichardt) Humber and *Entomophaga sphaerosperma* Fres. have been credited to cause the collapse of EHL outbreaks in Newfoundland and have been commonly recovered from mature larvae in the second year of an outbreak. (Otvos 1973) *E. aulicae* has potential to be used as an inundative tactic because it is already an established species in Newfoundland's forests and it is likely to affect few non-target species. An application of this pathogen might also have an inoculative effect when the fungus spreads from larvae initially infected to uninfected larvae. Mass production of hyphal bodies and their dissemination in the field, would constitute a convenient and effective method of augmenting low levels of the fungus during the pre-outbreak phase of the EHL and may also be of value as an insecticide to be applied during outbreaks.

Research, conducted throughout 1983-1995 by Dr. R.A. Nolan and Dr. F. Murrin of Memorial University with financial support and cooperation from the Canadian Forest Service (CFS) - St. John's, was directed to characterize and artificially mass-produce the fungus. The following summarizes the progress on this project.

Detailed studies on the life cycle of the fungus and how it invades the insect body have been completed and methods of culturing the fungus on defined medium developed. Protoplasts are the initial and only developmental stage within the larval hemocoel until the walled hyphal bodies are formed in the dead or dying host larva. The fungal protoplasts utilize the nutrients in the insect hemolymph to weaken the host larvae (Nolan 1988). The hyphal body produces the conidiophore, which emerges from the cadaver and then produces the infective conidium (Murrin and Nolan 1987, Murrin and Nolan 1989). Hyphal body production in-vitro also leads to conidium production (Nolan 1993).

Mass fermentation studies have defined the media and growing conditions, and use of the partition fermentation conditions have greatly increased the hyphal body production (Nolan 1986, Nolan 1990, Nolan 1993, McDonald and Nolan 1995). Over 7 billion fungal hyphal bodies can be cultured with a medium at the 10-litre fermentation level in 6 days at facilities at Memorial University. The patented medium has application to support hyphal body and conidium production of *E. aulicae* isolates from widely separated geographical regions in Canada as well as other species of *Entomophaga*. Additional *E. aulicae* isolates need to be recovered from the field to obtain an inoculum that is more virulent and osmotically stable than the present inoculum. The initiation of larger scale production of fungal material and field trials is dependent on the success of further laboratory studies. The biology of *E. aulicae* in the field requires significant further studies before experiments to initial artificial epizootics may commence.

Inoculative Control Tactics

A. Natural Enemies of the EHL in Newfoundland

Natural enemies of the looper help to limit the size and duration of looper outbreaks and are important in keeping looper numbers low between outbreaks. However, the present complex of natural enemies (Otvos 1973) fails to prevent widespread outbreaks and tree mortality and potential natural enemies should be considered for introduction from other areas of Canada or the world. Parasitization of the egg and early larval stages of the EHL is generally low (Otvos 1973). These life stages represent unfilled niches that could be exploited by new introductions. Such introductions would also have the advantage of reducing the level of defoliation during the year of attack because the parasitized loopers would die before reaching the most damaging stages. The most common parasite now is *Winthemia occidentis* Rnd., a fly obtained from the western hemlock looper (WHL) and oak looper (OL) in British Columbia and introduced in 1949-51(Otvos 1973). The success of this introduction is indicative of the potential of the inoculative strategy.

B. Screening of Exotic Parasitoids

A cooperative project was undertaken during 1991-1995 with the International Institute of Biological Control to identify parasitoid species suitable for screening against the EHL. Twenty geometrid species were recovered from annual surveys in coniferous forests in the Swiss Alps and of these three were identified as sources for four parasitoids considered suitable for screening: *Epirrita autumnata*, (Borkhausen), *Agriopis aurantiaria* Hubner and *Poecilopsis isabellae* Harrison. Two univoltine species of *Dusona* (Hymenoptera: Ichneumonidae), *D. contumax* Forster *ex. A. aurantiaria* and *D.* sp. *ex. P. isabellae*, and two univoltine species of *Aleiodes* (Hymenoptera: Braconidae), *A.C.F. gastritor* Thunberg *ex. E. autumnata* and *A. sp. ex. P. isabellae*, were reared in the laboratory and exposed to their native hosts to determine adult longevity, attack frequency and duration, and egg production. Small numbers of these parasitoids were shipped to Newfoundland and screened in the laboratory against the EHL (West and Kenis, *in press*). The parasitoids screened did not readily attack and none developed on EHL larvae. All parasitoid eggs recovered from the EHL larvae attacked were encapsulated. *D. contumax, Dusona sp. ex P. isabellae, A. gastritor* and *Aleoides sp. ex P. isabellae* are not recommended for introduction against the EHL.

C. Identification of Parasitoids Suitable for Introduction from other Parts of Canada

Additional surveys are warranted in areas of Canada where the hemlock looper is present but rarely a problem, and where a high incidence of parasitism is found. Released and recovered EHL larvae could be used to advantage in such surveys. A project to identify parasitoid species attacking the EHL on Manitoulin Island in Ontario was initiated with CFS-Sault Ste. Marie in 1996. One to two thousand larvae were released per tree at a site near Sault Ste. Marie and between 2.5 and 4.5 % were recovered. Parasitism was low, only 1 species of tachinid and 2 species of ichneumonid were collected. At Manitoulin sites where 5000 EHL were released per tree less than 0.5% of the larvae were recovered and parasitism consisted of 1 ichneumonid specimen.

D. Nuclear Polyhedrosis Viruses

Nuclear polyhedrosis viruses (NPVs) belong to a class of insect viruses whose strains are species-specific. NPVs, therefore, are attractive from an ecological point of view. They have been used with success in forestry against the European pine sawfly, Douglas fir tussock moth and gypsy moth. However, NPVs are costly to develop for the small forestry market and virulent strains are not always readily available in nature. NPV is present but has not been found at high levels in looper populations, and this suggests low virulence. DNA of NPV isolated from EHL in Newfoundland and New Brunswick is distinct from the related WHL and OL in British Columbia although there is considerable overlap in banding-patterns. Current objectives include the construction of physical maps of both EHL-NPV and WHL-NPV, determination of the extent of cross-hybridization and location of baculovirus whose functions are known to be important in NPV virulence and host-specificity, development of a cell culture system for in vitro propagation of the EHL-NPV and WHL-NPV) and determination of the incidence of NPV's in wild populations (Dr. C. Lucarotti, CFS-Fredericton, and Dr. D. Levin, U. of Victoria, personal communication).

E. Gregarines

A protozoan parasite was recently discovered in the guts of EHL larvae in the Maritimes and was identified as a eugregarine (*Leidyana* sp.) (C. Lucarotti, CFS-Fredericton, personal communication). This protozoan may have a debilitating effect on the EHL, substantially extending the larval period. Although direct mortality may be of some importance, the indirect effects of gregarines may be substantial because the extended larval period allows other mortality factors such as birds, predators, parasites and pathogens additional time to attack loopers. Surveys of EHL populations in New Brunswick indicated that 50% of looper larvae were infected with gregarines in 1993 and 80% in 1994 (C. Lucarotti, CFS-Fredericton).

It has always been difficult to explain why EHL outbreaks are most severe in Newfoundland and Anticosti Island. If this is due to lack of a biological mortality factor found in areas where the looper is present but rarely a significant threat, then the finding of any agent that is found in high incidence in such areas is of great interest. A total of 873 EHL larvae were collected from 5 sites in Newfoundland in 1995 and a similar number was collected in 1996 from the Hawkes Bay and Steady Brook (Marble Mountain) areas. None of these larvae contained gregarines (C Lucarotti, CFS-Fredericton) and thus it appears that eugregarines have potential as introduced biological control agents in Newfoundland.

MATING DISRUPTION WITH PHEROMONE

The use of pheromones to disrupt mating represents a non-lethal form of control and is under current investigation. This strategy may be particularly effective in combating isolated infestations of the EHL (see chapter by Bowers and West).

SILVICULTURE AND HARVESTING

Current research on the factors influencing the spatial dynamics of EHL will assist forest managers in developing silvicultural and harvesting plans (see chapter by A.L. Carroll).

CONCLUSIONS

Efficacy data from studies in Newfoundland has contributed to the registration of formulations of *B.t.* and tebufenozide for use against the EHL. These are the only insecticides that are likely to be used in Newfoundland for the foreseeable future. The use of fenitrothion is precluded because the required buffer zones around water bodies make applications impractical. Inundative releases of the *Entomophaga* fungus and NPV virus require substantial investment in a limited market which is unlikely to return significant profits. However, inoculative strategies with these pathogens should be explored. Searches for hemlock looper parasitoids, particularly those attacking larvae, should continue in the event of finding a species that could exploit a niche currently vacant in Newfoundland populations. Inoculative releases with imported gregarines should be evaluated following laboratory testing against EHL larvae collected in Newfoundland. Non-lethal forms of pest management are in early stages of investigation and include mating disruption by pheromone inundation and evaluation of the effect of stand structure on EHL survival.

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BIODETERIORATION AND UTILIZATION OF BALSAM FIR STANDS DAMAGED BY THE EASTERN HEMLOCK LOOPER

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INTRODUCTION

Defoliation of balsam fir, *Abies balsamea* (L.) Mill., by the eastern hemlock looper (EHL), *Lambdina fiscellaria fiscellaria* (Guen.) and the eastern spruce budworm (ESBW), *Choristoneura fumiferana* (Clem.) periodically causes extensive foliar damage and tree mortality in Newfoundland. The most recent EHL outbreak beginning in 1983 killed an estimated 11 million m^3 of timber by 1993. Valuable timber is often lost because of sapwood deterioration which starts shortly after tree death. Economic salvage of killed timber is possible depending upon knowing the rates of sapwood deterioration and the factors influencing them.

Early biodeterioration studies of killed balsam fir throughout eastern Canada indicated a common pattern with regional rate differences (Basham 1959, Stillwell and Kelly 1964, Basham *et al.* 1974, Hudak *et al.* 1978). Soon after tree death, a reddish brown discoloration caused by *Amylostereum chailletii* (Pers.: Fr.) Boidin developed in the outer sapwood, followed by a white pitted saprot caused by *Hirschioporus abietinus* (Pers.: Fr.) Donk. Within 1 year after tree death advanced saprot was reported in Ontario (Basham 1959) but it did not appear until the third year in Newfoundland (Hudak *et al.* 1978). Regional differences in climate and intensity of secondary insect attack were postulated as the principle causes of the rate differences (Basham *et al.* 1976).

A major ESBW infestation from 1972-83 caused extensive severe defoliation and tree mortality of balsam fir in Newfoundland. A detailed study of ESBW killed balsam fir from this infestation revealed secondary xylem and phloem insects were the major factor influencing sapwood deterioration (Warren 1989). The major secondary insects which attacked stressed and recently killed balsam fir are listed in Table 1. The two most important secondary insects were siricid woodwasps, *Sirex spp.*, and the balsam fir bark beetle, *Pityokteines sparsus* LeC. Secondary insect activity determines the establishment of the major sapwood decay fungi. Siricid woodwasps inoculate *A. chailletii* into the sapwood during oviposition in stressed and recently killed trees (Stillwell 1966). Balsam fir bark beetles facilitate the establishment of *H. abietinus* (Basham 1959). Two other basidiomycete decay fungi not associated with secondary insects and not previously isolated from balsam fir sapwood were identified as *Panellus mitis* (Pers.: Fr.) Singer and *Hohenbuehelia pinacearum* Thorn. Association analyses indicated the decay fungi function independently of each other and competitively inhibit colonization of a stem region by another decay fungus (Warren 1989). Monitoring of secondary insect activity in recently killed balsam fir timber could be used to predict the type and rate of sapwood deterioration and dictate wood salvage schedules.

METHODS

The EHL infestation which started in 1983 provided the impetus to verify and compare deterioration patterns with those of ESBW killed timber. Three study areas were established throughout Newfoundland to assess tree mortality and the progression of sapwood deterioration (Fig. 1). Tree mortality was assessed in the fall of the year. A tree was considered dead when discoloured cambium occurred entirely around the stem at breast height. Sapwood deterioration and secondary insect activity were assessed annually for 5 years according to the sampling procedures in Fig. 2. Wood disk samples for defect measurements and fungal isolations were taken at 1.0 m intervals. Wood chips were removed from the inner bark, outer sapwood, inner sapwood and heartwood along a disk radius to monitor the progression of sapwood deterioration and the fungi responsible for the defect. Defect fungi were grown and maintained on 2% malt agar media and identified using procedures provided by Nobles (1965). Half metre stem bolts were taken at breast height, mid stem and just below 7.6 cm dia. for assessment of secondary insect activity.

RESULTS

Results of tree mortality assessment are presented in Table 2. Immature and semimature even aged balsam fir stands were susceptible to high tree mortality, 99% and 94% respectively, after 1-2 years of severe looper defoliation. Mature all aged stands with older, larger trees (65% trees >70 yr old) were able to withstand 1-2 years of severe defoliation with only 44% mortality. Progression of total defect (stain and decay) and advanced decay for the three study areas are presented in Table 3. Brown stain appeared early in trees dead 0-1 yr. It progressed into incipient decay affecting about 35% of the tree volume after 4-5 yr. There was slow development of advanced decay, first appearing in

Table 1. Secondary insects attacking balsam fir xylem and phloem after spruce budworm defoliation in Newfoundland.

Sirex spp.	- siricid woodwasps (horntails)
Pityokteines sparsus LeC.	- balsam fir bark beetle
Trypodendron lineatum Oliv.	- spruce ambrosia beetle
Monochamus scutellatus Say	- white-spotted sawyer beetle
Pissodes dubius Rand.	- balsam bark weevil

trees dead 2-3 yr and progressed to affect only 3.2% of the tree volume after 4-5 yr. Sapwood deterioration patterns of EHL killed trees with high secondary insect activity are also included (Table 3). Sapwood deterioration patterns of EHL killed trees attacked by bark beetles and woodwasps are similar to the patterns observed for ESBW killed timber (Fig. 3, Warren 1989). In woodwasp attacked trees stain and incipient decay developed quickly but advanced decay was slow to develop affecting just 2% of wood volume after 4-5 yr. In bark beetle attacked trees defect progression was slow to start but once advanced decay appeared after trees were dead 2-3 yr it developed rapidly to affect 18% of the tree volume after 4-5 yr. Only 23% of the EHL damaged trees sampled revealed high secondary insect activity. The ratio of trees attacked was about 6:1 for woodwasps to bark beetles with bark beetles attacking only 3.2% of the trees. As expected from the secondary insect activity, *A. chailletii* was the most common decay fungus isolated from 39% of the trees sampled (Table 4). *H. abietinus* was isolated from less than 1% of the trees sampled. Two other sapwood decay fungi isolated were *H. pinacearum* and *P. mitis*, isolated from 21% and 17% of the trees sampled respectively (Table 4).

DISCUSSION

Immature and semimature even aged balsam fir stands are susceptible to high levels of mortality from severe EHL defoliation. The Georges Lake and Barren Lake study area had 99% and 94% tree mortality after one year of severe defoliation. Each area had 95% of the trees within their respective age classes. An all aged older stand in the Gallants area with over 65% of the trees >70 yr of age was able to withstand the same defoliation stress with only 44% of the trees dying. Mature and overmature trees appear to be able to withstand more defoliation stress than immature and semimature trees.

Rapid tree death after severe EHL defoliation affects the secondary insect activity and subsequent stem biodeterioration of killed balsam fir. Secondary insect activity in EHL damaged timber was not as high as in stands damaged by the ESBW. Only 23% of the EHL damaged trees had high secondary insect activity, 20.1% was from woodwasps and 3.2% from bark beetles, a ratio of about 6:1. In ESBW damaged timber about 70% of the trees were affected by high secondary insect activity, 38.7% by woodwasps and 31.5% by bark beetles, a ratio of about 1:1 (Warren 1989). The higher incidence of woodwasp activity and associated infection by *A. chailletii* in EHL damaged balsam fir causes a delay in advanced saprot development as observed in Table 3. Woodwasp attacked trees developed a higher percentage of sapstain but advanced decay did not appear until after trees were dead 4 yr. and affected only 2.0% of the merchantable tree volume after 5 yr. Woodwasp activity delays the progression of advanced saprot in killed standing timber by inoculating the fungus *A. chailletii* during oviposition. This fungus causes primarily a red-brown sapstain and incipient decay. Once established, *A. chailletii* inhibits the establishment of more aggressive advanced decayers such as *H. abietinus*, prolonging the economic salvage of killed timber. In EHL killed balsam fir attacked by bark beetles, advanced saprot appeared after trees were dead 2-3 yr and rapidly developed to affect 18.9% of the merchantable tree volume after 5 yr. Advanced saprot appears earlier and develops quicker in trees attacked by bark beetles than those by woodwasps. In areas with high populations of *P. sparsus*, a white pitted saprot caused by *H. abietinus* can render timber unsalvageable within two years (Basham, 1986). Only 3.2% of the EHL damaged trees were attacked by bark beetles therefore advanced saprot development caused by *H. abietinus* was quite low.

The concern in EHL damaged timber is saprot development in the 77% of trees not affected by high secondary insect activity. Isolation frequency and the percentage of trees affected by major decay fungi showed *H. pinacearum* and *P. mitis* were more prevalent than *H. abietinus* in sapwood

Table 2. Balsam fir mortality after severe hemlock looper defoliation in Newfoundland.

			% defoliation and mortality assessment												
Study Area	Defoliation History	Av. Stand Age (yr)	Summer 1986				Spring 1987				Fall 1987				Total # tress
			L-M	S	D_{0-2}	D_L	Sur.	Mor.	D_{0-2}	D_L	Sur.	Mor.	D_{0-2}	D_L	
Gallants	1984-L 1985-L	77 mature	17	37	29	16	46	2	36	16	40	0	44	16	818
Barren Lake	1985-L 1986-L	56 semimature	0	92	1	7	44	30	19	7	2	0	91	7	924
Georges Lake	1986-S	37 immature	2	98	0	0	32	25	43	0	7	0	93	0	916

Defoliation levels	L - light, M - moderate, S - severe
Mortality assessment	Sur. - surviving, cambium living and healthy, possibility of recovery if no subsequent defoliation
	Mor. - moribund, cambium living but not healthy, tree with 100% defoliation, not expected to live
	D_{0-2} - trees which have died as a result of recent defoliation
	D_L - trees dead several years prior to assessment and defoliation

Table 3. Sapwood deterioration of balsam fir killed by hemlock looper defoliation in Newfoundland.

		% defect volume by mortality class (years dead)											
Study Area	Av. Stand Age (yr)	0-1 yr		1-2 yr		2-3 yr		3-4 yr		4-5 yr		Secondary insects (% trees attacked)	
		adv.	tot.	adv.	tot.	adv.	tot.	adv.	tot.	adv.	tot.	BB	WW
Gallants	77 mature	0.0	16.2	0.0	6.5	1.0	20.0	0.4	26.2	1.3	41.1	3.2	22.3
Barren Lake	56 semimature	0.0	0.0	0.0	3.2	0.8	15.7	0.0	27.4	4.1	39.0	5.3	22.4
Georges Lake	37 immature	0.0	0.0	0.0	6.3	0.3	22.0	0.0	31.8	4.6	34.6	1.3	15.4
Overall		0.0	6.5	0.0	9.2	0.7	19.3	0.2	28.4	3.2	37.1	3.2	20.1
Bark beetle trees		0.0	3.9	0.0	6.5	0.0	14.8	8.4	44.9	18.9	55.2	3.2	
Woodwasp trees		0.0	10.5	0.0	18.8	0.0	25.9	0.0	36.2	2.1	42.6		20.1

Defect types	adv. - advanced decay, noticeably softened wood
	tot. - total defect, including decay and stain
Secondary insects	BB - bark beetles
	WW - woodwasps

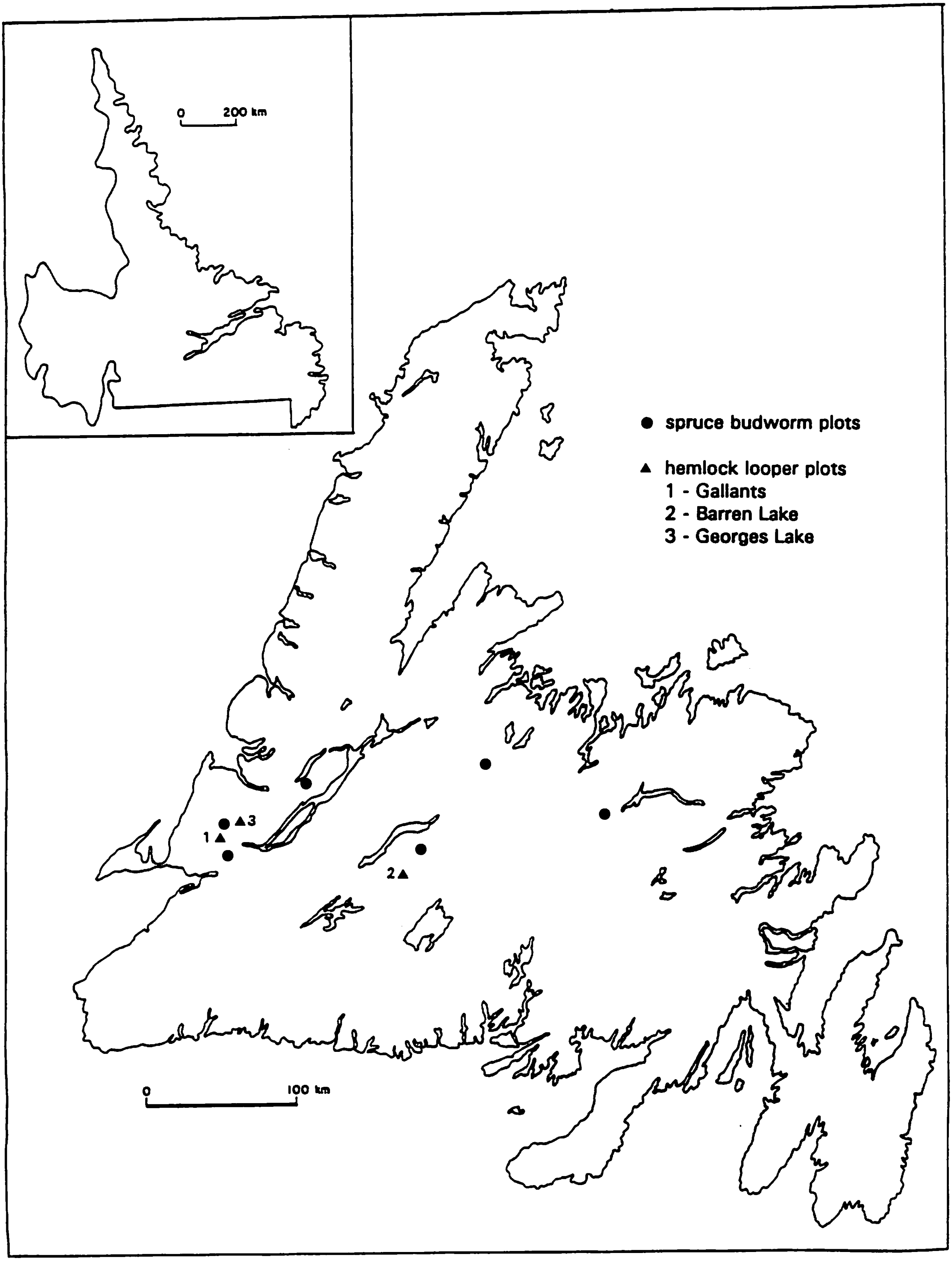

Figure 1. Locations of study areas for assessing tree mortality and sapwood deterioration of insect damaged balsam fir.

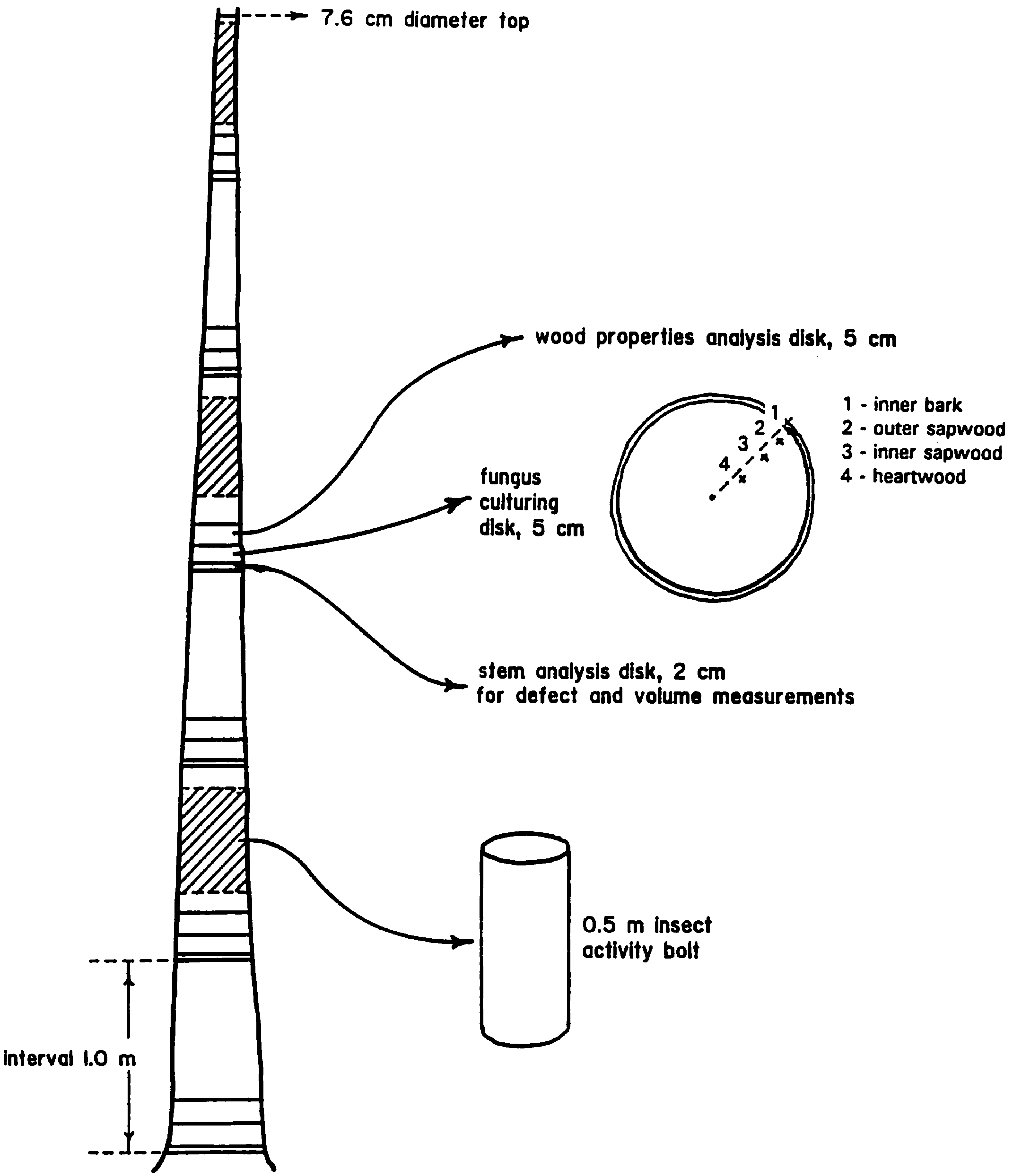

Figure 2. Stem sampling procedures to assess sapwood deterioration of insect damaged balsam fir trees.

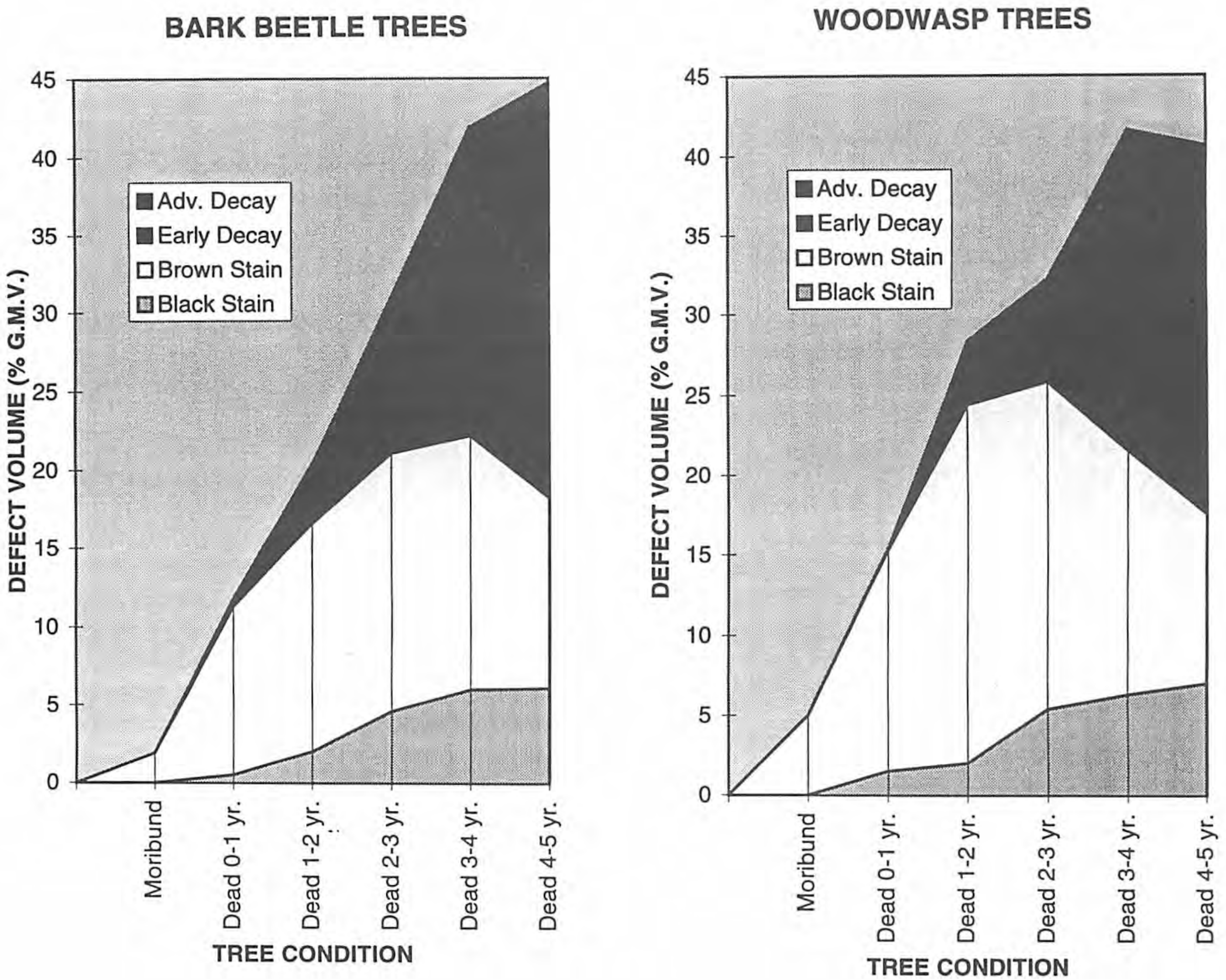

Figure 3. Cummulative progression of defect volumes in dead balsam fir trees with high bark beetle or woodwasp activity.

Table 4. Frequency of the major sapwood decay fungi isolated from balsam fir stems killed by eastern hemlock looper and spruce budworm defoliation in Newfoundland.

Fungus Species	Hemlock looper		Spruce budworm	
	Frequency # isolates	% trees sampled	Frequency # isolates	% trees sampled
Amylostereum chailletii (Pers.: Fr.) Boidin	462	39.1	516	54.3
Hohenbuehelia pinacearum Thorn	110	21.0	106	23.1
Panellus mitis (Pers.: Fr.) Singer	90	16.7	109	23.6
Hirschioporus abietinus (Pers.: Fr.) Donk.	4	0.7	276	26.3
Kirshchteiniella thujina (Peck.) Pom. & Eth	85	21.4	173	37.1

deterioration. *H. pinacearum* and *P. mitis* have not been shown to be associated with any secondary insect activity. Preliminary field observations indicated infection was associated with dead branch stubs. Decay tests from the ESBW research indicated these two fungi were quite aggressive decayers but required an associate scavenger fungus to function effectively. *Kirschteiniella thujina* (Peck.) Pom. & Eth., a dematiaceous hyphomycete, was identified as the most common scavenger associate of the above two decayers (Warren 1989). This sapwood deterioration system was easily recognized by the distinct black stain zone, caused by *K. thujina*, in advance of the saprot. Sapwood deterioration by this system is slower than by *H. abietinus*, and is responsible for appearance of advanced saprot in trees dead 2-3 yr. which have not been attacked by bark beetles.

SUMMARY

Tree mortality and sapwood deterioration were studied for balsam fir trees killed by EHL defoliation and compared to those ESBW damaged timber. Immature and semimature trees had very high mortality rates after one year of severe EHL defoliation whereas mortality in mature and overmature trees was much lower. Tree mortality usually occurs after 4-5 years of successive severe defoliation of current growth by ESBW.

Secondary insects, primarily woodwasps and bark beetles influenced the establishment of the major decay fungi *A. chailletii* and *H. abietinus* respectively. A higher 6:1, woodwasp to bark beetle ratio was observed in EHL killed timber compared to a 1:1 ratio in ESBW killed timber. The lower overall high secondary insect activity in only 23% of EHL damaged trees, compared to 70% in ESBW damaged trees, resulted in a different sapwood deterioration system involving two recently identified decay fungi *H. pinacearum* and *P. mitis*. This deterioration system was easily identified by the association of decay fungi with dematiaceous fungi, primarily *K. thujina*, which produced a black stain zone preceding the saprot as it progressed into the stem.

The low incidence of bark beetle activity and associated infection by *H. abietinus* resulted in limited early salvage losses of EHL damaged timber to advanced saprot. In trees with high woodwasp activity advanced saprot is delayed by *A. chailletii*, the fungus inoculated during woodwasp oviposition. Field inspections have observed sound standing stem boles 7 yr. after tree death. Sapwood deterioration by *H. pinacearum* and *P. mitis* in the majority of EHL damaged stems, not affected by secondary insect activity, is the determinant for salvage scheduling. Advanced decay is slower to develop, than with *H. abietinus*, appearing after trees were dead 2-3 yr. and did not exceed 5% after trees were dead 5 yr. Research is continuing on determining the sapwood penetration and deterioration rates for *H. pinacearum* and *P. mitis* in killed balsam fir.

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DETECTION AND CLASSIFICATION OF INSECT DAMAGE WITH REMOTE SENSING

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INTRODUCTION

Early detection and classification of defoliation by eastern hemlock looper (EHL), *Lambdina fiscellaria fiscellaria* (Guen.), is crucial for effective forest resource management in Newfoundland. Historically ground and aerial surveys provided most of the information on the distribution and severity of defoliation and subsequent tree mortality. More recently, remote sensing methods have been used to monitor forest pest damage (Murtha, 1972; Dottavio and Williams, 1983; Franklin, 1989; Franklin and Hudak, 1989; Leckie *et al.*, 1989; Riley, 1989; Moulton *et al.*, 1990; Luther *et al.*, 1991; Power and D'Eon, 1991). Remote sensing research involving EHL defoliation began in Newfoundland in 1987. Studies were aimed at i) developing methods for detecting and classifying damage, ii) estimating foliar biomass in defoliated stands, and iii) discriminating defoliation by EHL from other insect pests. Here I summarize the results of that research and briefly discuss the potential of recent and anticipated advances in remote sensing for integrated forest resource management.

STUDY AREAS AND SATELLITE IMAGERY

Data were acquired by high resolution satellite sensors for study areas near Hawkes Bay on the Northern Peninsula, Western Newfoundland (Fig. 1) where the dominant forest cover was semi-mature balsam fir, *Abies balsamea* (L.) Mill. One area became severely defoliated by the EHL in 1987 and 1988 and was the site of a Forestry Canada experimental spray program against the looper (West *et al.*, 1989). A second area, north of Hawkes Bay, experienced a simultaneous outbreak of the EHL and the blackheaded budworm (BHBW), *Acleris variana* (Fern.), in 1990 and presented an opportunity to investigate the ability of satellite imagery to discriminate simultaneous damage from both insects.

Several Landsat Thematic Mapper (TM) - 30 August 1987, 20 September 1989, 6 August 1990, and SPOT High Resolution Visible (HRV) - 29 August 1987, 12 June 1988, 18 July 1988, 19 August 1988, satellite images were acquired. SPOT HRV images are three band digital data with 20 m spatial resolution. The wavelengths sensed correspond roughly with the green, red and infrared portions of the electromagnetic spectrum. Landsat TM images have seven bands with a 30 m spatial resolution. For all studies, standard geometric correction procedures based on ground control points were used to register each image to the Universe Transverse Mercator (UTM) coordinate system to allow for comparisons among the different images and transfer of digital products to Geographic Information Systems (GIS).

CLASSIFICATION OF DEFOLIATION

Detection and classification of defoliation requires that damaged foliage be discriminated from background variation in the forest canopy. One method of discriminating damage in remote sensing imagery involves a *supervised classification* of the image data. An operator selects areas in the digital image which represent the classes of interest on the ground (Lillesand and Kiefer, 1979). The digital image data associated with each 'training' area are then used to develop signatures for each land cover class. The signatures are input to a maximum likelihood classifier which assigns each pixel to the class for which the statistical probability is highest. A prior knowledge of the study area is required and the forest classes of interest must be predetermined.

In the study of EHL defoliation, forest parameters were recorded in the field at 75 randomly selected sites, each measuring 3600 m^2 and corresponding to a 3x3 pixel window on the digital image. Each pixel was assigned to a cover class based on the field records as follows: 1. lake sediment, 2. water, 3. marsh, 4. meadow, 5. light defoliation (1-30% foliage loss), 6. moderate defoliation (31-60% foliage loss), 7. severe defoliation (61-100% foliage loss), 8. softwood regeneration, and 9. healthy balsam fir. Supervised classifications with an image analysis system separated the three levels of defoliation from all other land cover classes.

Maps produced from the classifications (Figure 2) were compared with aerial sketch maps of the area produced by trained Canadian Forest Service personnel from helicopter platforms. In general, the classification maps showed good overall agreement. Classification accuracy was assessed quantitatively for the August 1987 image using discriminant function analysis for 3600 randomly selected pixels and based on field observations at randomly selected sites. A contingency table showing the results of the classification and field verification for the SPOT HRV August 1987 image is contained in Table 1.

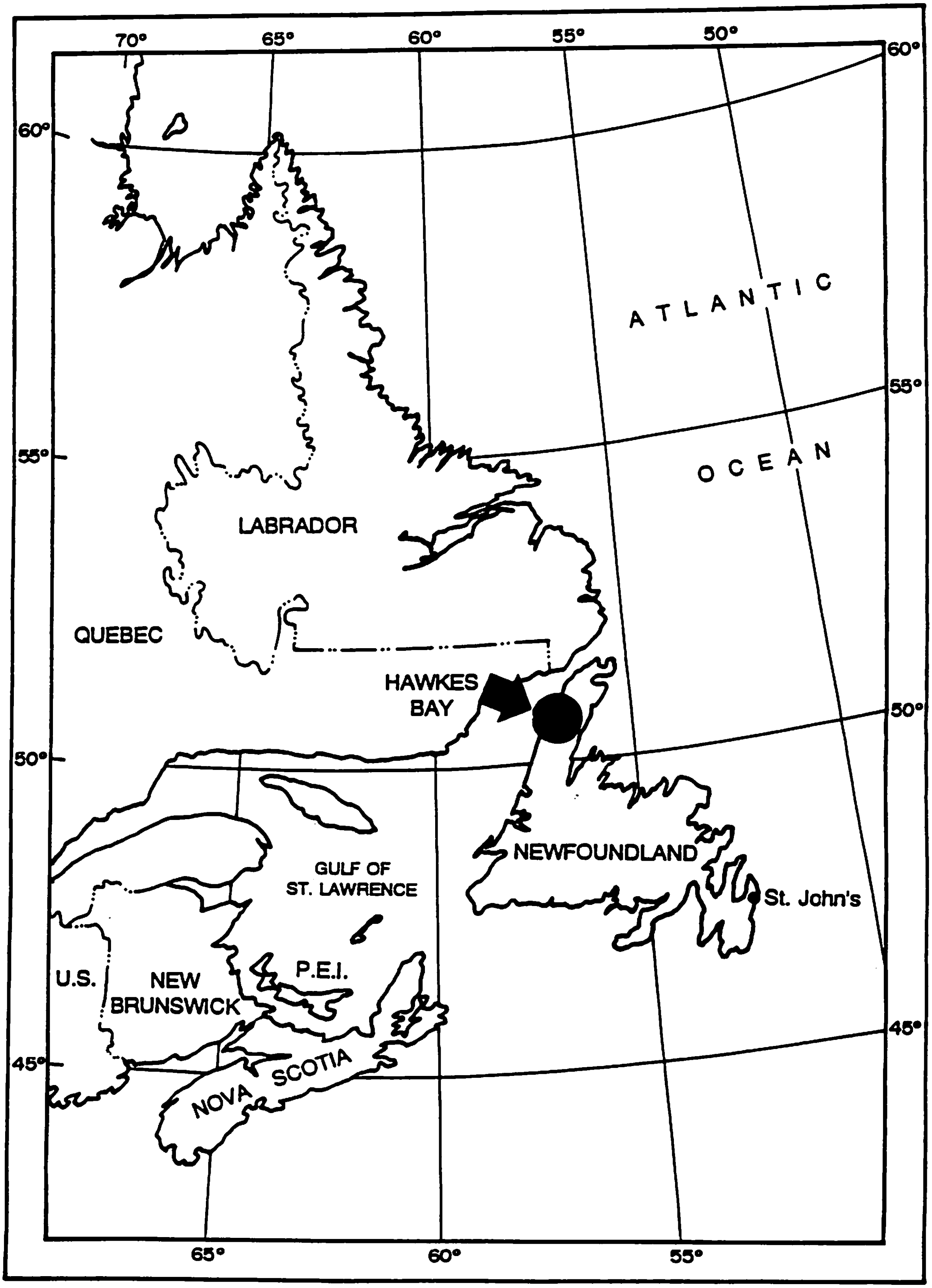

Figure 1. Hawkes Bay study area, Newfoundland.

Table 1. Percent agreement between field observations and satellite image classification for eight land classes mapped by supervised classification of SPOT HRV image of 29 August 1987 near Hawkes Bay, Newfoundland.

Number of pixels and percentage classified into class										
From Class	1	2	3	4	5	6	7	8	Total	Omission
1 Lake Sediment	45	0	0	0	0	0	0	0	45	0
	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
2 Water	0	144	0	0	0	0	0	0	144	0
	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
3 Recent Cutovers	0	0	45	9	0	0	0	0	54	9
	0.00	0.00	83.33	16.67	0.00	0.00	0.00	0.00	100.00	16.67
4 Marsh	0	0	9	36	0	0	0	0	45	9
	0.00	0.00	20.00	80.00	0.00	0.00	0.00	0.00	100.00	20.00
5 Light defoliation	0	0	0	0	72	0	0	0	72	0
	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	100.00	0.00
6 Mod/Severe defoliation	0	0	0	0	0	45	0	0	45	0
	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	100.00	0.00
7 Regeneration	0	0	0	0	0	0	135	9	144	9
	0.00	0.00	0.00	0.00	0.00	0.00	93.75	6.25	100.00	6.21
8 Balsam Fir Forest	0	0	0	0	9	9	0	135	153	18
	0.00	0.00	0.00	0.00	5.88	5.88	0.00	88.24	100.00	11.76
Total	45	144	54	45	81	54	135	144	702	45
Percentage	6.41	20.15	7.69	6.41	1.53	7.69	19.23	20.51	100.00	6.41
Commission	0	0	9	9	9	9	0	9	45	
Percentage	0.00	0.00	16.67	20.0	11.11	16.67	0.00	6.25	6.41	

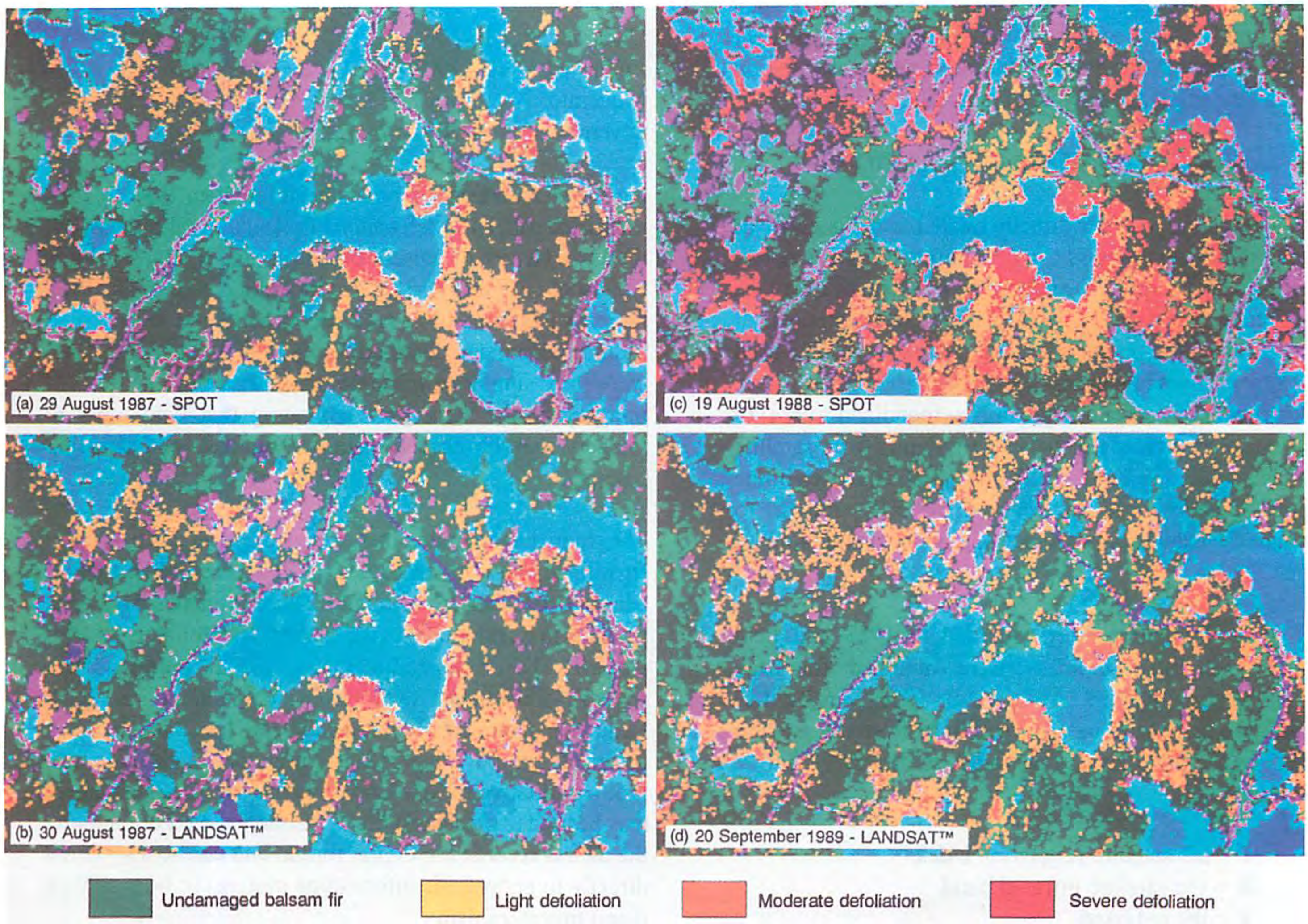

Figure 2. **Classification of hemlock looper defoliation, Hawkes Bay study area, Newfoundland.**

The overall classification accuracy was 93% with the lower acceptable limit to give a 99% confidence level equal to 90.6%. A comparison of digital classifications of June 1988 and August 1988 images confirmed a decrease in the area of healthy balsam fir from 44% to 30% of the total area and a corresponding increase in the total area of defoliation.

Generally, defoliated balsam fir stands were found to have a lower reflectance than healthy stands at each image date. It is noteworthy that the mean reflectance value of healthy stands in June which were later defoliated was lower than that for stands which remained non-defoliated. This apparent potential to predict areas of defoliation from pre-defoliation satellite imagery is the subject of ongoing research.

FOLIAR BIOMASS ESTIMATION

Since spectral response is directly related to the quantity of vegetation, foliage biomass can be computed from remotely sensed satellite imagery. The pattern in wavelength intervals, green, red, infrared, etc., can be related to field estimates of biomass at specific points in time and therefore can be used to monitor changes in biomass caused by insect infestations. The objectives of a second study in Newfoundland were i) to estimate foliar biomass of balsam fir stands from satellite imagery acquired in 1987, 1988 and 1989, ii) to determine biomass changes over time caused by EHL, and iii) to determine the relation between defoliation level and biomass change.

Classes of defoliation were recorded in 1988 and field estimates of foliar biomass were obtained for each defoliation class in 1989. A vegetation index was used to estimate the amount of balsam fir foliage from the satellite imagery at the pixel level. This index computes F=IR/R + other bands;

F = the satellite vegetation index
IR = the satellite infrared band
R = the red band

The index provides a relative measure of balsam fir foliage. However, the correlation between these indices and the field measures was very high (R^2=0.96), therefore, they were used to compute absolute measures of biomass (kg/ha) for each pixel.

Data from the field samples were used to derive mean foliar biomass estimates for each defoliation class. For each year, a random sample of 50 pixels per class was assigned the mean class biomass value derived from the field samples and regression models were developed. These models were used to calculate the biomass values for all pixels in the study area.

Mean foliar biomass estimates derived from the 1988 satellite image corresponded well with the mean field estimates obtained that year (Figure 3). The values decreased with increasing level of defoliation as follows:

	Field Estimates (kg/ha)	Satellite Estimates (kg/ha)
Undamaged	16 700	15 800
Light	13 400	11 500
Moderate	6 600	8 700
Severe	4 900	4 100

An overall reduction in biomass occurred from 1987 to 1988 associated with EHL defoliation (Table 2). Total biomass for the 2 672 ha area of balsam fir was about 40.6 million kg in August of 1987 and 36.3 million kg in August of 1988. Total biomass increased to about 37.5 million kg in 1989. Foliar biomass estimates obtained using SPOT imagery in 1987 were very similar to those obtained with the Landsat TM imagery of the same year indicating that both types of imagery may be used to estimate biomass of balsam fir forests.

The study demonstrated that calibrated estimates of balsam fir foliage biomass can be derived from satellite imagery if adequate field data are available. These estimates have great potential in monitoring change caused by defoliators such as the EHL. The use of satellite imagery for this purpose offers several advantages over traditional survey methods. Estimates from satellite imagery can be obtained more accurately for individual stands within management units at little cost relative to field sampling and the satellite imagery may be used to obtain additional resource data. Furthermore, the data is recorded in digital format and can be transferred directly to geographic information systems to be used with forest inventory data.

EASTERN HEMLOCK LOOPER AND BLACKHEADED BUDWORM

The blackheaded budworm (BHBW), is another important defoliator of balsam fir stands in Newfoundland. Whereas the EHL feeds openly on needles of all ages throughout the crowns of trees, the BHBW feeds enclosed on expanding new shoots. A third study examined the influence of defoliation by both the BHBW and EHL on spectral reflectance values and also determined the accuracy for classifying light, moderate and severe classes of defoliation by each insect with Landsat TM spectral bands.

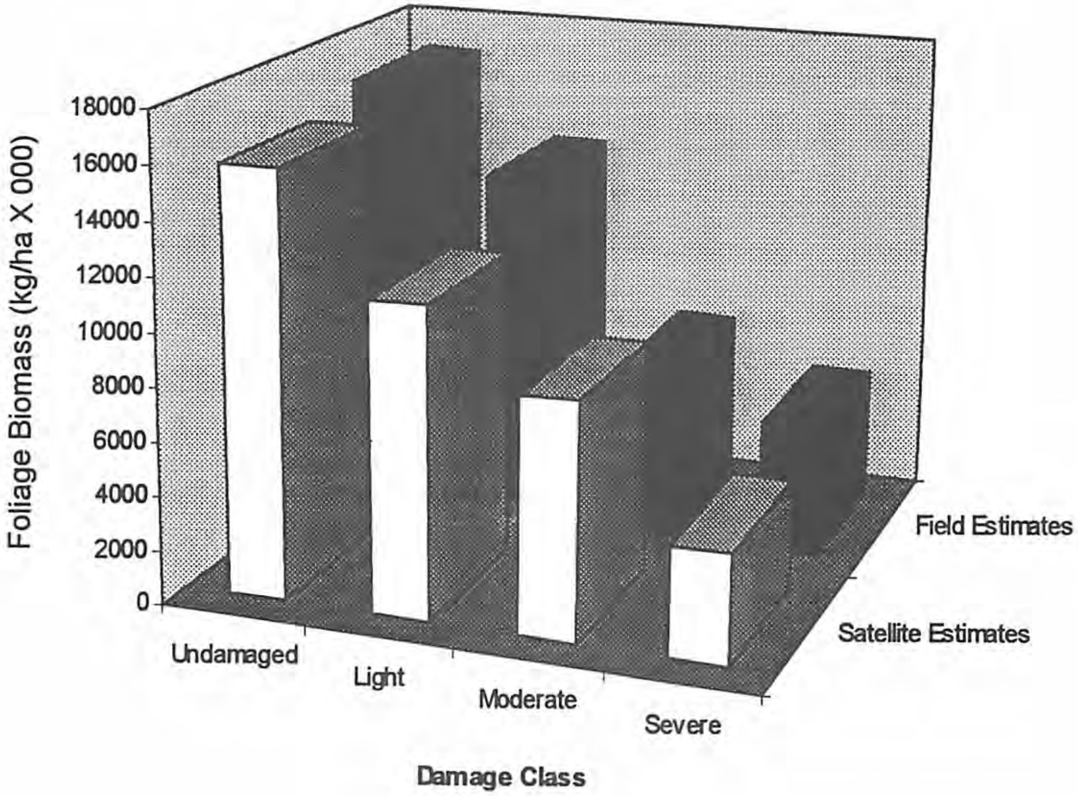

Figure 3. Mean foliar biomass estimates for undamaged and hemlock looper defoliated balsam fir in Newfoundland, 1988.

Table 2. Total balsam fir foliar biomass (kg) from satellite imagery by eastern hemlock looper defoliation class for Hawkes Bay study area, Newfoundland, 1987 to 1989.

Defoliation	1987		1988	1989
Class	SPOT	LANDSAT	SPOT	LANSAT
Undamaged	35 957 000	3 4917 000	28 148 000	31 172 000
Light	4 078 000	4 593 000	3 706 000	5 193 000
Moderate	448 000	585 000	4 020 000	1 115 000
Severe	151 000	141 000	442 000	0
Total	40 634 000	40 235 000	37 480 000	

The defoliation by the EHL and the BHBW were classified at specific sites on the ground as light < 25%, moderate 26-75% or severe > 76%. Each site was identified on the UTM registered digital satellite image and spectral reflectance values of a 3x3 pixel area centered on each site extracted. Only sites in relatively homogeneous areas greater than 60x60 m and with little or no defoliation prior to 1990 were used. A total of 315 pixels were included in the analysis.

Bivariate correlations between Landsat TM spectral bands and percent defoliation by the EHL and the BHBW were examined to determine the significant contributions to spectral response by each type of defoliation. Sites were then assigned to defoliation classes depending on the percent defoliation recorded at each site. T-tests were done for each pair of classes to determine optimum spectral bands for discriminating types and levels of defoliation.

The highest correlation between spectral bands and defoliation occurred in the near and middle infrared portion of the spectrum and were higher for the EHL (-0.78) than the BHBW (-0.54). The latter was expected as the looper feeds on both the new and old foliage, whereas the budworm attacks primarily new shoots resulting in less overall defoliation. Generally weak correlations occurred in the visible portion of the spectrum. Similar results have been reported by researchers for the spruce budworm (Leckie *et al.*, 1988 a,b).

Significant differences between classes of defoliation occurred for several spectral bands of Landsat TM (Table 3). The highest number of significant bands discriminating undamaged balsam fir occurred for the moderate and severe defoliation classes. A greater number of significant bands for separating levels of BHBW defoliation occurred between the light and severe classes than between the light and moderate classes and between the moderate and severe classes.

All bands were significant (t-test; α=0.01) for discriminating the severe EHL defoliation class from both the light and moderate BHBW classes. Only bands TM1 and TM3 were significant for discriminating the light EHL defoliation class from the light and moderate BHBW class. Bands TM1, TM4, TM5 and TM7 were the most useful overall for discriminating among defoliation classes .

Discriminant analysis was used to separate defoliation classes on the basis of Landsat TM spectral reflectance bands. Discriminant functions were generated based on pixels with known classes of defoliation from field records. A set of pixels with known defoliation but excluded from the discriminant analysis were used to test classification accuracy. Discriminant analysis was done separately for EHL and BHBW and repeated for all classes of defoliation for both insects together.

Areas of EHL defoliation classes were at least 85% in agreement with the field classification with a mean class accuracy of 93%. The light and moderate looper defoliation classes were 100% and 93% correct, respectively. No sites were sampled for severe EHL defoliation without damage in previous years. The accuracy of BHBW defoliation classes were lower than those for EHL. This was expected with the lower correlation coefficients for BHBW defoliation. The accuracy of light, moderate and severe BHBW defoliation classes were 71%, 84% and 89%, respectively, with a mean class accuracy of 82%. The mean accuracy of all classes of defoliation for both EHL and BHBW was 79% (Table 4). These results suggest that Landsat TM data may be used for accurate classification and mapping of areas simultaneously defoliated by the EHL and the BHBW.

GEOGRAPHIC INFORMATION SYSTEMS

Defoliation maps can be transferred in digital format directly to GIS. This was accomplished with the defoliation maps produced from the satellite classifications of EHL defoliation. The 1987 defoliation mapped in the June 1988 image was subtracted from the defoliation mapped in the August 1988 image to produce a map of new 1988 defoliation. The 1988 defoliation map was transferred in digital format directly to the ARC/INFO GIS and combined with the corresponding forest inventory map to produce area and volume statistics for individual stands by 1988 defoliation classes. This transfer represents a critical link in the capability to update forest inventory maps efficiently and accurately using information extracted from remote sensing imagery.

RECENT AND ANTICIPATED ADVANCES

Recent studies in Newfoundland have demonstrated new methods of mapping and quantifying EHL and BHBW defoliation classes from space. We have shown that calibrated estimates of balsam fir foliage biomass can be derived from satellite imagery if adequate field data are available. These estimates have great potential in monitoring change caused by defoliators such as the EHL. Furthermore, the direct transfer of digital defoliation maps to forest inventory GIS is efficient, objective and facilitates the analysis of continuously changing forest conditions.

Forests represent the most complex ecosystems and recent advances in remote sensing technology and analytical methods provide unprecedented opportunity to monitor and analyze basic parameters of forest communities, including

Table 3. Plot of bands with a significant difference between undamaged balsam fir and eastern hemlock looper (EHL) and blackheaded budworm (BHBW) defoliation classes (t-test; $\propto = 0.01$)

Defoliation Classes[a]	**Spectral Band**					
	TM 1	**TM 2**	**TM 3**	**TM 4**	**TM5**	**TM 7**
1 VS 2	*			*	*	*
1 VS 3	*		*	*	*	*
1VS 5		*		*		*
1VS 6	*	*		*	*	*
1VS 7	*	*		*	*	*
2 VS 3			*	*	*	*
2 VS 5	*		*			
2 VS 6	*		*			
2 VS 7	*	*		*		*
3 VS 5	*	*	*	*	*	*
3 VS 6	*	*	*	*	*	*
3 VS 7	*	*	*		*	*
5 VS 6	*				*	
5 VS 7	*			*	*	*
6 VS 7				*		*

[a] 1. Undamaged balsam fir
2. EHL Light Defoliation
3. EHL Moderate Defoliation
4. EHL Severe Defoliation
5. BHBW Light Defoliation
6. BHBW Moderate Defoliation
7. BHBW Severe Defoliation

Table 4. Percent agreement between field observations and satellite image classification of sites defoliated by the eatern hemlock looper (EHL) and the blackheaded budworm (BHBW) in Newfoundland.

Number of pixels and percentages classified into class

Observed Class	1	2	3	5	6	7	Total	Omission
1. Undamaged Balsam Fir	23	2	0	2	0	0	27	4
	85.2	7.4	0.0	7.4	0.0	0.0	100.0	14.8
2. EHL Light Defoliation	0	10	0	2	1	0	13	3
	0.0	76.9	0.0	15.4	7.7	0.0	100.0	23.1
3. EHL Mod. Defoliation	0	0	18	1	0	1	20	2
	0.0	0.0	90.0	2.9	0.0	5.0	100.0	10.0
4. EHL Sev. Defoliation				no sites in sample				
5. BHBW Light Defoliation	10	11	0	29	12	1	63	34
	1`5.9	17.5	0.0	46.0	19.1	1.6	100.0	54.0
6. BHBW Mod. Defoliation	0	1	0	2	14	0	17	1
	0.0	5.9	0.0	11.8	82.4	0.0	100.0	5.9
7. BHBW Sev. Defoliation	0	0	1	0	0	17	18	3
	0.0	0.0	5.6	0.0	0.0	94.4	100.0	16.7
Total	33	24	19	36	27	19	158	47
Percentage	20.9	15.2	12.0	22.8	17.1	12.0	100.0	29.8
Commission	10	14	1	7	13	2	47	
Percentage	30.0	58.3	5.3	19.4	48.2	10.5	29.8	

solar radiation, CO_2 exchange, biochemical content and biomass of canopies, growth and growth efficiency in relation to biotic and abiotic environmental factors (Peterson *et al.* 1988; Running *et al.* 1989; Botkin and Simpson, 1990; Bartlett *et al.* 1990; Ahern *et al.* 1991; Roughgarden *et al.* 1991) and their joint effects on forest pests at the stand, landscape, regional or global level.

Continued international cooperation will lead to further development of new airborne and satellite technology providing major improvements in detection and monitoring of forest ecosystem parameters at the stand, landscape, regional, national and global scale (Wickland, 1991; Ustin *et al.* 1991). As satellite imagery improves in character and parallel improvement in their analysis are made, it is expected that a stronger operational role for satellite data will evolve in many forestry activities. Furthermore, critical research in remote sensing is anticipated to provide predictive models to improve the integrated management of complex forest ecosystems in the context of sustainable development.

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A SOCIO-ECONOMIC ANALYSIS OF THE EASTERN HEMLOCK LOOPER IN NEWFOUNDLAND

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INTRODUCTION

The forests of Newfoundland and Labrador provide a multitude of both timber values, notably pulpwood and lumber, and so-called non-timber values such as aesthetic beauty, wildlife habitat, soil protection, and a wide range of recreational services. Unfortunately, the forests also serve as a host to various insect pests. The eastern hemlock looper (EHL), *Lambdina fiscellaria fiscellaria* (Guen.), is one such pest that, due to its destructiveness, continues to threaten to various degrees the values of the goods and services which we gain from our forests. When a pest outbreak occurs, the management decision is whether to treat the infested area given the existing treatment technology and its associated costs, and the estimated value of the forest resource treated. This decision calls for further information on the micro-economic consequences of the anticipated damage in the absence of treatment. The critical first step in obtaining this information is a cost-benefit analysis of the treatment options in the area in question. This paper produces a simple, but readily generalizable framework for undertaking such an analysis. To demonstrate the methodology, we use available economic, biological, and treatment efficacy data to estimate the net social benefit of controlling the looper under a variety of assumptions. This information is then analysed in an attempt to estimate the value of timber loss due to looper induced tree mortality in the province since the most recent major outbreak in 1983.

Our main finding is that for the data and treatment technologies considered, a positive social net benefit of operational control programs results when timber values are considered. Where non-timber values associated with the infested area are present, they will add to the social benefit of control programs. The methodological problems associated with the estimation of non-timber values are, however, beyond the scope of this paper. They are referred to here, therefore, in a qualitative sense only.

This paper is organized as follows. Section two comments on the economic significance of the forest sector in view of current wood supply issues. Section three describes the operational EHL control program on which we have based our analysis. Section four presents the methods, data and assumptions used and the results of cost - benefit analysis. Section five is a sensitivity analysis. Section six presents an analysis of the economics of EHL infested forest damage in Newfoundland and Labrador. Finally, section seven presents the conclusions.

CURRENT SIGNIFICANCE OF THE PROVINCIAL FORESTRY SECTOR

The forestry sector of Newfoundland and Labrador is comprised of the pulp and paper industry, the lumber industry and the value added forest products industry. In 1995, the forestry sector as a whole accounted for about 3% of the provincial Gross Domestic Product (GDP)[1]. The primary forestry sector alone accounted for 12% of primary sector GDP, while the newsprint industry comprised 24% of the manufacturing GDP. In 1991, one in every 25 jobs were in the forestry sector. This translates into about 3600 person years of employment. This is in turn equivalent to about 5,000 direct and 3,000 indirect jobs (O'Neill 1992; Forestry Canada 1992).

Today the pulp and paper industry supports three mills located in Corner Brook, Grand Falls and Stephenville. The total annual capacity is 760,000 tonnes of newsprint. Newfoundland newsprint mills shipped 733,400 tonnes of product in 1995, valued at $665 million.

The sawmill industry has long been a vital element of the Newfoundland economy. Many of the sawmills on productive unalienated Crown land in coastal areas remain an important source of employment and supplementary income for many rural Newfoundlanders. These mills are often very small, providing sawlogs and materials for local residential construction, fishing supplies, and sheds. The industry has been plagued with inefficiencies largely due to the number of these small mills. In 1991, 94% of mills produced less than 100 Mfbm annually (Trelawny 1994).

Lumber production has risen dramatically in the last couple of years as local producers focus on capital improvements, value-added production and exports. After averaging 46 million board feet per year during the mid-1980s to the early

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[1] Data and estimates provided by Newfoundland Statistics Agency based on Statistics Canada, Catalogue 15-203.

1990s, lumber production has averaged 70 million board feet during the last three years (1994-96). The annual value of lumber production in the province is estimated to be in the \$22 to \$35 million range.

The value-added forest products industry in the province remains at a rudimentary stage despite over a century of industry development. Although small quantities of a number of products are currently produced including window and door frames, roof and floor trusses, surveying stakes, prefabricated homes, and furniture, the industry does not add substantially to the local economy.

Wood Supply Issues

Unplanned and uncontrolled forest depletion such as that caused by forest pests threaten both consumptive and non-consumptive forest uses. Pest control is thus a concern in principle whether forests are managed primarily for timber or non-consumptive uses. The issue of timber supply is itself complex as it has both physical and economic dimensions, each with short-term and long-term effects (Milne 1991).

Mature and over mature timber make up 45% of the forests in the province. Most of the short-term supply is thus susceptible to attack from insects and diseases. It is also vulnerable to forest fire. These occurrences can cause short-term supply problems and reduce non-timber benefits. In the case of forest fire, a short-term supply deficit develops. Insect damage causes a short-term surplus and influences harvesting priorities and access road construction as an attempt is made to harvest damaged timber.

The estimated rotation period for balsam fir in Newfoundland is 50 to 60 years (Milne 1990). Thirty-five percent of stands are in this age class. These stands are largely isolated and fragmented by highgrading and repeated insect attack, although large scale precommercial thinning in western regions has somewhat improved the composition and vigour of these stands (Flight and Peters 1992).

The 20 Year Forestry Development Plan, 1996-2015 (Tulk *et al.* 1996) recently released by the Provincial Government contains a timber resource analysis that now forms the basis for the Province's overall forest management strategy. The analysis refers to the most recent review of the timber supply, started in 1994. This review, like the earlier one (Flight and Peters 1992) indicates a substantial annual deficit for insular Newfoundland. The total softwood allowable annual cut (AAC) for the Island over the 80-year planning horizon is projected at 2 055 050 m^3 from a total land base of 1 595 500 ha. In the absence of an annual silviculture program of planting and spacing involving 8 442 ha, the AAC drops to 1 919 150 m^3. In the period 1990-95 the AAC fell by 15% or 354 950 m^3 annually. This constitutes a significant reduction in supply, which should greatly influence the adoption of new management strategies.

The wood supply (AAC) on the Island stands at 551 850 m^3 and 1 503 200 m^3 on Crown Lands and company lands respectively. In Labrador the supply remains at an estimated 580 000 m^3. The projected annual wood requirements (demand) for the period 1995-99 from Crown Lands, company lands and Labrador are, respectively, 480 000 m^3, 2 056 000 m^3 and 100 000 m^3. For 1995, this translates into an annual wood shortage for the Island as a whole of 480 950 m^3; and a wood surplus in Labrador of 480 000 m^3. That is, on the Island demand currently exceeds supply by 23%. The figure for company lands alone is 37%. Actual consumption as controlled by regulation is said to exceed the 1995 AAC by 12%. Based on demand projections for 2000-2015, the annual wood shortage forecast for the Island is 602 750 m^3. It is cautioned that the cost of accessing timber in the sensitive northern ecosystems of Labrador will severely limit the potential of this source in mitigating wood shortages, at least in the foreseeable future. Furthermore, as Milne (1986) points out, AAC figures should be viewed with caution as the data used typically do not recognize economic accessibility, does not fully incorporate the effects of pest infestations, or take into account improvements in forest management strategies. Some of these problems will thus remain even if AACs are recalculated on a regular basis as new data become available from forest inventory programs.

As the demand for timber continues to grow, competition among user groups will likely intensify. The saw milling industry is expected to face considerable problems in the near future as it becomes increasingly more difficult to obtain sawlogs on Crown Lands. The larger mills in particular will be negatively affected by shortages of stud-wood and larger size logs, while smaller push-bench mills may have less difficulty maintaining production for the local market (Tulk *et al.* 1996). However, small mills and fuelwood users may be adversely affected if resources on designated non-productive lands (not included in AAC calculations) prove insufficient to meet current levels of demand.

It is evident from an analysis of the age structure of the inventory that the wood supply shortages in Newfoundland are intractable, immediate, and severe. They call for a long-term commitment to sound forest management practices in order to improve the productive potential of the resource base. In the short-term it is imperative to identify strategies by means of bioeconomic analysis that will help bridge the current gap between demand and supply. Where economically warranted, forest pest control is one such strategy.

AN ECONOMIC ANALYSIS OF HEMLOCK LOOPER CONTROL PROGRAMS

The consumptive and non-consumptive benefits of forest resources are outlined above. Forest managers must weigh the benefits and costs of securing supply through interventions against natural forest depletions such as pests and forest fires. This section attempts to aid forest managers in this decision through the use of a cost-benefit analysis.

The analysis focuses on the 1989 Control Program, the year for which detailed cost data was made available by the Provincial Department of Forestry and Agriculture (DFA). The area treated during the 1989 Operational Control Program was in the Castors River - Leg Pond area and is the 'study area' for the cost-benefit analysis. The information on the 1989 operational spray program provided by the DFA includes technical details of the operation and a DFA generated assessment of its effectiveness in controlling looper numbers, and preventing defoliation and mortality.

The 1989 Operational Spray Program

The forecast of defoliation by the hemlock looper jointly compiled by the Canadian Forestry Service (CFS) and the DFA in 1988 indicated that approximately 27,500 ha of defoliation would occur throughout insular Newfoundland in 1989. Moderate and severe defoliation was forecast for 10,500 ha, of which 7,600 ha was forecast to occur on the Northern Peninsula in Forestry Management Unit 17 in the Castors River area. Based upon this forecast, a proposed program was developed by the DFA in conjunction with the Province's two pulp and paper companies to spray eight blocks (5,362 ha) in the Castors River - Leg Pond area. Six of these blocks were to receive two treatments, while the other two were to receive only one application (one due to low looper population and the other due to poor weather).

Due to the small scale of the program, one single-engine aircraft equipped with AU4000 Micronair spray atomizers was used to apply the insecticide. Futura XLV, a water-based *B.t.* formulation was used with a concentration of 30 BIU per ha. This formulation was used because; (1) it has been used successfully in other jurisdictions, notably Ontario and Quebec; (2) there was no indication at the time that either water-based or oil-based *B.t.* was more effective; (3) water-based *B.t.* is easier to work with; (4) evaporation is not a problem if small aircraft are used (as they were in 1989); (5) with a water-based formulation there is no clogging of the atomizers if condensation should occur over night during the spray season; (6) in 1989 Futura XLV was the only type of water-based *B.t.* registered (under a temporary permit) by the Federal Government for operational use; (7) oil-based *B.t.* (Dipel) was available in 1989, but the price of the water-based formulation was down substantially (about 30%) in that year (Crummey 1994).

The operation began on the evening of July 2 and ended in the morning of July 23, with spraying occurring on 11 of the 22 days. Due to poor weather, the operation required three weeks rather than two weeks as originally anticipated. Spraying occurred in only 29% of the 42 possible spray periods.

Sampling of larvae populations began in mid-June, with few larvae originally detected. Difficulty arose in the determination of appropriate sample sites due to the inaccessibility of the sample plots. The accessible areas often had unrepresentative tree clusters. The problem of inaccessibility by both road and helicopter resulted in the following problems: (1) Samples for the spray blocks could not be taken from the entire spray area; only a portion of individual spray blocks could be sampled. (2) There was a difficulty in finding suitable border areas with a significant looper population for purposes of comparison with the spray block measures. As a result, no border areas were reportedly used at all, only a reference control plot. (3) There was also a difficulty in finding suitable control plots due to inaccessibility and the lack of surrounding areas with adequate looper populations. This suggests that the control plots chosen may not have been a part of the treated, already declining infestation, but rather a pocket of that infestation that was not in decline.

These problems were compounded by the presence of black-headed budworm in the area, which develops on a cycle similar to that of the looper but hatches one to two weeks earlier. Budworm larvae were found in all spray areas and in the region surrounding the spray areas (particularly to the north and east of Castors River). The black-headed budworm is blamed by forestry officials for most of the early defoliation in the general area of the spray blocks.

For these reasons, only one control plot could be formed by the DFA that had sufficient larval numbers. An additional site was later found by the CFS but only one tree was sampled. An estimate of defoliation on this second plot was made by the CFS. Subsequent to the estimate by the CFS, the DFA made a detailed assessment of defoliation on the same plot.

Results of the 1989 Operational Spray Program

The DFA collected pre-spray and post-spray data from both the spray blocks and the control area. A high variation in looper larvae numbers was found, characteristic of a declining looper outbreak. As indicated in Table 1, the infestation as a whole in management unit 17 was in decline during this period.

Table 2 compares the foliage-saved in the treated areas in comparison to (a) the DFA control plot, (b) the CFS control plot with CFS estimates of defoliation, and (c) the CFS control plot with DFA measures of defoliation. These calculations are based upon the percentage difference between post-spray control plot defoliation and treated area defoliation. Treated-area defoliation is defined as the difference between pre-spray defoliation and post-spray defoliation. In comparison to the DFA control plot, the spray program resulted in 77% current growth saved and 95% old foliage-saved. In comparison with the estimated defoliation for the CFS control plot with CFS estimates of defoliation, the spray program protected 67% of current growth from defoliation and 75% of old foliage. Actual post-spray measures by the DFA show that for the CFS control area these measures are 68% and 93% for current and old growth respectively. Due to the presence of the black-headed budworm in the area, it is unclear how much defoliation is certain to have been caused by the looper.DFA officials deem the 1989 spray program to be a qualified success in terms of limiting defoliation and minimizing tree mortality. The DFA identified a number of complicating factors in their program including: (1) the presence of black-headed budworm in many treated areas and surrounding regions, which may have been responsible for a portion of the new growth defoliation in the spray areas and in the control plots, (2) there was a noticeable amount of pre-spray defoliation, and tree mortality from severe defoliation in previous years in the treatment area, (3) difficulty in sampling were encountered due to inaccessibility and the problem of finding border areas and control plots that were not influenced by the black-headed budworm, yet had sufficient looper larvae numbers to be comparable to the spray areas.

Operational spray results from the program suggest that the Futura XLV formulation was very effective at reducing larvae population and providing foliage protection. A number of factors, however, suggest that the results of the 1989 operational spray program should be viewed with caution. The control plots used probably do not represent the treated areas as they contained above average looper larvae counts before spraying (Table 2). This suggests that the control plot has a much greater potential for defoliation due to the greater concentration of looper larvae. In addition, it would appear that the efficacy of the water-based Futura formulation used (XLV) is unclear. Tests on the efficacy of various formulations of *B.t.* by West *et al.* (1989) indicated poor protection by Futura XLV in comparison to oil-based Dipel formulations. However, recent testing of high potency aqueous formulations indicated excellent efficacy (West *et al*In press). The blackheaded budworm has been mentioned as a complicating factor but it is unclear what role it plays in the high defoliation levels of current growth particularly in the DFA control plot. The effect of the budworm on the mortality of the looper is also unclear.

A final point concerns the timing of the exercise. As illustrated in Table 1, the infestation in the treated area (a part of Forest Management Unit 17) was already in decline at the time of spraying in 1989. The sharp decrease in defoliation during 1988 as compared to 1987 suggests a collapse of most of the population. Coincidentally, this collapse occurred at the time the black-headed budworm infestation became apparent in this region. This suggests that the budworm may have been a factor contributing to looper mortality. If this was indeed the case, then this trend would have continued during 1989 undermining the perceived effectiveness of the spray as determined by the amount of larvae mortality. That is, larvae mortality would have been affected by not only by the budworm, but also by the natural decline of the population as the infestation ages.

The Costs of the 1989 Operational Spray Program

The variable and fixed costs of the 1989 looper program are shown in Table 3. These costs were shared between the Crown and the forest companies. In 1989, the program cost was shared one-third crown and two-thirds other tenure holders. All revenues recovered from the forest companies for spraying done on their limits are returned to the Provincial Treasury. Table 4 shows how the 1989 program cost was shared and hectares treated by forest land tenure.

COST-BENEFIT ANALYSIS

Background

The evidence discussed in earlier sections suggests that the hemlock looper is an effective tree-killer in its own right and in combination with other pests such as the spruce budworm. The looper thus poses a threat to the whole spectrum of forest use, including timber supply. For

Table 1. Area of defoliation caused by the eastern hemlock looper in the study area (Unit 17) and the reference area (Unit 18) 1983-93.

Year	Forest Management Unit 17 Area Defoliated (ha)			Forest Management Unit 18 Area Defoliated (ha)		
	Light	Moderate/ Severe	Total	Light	Moderate/ Severe	Total
1983	-	-	-	-	-	-
1984	-	-	-	-	-	-
1985	5,492	-	5,492	1,416	-	1,416
1986	37,400	17,544	54,944	2,429	-	2,429
1987	5,826	60,234	66,060	-	-	-
1988	3,369	8,419	11,788	65	241	306
1989	2,959	5,708	8,667	525	2,229	2,754
1990	400	58	458	12,600	2,200	14,800
1991	-	15	15	-	1,730	1,730
1992	-	-	-	-	-	-
1993	-	-	-	-	-	-

Notes a) Defoliation classifications: Light = 6-25%; Moderate = 26-75%; Severe = 76-100%. Includes all forest land.

b) 1991 values for productive forest land (>35 m^3 per ha at rotation). Defoliation volumes available for 1991 only: Unit17 - 700 m^3 severely defoliated. In Unit 18 - 2,000 m^3 moderately and 154,000 m^3 severely defoliated.

c) forecast

Source Department of Forestry and Agriculture, Government of Newfoundland and Labrador, and the Forest Insect and Disease Survey of the Canadian Forest Service

Table 2. Foliage saved and eastern hemlock looper larval numbers for the 1989 spray program.

	Foliage Saved[a] (%)		Larval Population[b]		
	Current Growth	Old Foliage	Pre-Spray	Post-Spray	% Mortality
With reference to:					
DFA Control Plot[c]	77	95	443	35	92
CFS Estimates[d]	67	75	216	130	40
DFA Measures[e]	68	93	--	--	--
Treatment Area	--	--	128	25	80

Note a) Foliage-saved calculations are based upon the difference figures between pre-spray and post-spray defoliation for the treatment areas and the post-spray defoliation measures only for the control plots.
b) Larval Population based upon the average number of larvae per sample in the given area.
c) Control plot is the DFA selected control plot for the exercise.
d) CFS estimates of mortality in the control block chosen by Canadian Forest Service.
e) DFA measures are actual measures of defoliation for the Canadian Forest Service control plot carried out by DFA during the post-spray period.

Source Based on data in Crummey (1989).

reasons mentioned above, we abstract from non-timber values in the following analysis. However, if non-timber values are present, as they typically are, they will unequivocally strengthen the case for pest control *ceteris paribus* if the control agent is environmentally benign. We assume that the task of pest management is to protect foliage to prevent the timber loss that results from tree mortality and eventual saprot. This is achieved by reducing the looper population density as quickly as possible after the onset of the infestation. The window of harvesting opportunity closes about five years after tree death. After this time, the technical properties of the long, clear bole of the tree no longer meet merchantability standards, rendering the wood essentially useless. Although saprot sets in gradually, the marked threshold effect at about year five (when pulp quality is affected) has implications for the decisions whether to spray in a given area. A simple operational rule is thus:

A. DO NOT TREAT the infested area in year t if harvesting in year t or $t+1$ is feasible,

B. CONSIDER TREATING the infested area if and only if harvesting is feasible in year a where $t+2 \le a \le t+6$ and PVNB $(a;\theta) \ge 0$ where PNVB denotes the present value of the social net benefit of spraying, and θ is the proportion of infested timber expected to be salvaged.

RANK AND TREAT infested areas in descending order of profitability subject to the budget constraint.

With no treatment to protect foliage from the looper, defoliation and tree mortality may occur. Historically, few areas in Newfoundland have been defoliated in two or more consecutive years (McNamee *et al.*, 1990). The mortality in year $t+1$ is thus primarily determined by the rate of defoliation in year t. Treatment is expected to reduce to reduce defoliation by at least 70% (West 1994), the reduction in volume mortality attributable to treatment can be estimated as described below.

Methodology

Given information about the bio-physical characteristics of the timber inventory, the site class, the size of the area, and delivered wood cost, the value of the saprot reduction per m^3 due to treatment can be estimated. The social net benefit is measured as the value of saprot reduction in year *a* less the program cost. The net benefit in year *a* is discounted back to the present (the year of the spray program). The usual justification for discounting is the time value of money; the idea that the decision to incur (out-of-pocket) expenses to spray now has an opportunity cost that must be carried until the time of harvest. Discounting compensates the investor (the public here) for the delay between the time of outlay and the time of receipt of the benefit from harvesting.

The cost-benefit analysis involves four scenarios, each representing a different percentage of foliage-saved and therefore a different average defoliation. Scenario A (the control plot) receives no treatment, hence foliage-saved is 0%. This is our 'control' with which we compare the foliage-saved of the other three scenarios. These scenarios include: Scenario B - an efficacy of 93% foliage-saved with insecticide spray; Scenario C - an efficacy of 75% foliage-saved using an insecticide spray; and Scenario D - an efficacy of 25% foliage-saved using an insecticide spray. There are two control plots used in the 1989 study area. These include a plot chosen by the DFA at the time of the pre-spray analysis, and a plot later identified by the CFS in which post-spray defoliation measurements were made by the DFA. The DFA control plot reported very high levels of current growth defoliation (100%) and old growth (90%) defoliation. It is doubtful how well this control plot reflects the expected defoliation of the treated areas.

The CFS control plot represented more plausible defoliation levels (72% new growth and 67% old growth as measured by the DFA) with respect to experimental trials, and a more reasonable looper larvae count with respect to the treatment blocks. Therefore, the CFS control plot was chosen to represent the control scenario (Scenario A) in the analysis.

Since old growth defoliation is the main contributor to mortality, it was used as the measure of average defoliation in each scenario. For our control plot with 0% foliage-saved this figure was 67%. Sixty-seven percent is therefore the average defoliation level for Scenario A, and the defoliation level used to determine mortality in the area in the preceding year.

The foliage-saved percentages in the other three scenarios are thus calculated with reference to 'expected' average defoliation under no treatment (67%). The foliage-saved percentages for Scenarios B, C and D were calculated using the following formula (West *et al.* 1987):

$$FS = \frac{DEF_{control} - DEF_{treatment}}{DEF_{control}} X\ 100 \qquad \textbf{(1)}$$

where

FS = foliage saved (%)

$DEF_{control}$ = the average old growth defoliation for the control block

$DEF_{treatment}$ = the average old growth defoliation for the treated area.

Scenario B is based upon the efficacy reported by the DFA for the 1989 study area in which average old growth defoliation levels in the treated blocks (5%) were compared to the old growth defoliation levels in the control plot (under Scenario A). The percentage of "foliage-saved" was then computed using the above formula. Based upon 5% old growth defoliation for the treated area and 67% defoliation for the control plot, the foliage-saved was 93%. The 5% defoliation figure is the defoliation level used to calculate mortality in the preceding year for this scenario. This efficacy measure reflects the measured efficacy in the 1989 study of the water-based *B.t.* formulation Futura XLV (30 BIU).

Scenario C is based upon results by West *et al.* (1992) in testing the efficacy of the oil-based *B.t.* formulation, Dipel (Dipel 174 and 264 tested in 30 BIU and 40 BIU concentrations) in controlled experiments. The average one-year foliage-saved through treatment with Dipel for the research trials was 80%. Based upon this result, a foliage-saved percentage of 75% was used as an indication of the research tested efficacy of this insecticide treatment. This foliage-saved percentage corresponds to an average defoliation of 17% in comparison to the control plot used in Scenario A. Mortality in the preceding year is determined for this scenario based upon this defoliation percentage of 17.

Table 3. Allocation of the 1989 eastern hemlock looper program cost by component.

Item	Operational Costs ($)	Fixed Costs ($)
Supervisory Aircraft	-	-
Fixed Wing Spray Aircraft	65,407	-
Helicopter	106,286	2,807
Insecticide	62,525 (-5,437 carry over)	-
Supplies	5,189	14,912
Salaries	51,084	53,937
Purchased Services	6,437	11,367
Meals and Accommodation	12,529	14,230
Propane and Furnace	-	800
Computer	-	1,000
Other Transport and Communication	220	1,410
Total:	309,677	100,463

Note a) Cost sharing formula for 1989 program: 1/3 Crown, 2/3 other tenure holders.
b) Fixed costs are defined by the Department of Forestry and Agriculture.
c) No supervisory aircraft used during 1989 program due to the small scale of program.

Source Insect and Disease Control, Department of Forestry and Agriculture, Government of Newfoundland and Labrador

Table 4. The 1989 eastern hemlock looper program costs by land tenure.

Forest Tenure	Area Treated		Program Cost	
	ha	(%)	(billed)	(actual)
Crown	1,861	34.7	144,382	175,896
Abitibi-Price to Crown	455	8.5	35,300	26,323
Corner Brook Pulp & Paper	3,046	56.8	235,895	107,458
Total:	5,362	100	415,577	309,677
Average Cost per hectare treated ($):			77.50	57.75

Note
a) Program cost shares are 1/3 Crown, 2/3 other tenure holder(s).
b) Billed Program costs include insecticide used plus carry-over to the 1990 Program (cf. Table 8)
d) 69.7% of the area treated received two applications of *B.t*, i.e., total area treated = 9,100 ha.

Source Calculated from data provided by Insect and Disease Control, Department of Forestry and Agriculture, Government of Newfoundland and Labrador.

$$APC = \frac{YSD - 0.5569}{2.435}$$

The final scenario, Scenario D, is an arbitrarily chosen efficacy to bridge the gap between the research supported efficacy of 75% foliage-saved and the scenario of no foliage-saved in the control plot. The foliage-saved percentage chosen is 25%, which represents an average defoliation of 50%. Therefore, mortality in the preceding year for this scenario is based upon a defoliation percentage of 50.

To estimate mortality and volume decay in the dead timber in our study area, we use the ESSA system of equations estimated on empirical stand-level data for Newfoundland (McNamee *et al.* 1990; Hudak *et al.* 1971). Assuming that defoliation occurs in one year only, volume mortality in year $t+1$, M_{t+1}, is given by

$$M_{t+1} = 1.327e^{.037DEF_t} \qquad (3)$$

where

DEF_t is the area defoliation in year t. DEF_t and M_{t+1} are both expressed in percentage terms. The volume decay is calculated as

where

APC is the average penetration of saprot in centimetres, and YSD is the years since tree death ($t+2 \leq a \leq t+6$). The percentage merchantable volume infected with saprot in a given year, VSR is then calculated as

$$VSR = 28.6616 - 2.044(DBH) + 29.65(APC) \qquad (3)$$

where

DBH denotes the diameter at breast height.

Given data on the area treated and stocking levels, equations (2) and (3) may be used to estimate, respectively, the volume mortality in m³ in year $t+1$ and the volume saprot in m³ in year a where $t+2 \leq a \leq t+5$. These physical measures are converted into dollar values by applying an appropriate delivered wood cost.

Data and Assumptions

1. The data describing the inventory in Forest Management Unit 17 is assumed to also describe that of the study area since the 1989 treatment blocks are in Unit 17.
2. The area treated is 5,362 ha with an average volume per hectare of 88.5 m³ per ha, resulting in a total volume for the treated area of 474,537 m³.
3. All standing volume is assumed to be balsam fir.
4. Four different defoliation scenarios are used: 67%, 5%, 17% and 50%. The corresponding treatment product efficacies are: 0%, 93%, 75% and 25%.
5. An average DBH of 10 cm is used to calculate saprot

penetration in equation (3). This value was chosen with reference to the appropriate empirical yield tables for balsam fir in Newfoundland in Page and van Nostrand (1973).

6. Stands found in the study area are either mature or over-mature based on the conventional, 'forester's volume rotation' rule. This implies that the stands are also mature using financial rotation rules since these reflect investor 'impatience' as manifested in shorter rotations. We can therefore abstract from optimal harvest timing issues in the analysis of the 1989 program.
7. In 1989 none of the spray blocks had been subject to silvicultural treatments.
8. In 1989 there was no spraying in the reference area (Unit 18).
9. After consulting with forestry officials and a representative of industry, it was decided to use an average delivered wood cost of \$33 per m^3 in 1989 dollars. It is assumed that the real value of roundwood will remain constant at \$33 for the period of the analysis (1989-1995).
10. (a) Two different values of θ, the salvage proportion, are assumed: 100% and the 12% rate for the 1983 to 1995 period as reported by Hudak *et al.* in this publication.
    (b) The treated stands in the study area are currently inaccessible. No allowance for road construction costs is made here. It was assumed that access roads to these stands would have been built in due course to recover uninfected timber. The additional costs associated with reorganizing harvesting and road construction priorities are ignored here.
11. Three real (net of inflation) discount rates are used: 3%, 8% and 10%.

Results

To appreciate the economic implications of the formulae given in section four, their physical implications must first be examined. Equation (2) predicts that defoliation in year *t* will cause mortality in year *t+1*. Saprot works on this dead timber in year *t+2*, and will result in a reduction of the amount of harvestable timber in that year. The amount of saprot calculated using equation (3), is then subtracted from the mortality to yield the harvestable timber in a given year. It is assumed that the timber can be salvaged for five years after mortality. By the sixth year following mortality (1996) the entire lot of timber killed in year *t+1* is no longer suitable for commercial salvage. The volume of salvageable timber in year *t+6* is thus set equal to zero for all scenarios due to this "threshold decay effect." The amount of salvageable timber per ha per year in each scenario is given in Table 5. The amount of mortality, and the magnitude of the reduction of salvageable timber due to saprot, depend upon the amount of initial defoliation [from eqns. (2)-(3)]. The amount of salvageable timber in a given year will therefore differ in each of the four scenarios. Consequently, the amount of salvage will approach zero more quickly in those scenarios with lower defoliation and lower mortality. Each scenario in Table 5 has two columns. The first column (θ=1.0) assumes that all salvageable timber is harvested. The second column (θ=0.12) assumes that only 12% of the timber is actually harvested.

Another way of viewing the physical process, and one that lends itself more readily to economic analysis, is through the volume loss per hectare due to saprot. Table 6 presents the volume loss per hectare due to saprot, calculated from eqn.(3) for each of the four scenarios. The progression of saprot varies since mortality differs between scenarios due to differences in previous defoliation levels. The better the treatment is in terms of efficacy, the less saprot will develop since both defoliation and mortality are reduced.

The volume loss is highest in Scenario A, which represents the no-treatment case (i.e., the equivalent to a product efficacy of 0% foliage-saved). The volume loss is lowest in Scenario B, which assumes the highest product efficacy of 93% (i.e., 93% of foliage-saved). Scenario C represents the next best option with a 75% efficacy (i.e., 75% foliage-saved). Scenario D represents a low efficacy of 25% (i.e., 25% foliage-saved). The volume loss due to saprot calculated for each of these scenarios constitutes the basic physical data for the cost-benefit analysis of the 1989 spray program.

Table 7 presents the loss attributed to saprot in each scenario expressed in present value terms. To provide a sensitivity analysis, a number of real discount rates are used here. By previous argument, saprot does not occur until year *t+2*. The value loss in 1990 is therefore zero. By 1996, all remaining timber defoliated in 1989 and killed by this defoliation in 1990 has deteriorated. The value loss, for 1996 is thus the value of the initial mortality if no salvage has been undertaken before that date. Since defoliation differs in each scenario, the value losses will also differ across scenarios for each year including year *t+6*, depending upon the extent of initial mortality. As expected, the value loss is greatest in the no-treatment scenario, and smallest in scenario B, which represents the highest product efficacy.

We define as the social net benefit of the treatment program in the difference in the present value loss per ha between a particular scenario and the no-treatment scenario. These estimates are presented in Table 8. For example, the value for 1991 in Scenario B, with a real discount rate of 3% is calculated from Table 7 as 59.35-5.98=53.37. The present value of the social net benefit is highest in Scenario B under all discount rates since the reduction in the volume loss due to saprot is largest where the treatment product with the highest efficacy is used.

As illustrated in Table 8, the net benefit in each scenario (B, C and D) increases over time, although from different initial levels in each scenario. Since the volume loss due to saprot increases over time in the absence of salvaging, the volume loss that can be reduced by treatment must also increase. This means that the net benefit of treatment increases the longer salvage operations are delayed. In each scenario, the net benefit reaches a maximum in year *t+6*, the year prior to that in which the threshold decay effect reduces the commercial value of the remaining mortality to zero.

Discussion

The scenarios have been developed to correspond to: undisturbed, no-treatment conditions (Scenario A); actual operational conditions in 1989 (Scenario B); experimental research trials (Scenario C); and a hypothetical reference case (Scenario D). Our scenarios thus differ in assumptions regarding defoliation, product type and efficacy, and the amount of available salvage. For the program to be economically efficient the social net benefit must be non-negative. That is, the present value of the benefit must be at least as great as present costs. In this analysis, the present value of the benefit is the reduced value loss that comes from the reduction in saprot attributable to the treatment program in 1989. The present cost is the cost per hectare of the treatment program in year *t*.

Given a real discount rate of 3% and the 1989 program cost of $76.49 per hectare, scenarios B and C generate a positive net social benefit in 1992 (year *t+3*) where the net present benefits per hectare are $98.11 and $91.88 respectively, see Table 8. It is in year *t+3* that the social benefit first exceeds the program cost per hectare. Scenario D does not provide a net social benefit until 1994 (year *t+5*), where the net present benefit per hectare is $93.22. These results show that the social net benefit of the treatment program increases as the efficacy increases or the cost of the program decreases.

For a real discount rate of 8% and the 1989 program cost, scenarios B and C still generate a positive net social benefit in 1992 (year *t+3*). In this case the net present benefits are $85.10 and $79.71 respectively. Scenario D does not provide a net social benefit in this case until 1995 (year *t+6*). Using a real discount rate of 10%, the net positive impact for Scenario B is still generated in 1992 (year *t+3*), however Scenario C does not generate a net positive benefit until 1993 (year *t+4*).

The decision whether to spray should consider (a) when harvesting will occur, (b) the efficacy of the formulation used, and (c) the cost of the spray program. There is clearly no gain from treating an area if harvesting will occur within a year of treatment as saprot has not yet affected the dead timber and there would be no saving of saprot loss to offset the cost of the program.

In general, if harvesting is planned to occur after year *t+1* treatment may be justifiable depending on product efficacy, program costs, timber value, stand age, stocking levels, and additional costs associated with unplanned harvest rescheduling and stand access.

SENSITIVITY ANALYSIS - COSTS

A sensitivity analysis based on the 1989 data shows that given a program cost per hectare of $141.90[2] and a discount rate of 3%, an efficacy of 20% foliage protection is required for the program to be cost efficient. That is, the present value of the benefit of treatment would exceed the treatment cost of $141.90 in year *t+6* if the treatment agent has an efficacy of at least 20 %. As the program cost falls, so does the efficacy required due to the smaller net social benefit necessary to offset the (lower) cost of the program. As the real discount rate is increased, the required efficacy for the

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[2] Cost for the 1989 operational spray program was $76.49 per hectare. Program costs can vary considerably from year to year and for the purposes of a sensitivity analysis we will use the average cost over the 1989-92 period of $141.90 per hectare, expressed in 1989 dollars. (Calculated from Department of Forestry and Agriculture, Government of Newfoundland and Labrador, and the Forest Insect and Disease Survey of the Canadian Forest Service.)

Table 5. Volume of harvestable mortality under alternative defoliation and salvage assumptions.

	Scenario A		Scenario B		Scenario C		Scenario D	
	DEF = 67%		DEF = 5%		DEF = 17%		DEF = 50%	
	θ=1.0	θ=0.12	θ=1.0	θ=0.12	θ=1.0	θ=0.12	θ=1.0	θ=0.12
YEAR OF HARVEST	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha
1990	14.0	1.7	1.4	0.2	2.2	0.3	7.5	0.9
1991	12.1	1.5	1.2	0.1	1.9	0.2	6.5	0.8
1992	10.4	1.2	1.1	0.1	1.6	0.2	5.6	0.7
1993	8.7	1.0	0.6	0.1	1.4	0.2	4.6	0.6
1994	7.0	0.8	0.3	0	1.1	0.1	3.7	0.4
1995	5.4	0.6	0	0	0.8	0.1	2.9	0.3
1996	0	0	0	0	0	0	0	0

Note DEF = defoliation
θ = salvage proportion

Table 6. Volume loss (m^3/ha) due to saprot under alternative defoliation and efficacy scenarios.

	Scenario A	Scenario B	Scenario C	Scenario D
	DEF=67% EFF=0%	DEF=5% EFF=93%	DEF=17% EFF=75%	DEF=50% EFF=25%
Year of Harvest	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)
1990	0	0	0	0
1991	1.908	0.192	0.301	1.108
1992	3.613	0.364	0.570	1.929
1993	5.319	0.536	0.840	2.839
1994	7.024	0.708	1.109	3.750
1995	8.743	0.880	1.379	4.661
1996[b]	14.010	1.412	2.212	7.478

Note a) DEF=defoliation, EFF=efficacy measured by foliage-saved
b) Assumes that with no prior harvesting, saprot in 1996 = total (merchantable) volume mortality in 1990

Table 7. Present Value Loss ($/ha) Due to Saprot Under Alternative Defoliation and Efficacy Scenarios and Various Real Discount Rates.

	Real Discount Rate = 3%				Real Discount Rate = 8%				**Real Discount Rate = 10%**			
	Scenario A	Scenario B	Scenario C	Scenario D	Scenario A	Scenario B	Scenario C	Scenario D	Scenario A	Scenario B	Scenario C	Scenario D
	DEF=67% EFF=0%	DEF=5% EFF=93%	DEF=17% EFF=75%	DEF=50% EFF=25%	DEF=67% EFF=0%	DEF=5% EFF=93%	DEF=17% EFF=75%	DEF=50% EFF=25%	DEF=67% EFF=0%	DEF=5% EFF=93%	DEF=17% EFF=75%	DEF=50% EFF=25%
Year of Harvest	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)
1990	0	0	0	0	0	0	0	0	0	0	0	0
1991	59.35	5.98	9.37	31.68	53.97	5.43	8.52	31.35	52.04	5.24	8.21	30.22
1992	109.11	11.00	17.23	58.24	94.64	9.54	14.93	50.53	89.58	9.03	14.13	47.83
1993	155.96	15.72	24.63	83.25	129.01	13.00	20.37	68.86	119.89	12.08	18.93	63.99
1994	199.95	20.16	31.58	106.73	157.76	15.90	24.91	84.22	143.92	14.51	22.72	76.84
1995	241.34	24.31	38.12	128.82	181.82	18.30	28.68	96.93	162.86	16.39	25.69	86.82
1996	375.91	37.90	59.36	200.66	269.77	27.19	42.59	143.99	237.25	23.91	37.46	126.63

Note a) DEF=defoliation; EFF=efficacy measured by foliage saved

b) Assumes that with no prior harvesting, the value loss due to saprot in 1996 = the value loss of total (merchantable) volume mortality from 1990.

program to be cost efficient also rises. At discount rates of 8% and 10%, efficacies of 30% and 37% are required respectively. It is worthy of noting that, given the parameters and assumptions of this analysis, the discount rate does not play a large part in the economic efficiency of various control program efficacies.

At first glance, this seems to suggest that any treatment which provides a measurable efficacy at a suitably low cost would be economically efficient also beyond year *t+6*, i.e., even after all the looper induced mortality has deteriorated on the stump. However, it is very important to realize that products with efficacies tested at less than 70% are not considered reliable. When products with such low efficacy levels are used, the results cannot be distinguished with any degree of confidence from the influence of the incidental environmental factors that are always at play.

As a result, economic analysis based on such data will be unreliable, if not inaccurate: for example, assuming an efficacy of only 25% (as in Scenario D), it can be shown that the treatment cost would have to exceed approximately $175 per ha for the program to be economically inefficient. In comparison to the $76.50 per ha cost of the 1989 program, such a program would be costly. Yet, the "benefit" of treatment in this hypothetical case cannot be attributed to the product used.

Timber Values

The timber value used in this cost-benefit scenario utilizes an estimate for delivered wood costs. This reflects the value of wood to the logger and is essentially the price which he is paid for roundwood at the processing site. It is worth noting that delivered wood cost is essentially the least value which can be attributed to timber and assumes no value-added processing.

In general, a discussion of commercial timber value involves a government perspective, and is in essence a value-added measure less government expenditure to maintain the resource base and provide necessary infrastructure. Value added is defined as the returns to the factors of production and can be calculated either directly or indirectly (Trelawny 1994). The most common calculation uses the indirect method in which the value of intermediate inputs such as fuel, electricity and raw materials are deducted from the value of product. The determination of value added is clearly beyond the scope of this present work, however, it would be beneficial to have some appreciation of what this value would be. Milne (1990) uses a value of $129 per m^3 derived from his earlier work in this area[3].

If a value of $129 per m^3 were assigned to the timber resources of the province, then the effect is to increase the present value of social net benefit of the spray program. The end result is that the 1989 program will show positive social net benefits in earlier years under all scenarios. Further, the program becomes much less sensitive to program costs and discount rates.

ECONOMIC IMPACT OF EASTERN HEMLOCK LOOPER INDUCED FOREST DAMAGE

The end result of a looper infestation is tree mortality and, in the event that harvesting does not or cannot occur, timber loss. This has two end results: (1) this timber, or a portion of it, is lost to local industry and so too is its value, and (2) growing stock has been depleted which affects long-term timber supply.

The result of timber mortality due to looper infestation is a gradual decline in timber suitability for secondary uses. A certain amount of wood fibre can and likely will be harvested in salvage operations to minimize the effects of the induced mortality. The exact amount of this salvage will depend on a number of factors including accessibility, timing and the extent of damage. Under usual circumstances, this salvaged timber will be more costly to harvest mainly due to access costs and may result in a 'glut' in timber supply in the short-term.

Timber loss due to looper damage can be attributed an economic cost, namely the foregone value of timber that was not salvaged plus the additional costs incurred to harvest and process damaged timber. Our analysis focuses on foregone timber values and ignores the increased costs of harvesting damaged timber. Table 11 shows the impact of tree mortality for the period 1983 to 1995. Over the entire period, the total volume loss was 11,289,300 m^3. Given a salvage rate of 12%, 1,385,000 m^3 of this volume loss was salvaged, leaving 9,904,300 m^3 in lost timber. Assuming a timber value of $33 per m^3 (delivered wood cost), then the total value of lost timber due to looper induced mortality during 1983-95 is $326.8 million. Assuming a timber value of $129 per m^3 as used in Milne (1990), the total value of lost timber is $1.28 billion.

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[3] Although it is unclear from Milne's work as to what current dollar value he uses, we assume that it is in 1989 dollars - the year previous to the release of his report.

Table 8. Present Value of Social Net Benefit ($/ha) Under Alternative Defoliation and Efficacy Scenarios and Various Real Discount Rates.

	Real Discount Rate = 3%			Real Discount Rate = 8%			**Real Discount Rate = 10%**		
	Scenario B	Scenario C	Scenario D	Scenario B	Scenario C	Scenario D	Scenario B	Scenario C	Scenario D
	DEF=5% EFF=93%	DEF=17% EFF=75%	DEF=50% EFF=25%	DEF=5% EFF=93%	DEF=17% EFF=75%	DEF=50% EFF=25%	DEF=5% EFF=93%	DEF=17% EFF=75%	DEF=50% EFF=25%
Year of Harvest	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)
1990	0	0	0	0	0	0	0	0	0
1991	53.37	49.98	27.67	48.54	45.45	22.62	46.60	43.83	21.82
1992	98.11	91.88	50.87	85.10	79.71	44.11	80.55	75.45	41.75
1993	140.24	131.33	72.71	116.01	108.64	60.15	107.81	100.96	45.90
1994	179.79	168.37	93.22	141.86	132.85	73.54	129.41	121.20	67.08
1995	217.03	203.22	112.52	163.52	153.14	84.89	146.47	137.17	76.04
1996	338.01	316.55	175.25	242.58	227.18	125.78	213.34	199.79	110.62

Note a) DEF=defoliation; EFF=efficacy measured by foliage saved

b) Assumes that with no prior harvesting, the value loss due to saprot in 1996 = the value loss of total (merchantable) volume mortality from 1990.

These losses are substantial. Assuming that 12% of effected timber was harvested, the 9.9 million m^3 lost represents approximately 4 years of harvest at historical rates. If solely used for the newsprint industry, this timber would meet wood fibre requirements for approximately 6 years based on harvest estimates and newsprint wood fibre requirements derived from average historical rates. As outlined earlier, shipments during 1995 were valued at $665 million and production accounted for 24% of manufacturing GDP during the year.

Over the long-term, tree mortality which does not lend itself to immediate and practical salvage causes a supply deficit. As outlined in section 2, current demand exceeds sustainable harvests on productive land. Unplanned harvesting or loss of supply stock can change sustainable yields and likely diminish future harvests. The impacts of a lowered AAC will be great. Currently timber from productive limits are mainly used in the sawmilling and newsprint industries. Both are high value-added industries and a decline in raw material resources to either would result in lowered production and employment.

Given the unpredictable nature of the looper and other pests, it can be assumed that non-consumptive impacts are also great. Induced tree mortality can harm aesthetic beauty, change wildlife habitat and result in soil erosion.

CONCLUSION

This paper develops a general cost-benefit model designed to guide forest pest control decisions. The model is applied to the EHL outbreak in Newfoundland. Using data for 1989, we find strong support for protecting forests by means of spray programs. This conclusion holds for a range of different treatment efficacies, costs and biological assumptions, even when timber values alone are considered. Deloitte and Touche (1992) also found a positive net present value associated with pest control in forestry. It should be emphasized that we attribute a value to the standing forest based on delivered wood costs; this is arguably a bottom line estimate of the forest value. Were non-timber values to be included, as they typically should be, the discounted net social benefit would be greater still. Expressed, alternatively, in terms of volume, the losses attributable to the EHL in the study period corresponds to over four years' of harvest at historical rates. This suggests that in the face of continued infestation, the looper induced timber losses might exert downward pressure on the AAC. This would come at a time when the wood supply situation on the Island is already in a precarious state due to the age structure of the growing stock caused by previous outbreaks of forest pests.

ACKNOWLEDGEMENTS

This paper is based on Wernerheim and Parsons (1994). We gratefully acknowledge the valuable comments on an earlier draft by R.J. West, A.G. Raske, G.R. Milne and H.R. Crummey. Any remaining errors or omissions are, of course, ours alone.

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THE EASTERN HEMLOCK LOOPER DECISION SUPPORT SYSTEM

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INTRODUCTION

Integrated pest management (IPM) is commonly defined as a practice whereby all available knowledge and techniques are evaluated and consolidated into a unified program to manage pest populations so that socio-economic and environmental damage is minimized (NAS 1969). Although IPM has been a pervasive paradigm in agriculture for several decades (Metcalf and Luckman 1982), its implementation in forestry has been difficult given the spatial and temporal complexity of forest systems (Waters and Stark 1980). However, significant advances in information management tools such as database management and geographic information systems (GIS) provide opportunities to construct decision support systems that address the complexity of forest systems and thereby reconcile forestry and IPM.

Successful development of a forest pest decision-support system is dependent upon detailed information on pest biology and forest conditions (Saarenmaa 1990). In Canada, there exists an extensive body of knowledge pertaining to insect pest-forest interactions from a variety of sources such as: i) the former Forest Insect and Disease Survey of the Canadian Forest Service that, for a number of decades, conducted annual surveys of pest populations throughout Canada (Power 1988); ii) extensive forest inventory databases maintained by individual provinces and companies; iii) federal, provincial and industrial agencies that have conducted and documented forest pest control programs; iv) various institutions that have conducted detailed studies of forest pest biology and impacts; and v) climate data compiled by federal, provincial and private agencies. Combined with an information management tool, such as a GIS, these data can provide the foundation for computer-based decision support toward integrated forest pest management.

In 1988, a project was initiated to develop a decision-support system to facilitate integrated management of the eastern hemlock looper (EHL) *Lambdina fiscellaria fiscellaria* (Guen.), in Newfoundland. The aim of the project was to consolidate available knowledge and data into a system that could provide temporal and spatial predictions of pest impacts under available alternative management strategies (McNamee *et al.* 1990; Carroll *et al.* 1995). This chapter briefly reviews the structure of the EHL decision support system (EHLDSS) and then presents the results of an evaluation of the system's predictive capacity.

THE SYSTEM

Due to a distinct preference for particular foliage types by many herbivorous insects, defoliation seldom results in rapid plant mortality (Mattson et al. 1988). However, when populations are high, EHL larvae tend to feed indiscriminately on balsam fir foliage (Carroll 1956) resulting in considerable mortality following 1 or 2 years of defoliation (Hudak *et al.* 1978). Consequently, EHL impacts can be simplified into three phases: defoliation, followed by tree mortality and then decay.

Prediction of future pest impacts modified by available control tactics is critical to decision making in IPM. Accordingly, EHLDSS was constructed of 5 individual models developed to predict: i) the probability of defoliation, ii) timber mortality, iii) timber decay, iv) the risk of an island-wide outbreak, and v) regional larval phenology (Fig. 1). To support management decisions, each model can be modified to reflect a stand's eligibility for control tactics, expected efficacies of various control measures, and acceptable mortality and decay volume thresholds (see Fig. 1).

Carroll *et al.* (1995) provided a detailed description of the component models of EHLDSS. Briefly, the prediction of defoliation risk was based upon two sub-models; the first designed to estimate the probability of impact to stands not previously defoliated, and the second developed to estimate the risk of defoliation continuing within stands that were defoliated during the previous year. Each sub-model was designed to estimate the probabilities of light, moderate and severe defoliation (defined by McNamee *et al.* 1990) for individual forest stands during the ensuing year. The mortality risk model was constructed to predict the volume of dead timber in an individual forest stand given its defoliation history and expected defoliation derived from the defoliation risk models. The decay risk model was designed to predict, up to 10 years into the future, the volume of timber subject to decay within a particular stand given its present and predicted defoliation scenario. The outbreak risk model was developed to provide a general indication of the probability of EHL populations increasing to outbreak conditions across the island of Newfoundland. Its form was derived from the observation that a rapid increase in hemlock

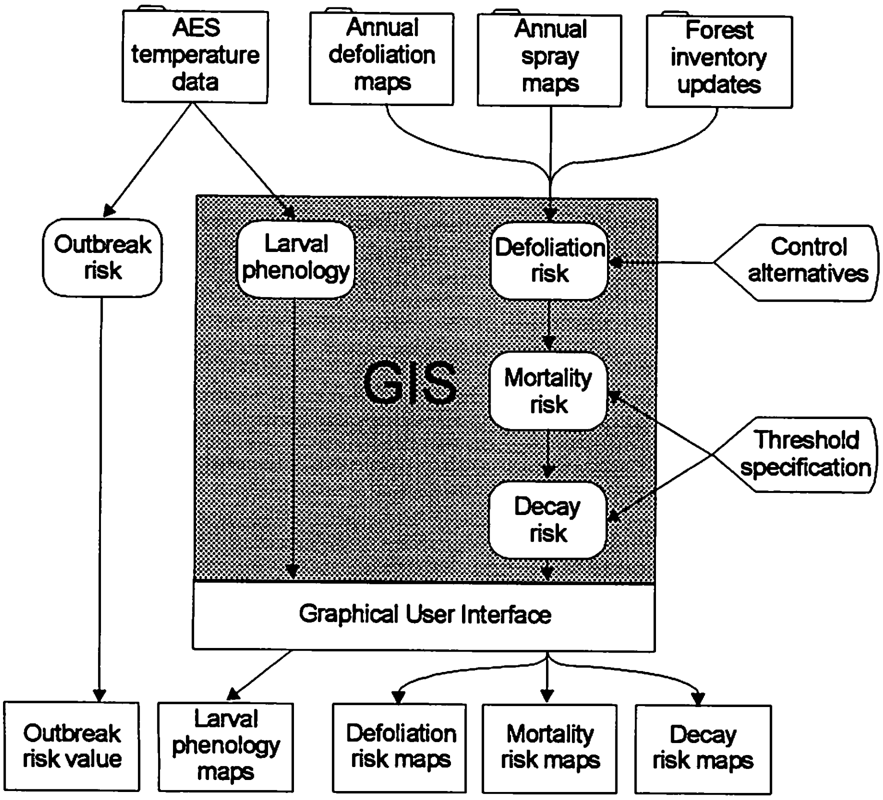

Figure 1. Schematic representation of the Eastern Hemlock Looper Decision-Support System. Defoliation, mortality and decay risk models are embedded in a geographic information system (GIS) and linked to a graphical user interface. Predictions, modified by user-specified control options and damage acceptance thresholds, are derived from annual inputs of digitized defoliation maps, maps depicting areas of control attempts (i.e. spray maps) and updates to the forest inventory database. Calculation of current and future regional larval phenology, as well as outbreak risk, are based on inputs from Atmospheric Environment Services (AES) weather stations. (Adapted from Carroll *et al.* 1995)

looper numbers to epidemic levels was often preceded by one or two years with above-normal temperatures (Otvos 1977). The larval phenology model was constructed as a means of determining the current developmental stage (i.e. eggs to fourth instar) and predicting the timing of future stages of looper larvae across Newfoundland thereby improving the timing of control programs.

Each model was embedded in a geographic information system, combined with a forest inventory database for the entire island of Newfoundland (maintained by the Newfoundland Department of Natural Resources), and linked to a graphical user interface. The operational version of EHLDSS allows users to display predictions in either map or tabular format. Defoliation, mortality and decay risk predictions can be viewed at any scale for the entire island of Newfoundland. Predictions of larval phenology are displayed at the map-section scale while island-wide outbreak risk predictions are produced in tabular format.

EHLDSS was designed to provide decision support in a number of critical areas. Advanced warning of outbreaks derived by the outbreak risk model was intended to provide forest managers with sufficient time to invoke measures that ameliorate the impacts of widespread EHL defoliation. For example, stands identified by the defoliation risk models as having a high probability of severe defoliation in years prior to an outbreak could be harvested before their destruction. Moreover, during and after outbreaks, EHLDSS could support management decisions intent upon prioritizing salvage operations. Spatial representation of looper-related timber mortality and decay would enable forest managers to schedule salvage operations based on the accessibility and distribution of damaged stands. The capability of EHLDSS to modify outputs according to various control alternatives was intended to support decision-making toward the rational use of insecticides. Based upon stand eligibility to receive control measures, expected efficacy of the control option and risks of defoliation and subsequent timber mortality before and after simulated control applications (chemical or biological), forest managers could choose appropriate control tactics.

EVALUATION

Since the completion of EHLDSS, low hemlock looper populations have precluded the potential to examine the predictive capacity of its component models. However, an increase in hemlock looper populations across insular Newfoundland during 1995 provided an opportunity to evaluate some of the models that comprise the present system. Clearly, predictions of the extent and distribution of EHL defoliation constitute the basis of the current decision-support system (Fig. 1; see Carroll *et al.* 1995). Accordingly, this evaluation was performed to assess the predictive capacity of the defoliation risk models within EHLDSS.

METHODS AND MATERIALS

The predictive capacity of the defoliation risk component of EHLDSS was determined through simple comparisons of the area and number of forest stands actually defoliated by the hemlock looper with that predicted by the system for 1995.

An area located near Corner Brook, Newfoundland (Fig. 2), encompassing over 100,000 ha, and covered predominantly by balsam fir forests was selected for study. This region was deemed most suitable for study primarily because (i) a complete data set was available at the time of this investigation, (ii) only a small fraction (<5%) of stands were subject to control efforts against the EHL during 1994 and 1995 (i.e., application of the biological insecticide *B.t.*), and (iii) there was no detectable damage by other forest defoliators throughout the area during 1995.

As described above, EHLDSS employs two sub-models to estimate risk of annual defoliation for an individual forest stand. The first predicts defoliation risk for stands not previously defoliated (initial defoliation), whereas the second predicts defoliation risk for stands defoliated during the previous year (continued defoliation). These models are described in more detail below.

The initial defoliation model was constructed using a logistic regression (Walker and Duncan 1967) of the following form:

$$\log_e[P/(1-P)] = x'B \quad (1)$$

where, P = proportion of stands experiencing defoliation during year t but not year t-1.
x'= vector of independent categorical variables.
B = vector of regression coefficients.

The vector of independent categorical variables comprised stand age class (grouped in 20 year intervals), stand species composition (proportion of balsam fir), EHL population trend (i.e., increasing or decreasing) and proximity of defoliation during the previous year. Defoliation proximity was based on 1:50,000 scale map sections, where 1 = previous year defoliation in the same map section, 2 = previous year defoliation in an adjacent map section or 3 = no previous year defoliation in or adjacent to the map section. When the model was applied in an a posteriori analysis of data from the two most recent EHL outbreaks (i.e. 1967-71 and 1983-87), it accounted for 80, 45 and 77%

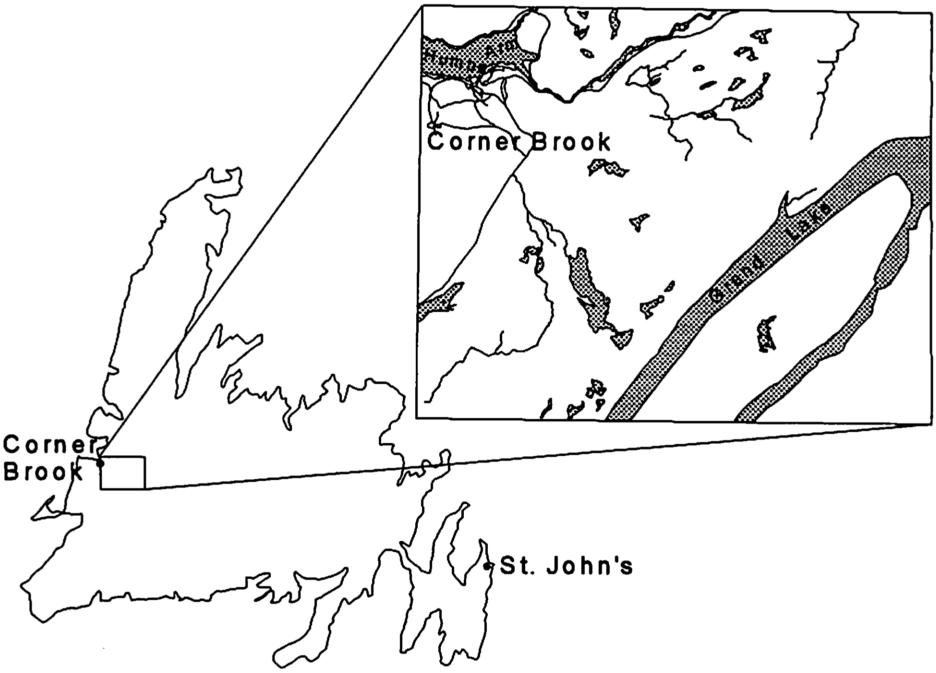

Figure 2. Schematic representation of the region near Corner Brook, Newfoundland utilized for evaluation of the predictive capacity of the Eastern Hemlock Looper Decision-Support System.

of the variation in the probability of light, moderate and severe defoliation, respectively (Carroll *et al.* 1995).

To quantify risk of continued defoliation for a particular forest stand, it was necessary to first define the number of consecutive years of defoliation that stands normally experience. Localized outbreak duration was examined by overlaying defoliation coverages (i.e., aerial sketch maps) from recent outbreaks. Within each outbreak only a small proportion of areas (<0.7%) experienced defoliation for more than two consecutive years. Therefore, it was assumed that a stand can only experience defoliation for a maximum of two years (Carroll *et al.* 1995).

The continued defoliation model was derived by overlaying successive years of defoliation coverages, beginning with the first two years of the 1967-71 and 1983-87 outbreaks and progressing in one year increments. For each overlay, areas that were not defoliated in the first year but were defoliated in the second year were removed as they did not represent continued defoliation. Continued defoliation-risk probabilities were simply calculated as the proportion of stands of each defoliation class in any year that were defoliated during the following year. Due to different defoliation-spread and persistence patterns during years when outbreaks increase and decline, separate model parameters were derived from the defoliation coverages for each outbreak phase (Table 1) (Carroll *et al.* 1995).

The continued defoliation model parameters from Table 1 can be interpreted as follows: for a stand that experienced light defoliation in a year when EHL populations are increasing (i.e., year t), the model predicts 52.3, 8.0, 1.8 and 37.9% probability that the stand will experience no, light, moderate and severe defoliation during the following year (i.e., year t+1), respectively.

Actual defoliation

Estimates of actual defoliation were obtained from defoliation sketch maps produced during the annual aerial defoliation survey conducted by the Newfoundland Department of Natural Resources in conjunction with personnel from the Canadian Forest Service. During aerial surveys, forest stands defoliated by the EHL are delineated on forest inventory and topographic maps and assigned to light, moderate or severe defoliation classes based on visual estimates of foliage loss in the manner described by Moody (1979). Sketch maps were digitized into ARC/INFO® geographic information system.

Predicted defoliation

To facilitate comparisons between actual and predicted defoliation, the traditional breakdown of defoliation into light, moderate and severe categories was ignored. Instead, stands were simply considered defoliated or intact. Furthermore, where the defoliation models calculate the risk (i.e., percent probability) of stands experiencing defoliation, a threshold of 35% was chosen (based upon trial runs of EHLDSS, a 35% threshold was considered to be most sensitive to defoliation risk). Finally, any stands subject to *B.t.* application during 1994 and 1995 were removed from the analysis.

The predictive capacity of the initial and continued defoliation models was assessed independently. By overlaying aerial sketch maps for 1994 and 1995, stands subjected to two consecutive years of actual defoliation were identified. These stands were compared directly against the 1995 predictions generated by the continued defoliation model. Stands subject to defoliation only during 1995 were compared with the predictions of the initial defoliation model.

RESULTS AND DISCUSSION

Predicted and actual defoliation differed by almost one order of magnitude. Whereas more than 12,000 ha of forest and nearly 2,000 stands were defoliated by the hemlock looper in the Corner Brook area during 1995, EHLDSS predicted ≥35% probability of defoliation for only 1649 ha and 262 stands (Table 2). The meager predictive capacity of the decision-support system can be attributed to several problems inherent in each of the defoliation prediction models.

The most accurate prediction of defoliation risk was generated by the initial defoliation model. Nevertheless, only 239 ha and 1514 stands were predicted to have a significant risk of initial defoliation, while 1021 ha and 6624 stands experienced actual defoliation for the first time during 1995 (Table 2). Substantial underestimation of initial defoliation risk suggests the four parameters of the initial defoliation model - stand age, species composition, outbreak trend, and defoliation proximity - are insufficient to realistically predict the probability of defoliation. Interestingly, considerable improvements in the prediction of initial defoliation risk would be likely if defoliation proximity was calculated at a finer resolution (i.e., stand level) than the 1:50,000 scale map section. (Note: a 1:50,000 scale map section encompasses >1,000 km2). Indeed, hemlock looper moths are poor fliers and unlikely to disperse great distances (Carroll 1956), thus defoliation proximity determined from map sections likely has little relevance to the quantification of initial defoliation risk.

Table 1. Continued defoliation probabilities for forest stands in years when eastern hemlock looper outbreaks are (a) increasing, or (b) decreasing in Newfoundland (from Carroll *et al.* 1995).

(a)	Defoliation risk year *t+1* (%)			
Year *t*	None	Light	Moderate	Severe
Light	52.3	8.0	1.8	37.9
Moderate	79.5	1.5	2.9	16.0
Severe	56.2	2.4	7.1	33.3

(b)	Defoliation risk year *t+1* (%)			
Year *t*	None	Light	Moderate	Severe
Light	83.8	1.5	2.2	12.7
Moderate	91.8	2.2	1.0	5.0
Severe	80.8	0.5	1.2	17.5

Table 2. Number of stands defoliated and area of defoliation caused by the hemlock looper in the Corner Brook area during 1995 versus that predicted to occur (35% probability) by the Eastern Hemlock Looper Decision-Support System. Initial defoliation refers to stands/areas defoliated for the first time in 1995, continued defoliation refers to stands/areas defoliated in 1994 and 1995.

	# Stands defoliated		Area defoliated (ha)	
	Actual	Predicted	Actual	Predicted
Initial defoliation	1021	239	6624	1514
Continued defoliation	863	23	5656	135
Total	1884	262	12290	1649

The poor predictive capacity of the initial defoliation model may arise from a more fundamental problem. Widespread defoliation across insular Newfoundland by the EHL and eastern spruce budworm (ESBW), (*Choristoneura fumiferana* (Clem.), during the last several decades has resulted in the destruction of almost 2.0 million ha of balsam fir forests (Otvos *et al.* 1979; Clark and Carew 1986; Raske et al. 1986). Furthermore, industrial forestry and domestic fuelwood consumption in Newfoundland are responsible for clear-cutting approximately 2.4 million m3 of timber per year (Flight and Peters 1992). Consequently, the distribution and abundance of mature and over-mature (i.e., >60 years-old) balsam fir stands has declined over historical levels. Indeed, a timber-supply deficit is anticipated within the next two decades (Flight and Peters 1992). Given the preference of EHL for old versus young balsam fir stands (Otvos *et al.* 1979), a reduction in the distribution and abundance of these stands has almost certainly influenced the dynamics of looper populations thereby precluding predictions of defoliation risk derived from historical population patterns.

The largest proportion of error in the defoliation risk predictions produced by EHLDSS was associated with the continued defoliation model. Less than 3% of the total area and number of stands actually defoliated for a second consecutive year in the Corner Brook area in 1995 were predicted to have ≥35% probability of defoliation (Table 2). Because the continued defoliation model assigns defoliation probabilities to individual stands based upon observed patterns from the two previous EHL outbreaks, it follows that the relative decrease in the prevalence of mature and over-mature balsam fir stands in the present landscape renders historical defoliation patterns irrelevant. Indeed, a decline in the frequency of preferred stand types suggests that the risk of continued defoliation should be much higher in remaining stands than that observed historically - a premise supported by the considerable underestimation of continued defoliation risk produced by the decision support system in this study.

Despite significant underestimation of the extent of EHL defoliation by EHLDSS, the defoliation models pinpointed regions where looper defoliation tended to predominate (Fig. 3). Qualitative identification of regions where defoliation may focus has considerable value. EHL outbreaks typically begin as small scattered infestations that remain somewhat

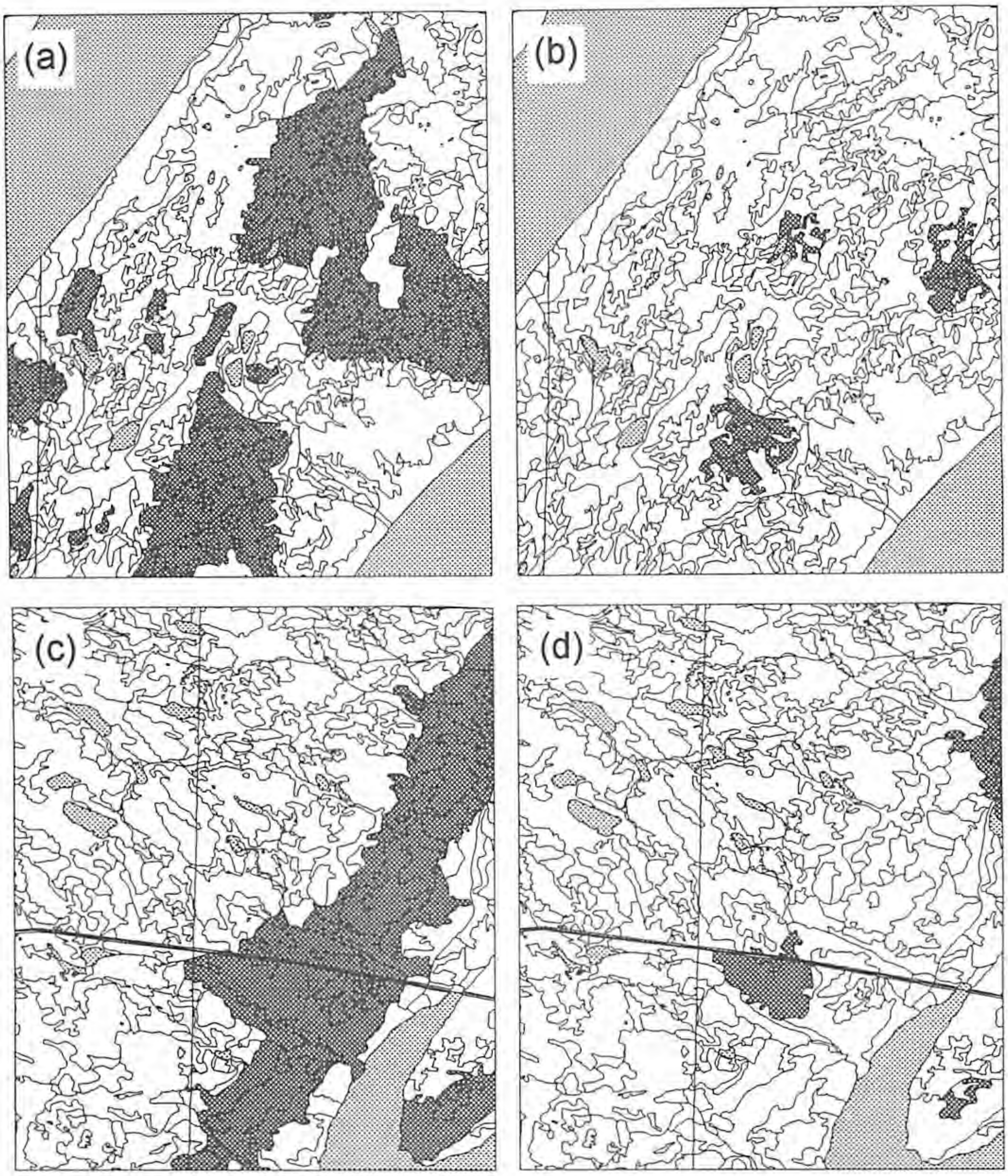

Figure 3. Actual defoliation (a, c) by the eastern hemlock in the Corner Brook region of Newfoundland during 1995 versus predicted defoliation (b, d) calculated by the Eastern Hemlock Looper Decision-Support System. Dark shading depicts defoliation (actual and predicted), light shading indicates water bodies. Predicted defoliation is represented as ≥35% risk.

localized due to limited dispersal of female moths (Carroll 1956; Otvos *et al.* 1973). Periodically, localized infestations expand sufficiently to coalesce into wide-spread outbreaks. Therefore, pinpointing the location of possible localized infestations may enable forest managers to limit the ultimate extent of damage.

The EHLDSS was developed to predict the temporal and spatial extent of hemlock looper impacts. However, even though predictions of defoliation risk tended to pinpoint the location of looper infestations, they significantly underestimated the extent of actual defoliation. Both the initial and continued defoliation models were derived from observed historical outbreak patterns. Consequently, their accuracy is dependent upon the future repeating the past. Unfortunately, the extensive natural and anthropagenic alterations to the forests of insular Newfoundland during the last several decades deminishes the probability that past events will be repeated within the foreseeable future. EHLDSS represents the current state-of-knowledge involving hemlock looper - forest interactions. Additional research in progress toward the development of process-based models simulating the interaction between EHL and balsam fir stand types will yield more accurate predictions of EHL impacts.

ACKNOWLEDGEMENTS

T. Gillis and B. Pike provided valuable technical assistance. C. Carroll provided a critical review of an earlier version of this manuscript. This project was funded by the Green Plan IFPM and Pest DSS Networks.

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APPENDIX I
SOME QUESTIONS ABOUT THE EASTERN HEMLOCK LOOPER OUTBREAK AND ITS CONTROL IN NEWFOUNDLAND

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The following questions-answers were prepared to provide information to questions asked about outbreaks of the easterm hemlock looper (EHL) and their control. The answers are based on information in the scientific literature inluding 1995, and the references to this literature are provided for further reading.

1. **Is this the first outbreak of the EHL in Newfoundland or have there been others?**

   Seven outbreaks of the EHL have been recorded in Newfoundland since 1912. The two most recent outbreaks, from 1966 to 1971 and from 1983 to 1995, were the most severe (18, 19, 92, 93,) extending over more than 500 000 ha.

2. **How do EHL outbreaks develop and how long do they last?**

   The outbreaks are cyclic, they usually develop during warm, dry weather as small, isolated infestations in mature or over-mature stands with high balsam fir content. These infestations expand rapidly and may coalesce to form large outbreak areas. Outbreaks have occurred at 7 to 18 year intervals and each lasted from 6 to 9 years, but individual infestations may collapse in 2-3 years (93).

3. **Can we be sure that there will be an outbreak in 1995?**

   Populations of the EHL increased decidedly in 1994 , particularly in central and western Newfoundland (53), including over 11 000 ha in the moderate and severe defoliation category. Based on fall egg samples at 1 100 locations, the total areas of infestations is forecast to cover 209 000 ha, including 119 000 ha in the moderate and severe defoliation category (54).

4. **What causes the collapse of EHL outbreaks?**

   The collapse of the outbreaks is caused by several factors: weather, starvation from excessive tree mortality, predators, parasites and diseases may all contribute (93). A cool, wet spring or several days of freezing temperature alone may reduce or eliminate an infestation. In addition to starvation caused by widespread tree mortality, disease caused by two native fungi appears to be the major factor terminating outbreaks. Weather characterized by high humidity, moderate rainfall and temperature (15-21°C) favours disease development (91).

5. **Does defoliation during EHL outbreaks cause tree mortality?**

   Some tree mortality was recorded for several of the earlier outbreaks, but very severe, large-scale tree mortality occurred during the 1966-1971 outbreak, when more than 10 000 000 m^3 were killed on about 100 000 ha (92). During the 1983 to 1995 outbreak an estimated 11 289 300 m^3 of balsam fir was killed..

6. **Did Newfoundland spray against the EHL in previous outbreaks?**

   A spray program using fenitrothion and phosphamidon was conducted in both 1968 and 1969 spraying 174 000 ha and 832 000 ha respectively (92, 93). Severely infested areas within the last outbreak were sprayed annually from 1985 to 1990, and in 1992 to 1995 as follows:

   1985 - 125 093 ha (122 728 ha with fenitrothion and 2 365 ha with *B.t.*);
   1986 - 84 448 ha (79 028 ha with fenitrothion and 5 420 ha with *B.t.*);
   1987 - 168 545 ha (164 362 ha with fenitrothion and 4 183 ha with *B.t.*);
   1988 - 68 966 ha (45 138 ha with fenitrothion and 23 828 ha with *B.t.*);
   1989 - 5 362 ha (all with *B.t.*);
   1990 - 10 616 ha (all with *B.t.*);
   1992 - 538 ha (all with *B.t.*);
   1993 - 15 424 ha (all with *B.t.*);
   1994 - 10 719 ha (all with *B.t.*);
   1995 - 47 893 ha (all with *B.t.*).

7. **Were the sprays successful in keeping trees alive?**

   An estimated 36 000 000 m^3 of trees were saved by spraying in 1968 and 1969 (92). The volume of trees saved by the 1983-1995 sprays has not been formally estimated because of complicating factors of salvage and pre-salvage, but it can be assumed to be about the same as that saved in the late 1960's.

8. **Were there any undesirable side effects from previous spray programs in Newfoundland.**

In 1968 there appeared to be a toxic effect on some birds but no dead birds were found in the treated areas. A few birds were observed exhibiting signs of "intoxication"; i.e. loss of equilibrium, tremors and difficulty to fly particularly in areas treated with phosphamidon (92). Phosphamidon appeared to be much more toxic to birds than fenitrothion. No studies were conducted on the toxicity of insecticides to birds in Newfoundland in 1969 (92). Toxic effects in 1968 were likely caused by inadvertent overlapping of flight lines. More advanced navigation now minimizes the occurrence of such overlapping. In 1977 fenitrothion, Matacil, and *B.t.* were used against the eastern spruce budworm (ESBW) and no mortality or other major impact on resident bird populations was recorded. No birds were observed exhibiting symptoms of insecticide poisoning (44). In 1985, 1986 and 1987 birds from areas sprayed with fenitrothion against the EHL had reduced cholinesterase activity but showed no abnormal behaviour in the field (40, 41, 113). Later sprays were not as intensively monitored because the earlier monitoring had indicated no significant impacts of operational spray programs.

9. **Did spraying against the ESBW in the 1970's or against the EHL in the 1980's create conditions that favored the development of a new outbreak of the EHL?**

There is no evidence to suggest this. The beginnings of a looper outbreak had been threatening before and also during the budworm outbreak in the late 1970's. However, a looper outbreak did not materialize at that time because the ESBW is a competitor for the same food resource. The budworm hatches in early June and depletes the food before EHL larvae hatch. When budworm populations subsided the looper was able to reach outbreak levels in the mid 1980's (55). The spray programs of the late 1980's can not be linked to the current rise in EHL populations.

10. **How does the EHL compare to the ESBW in its ability to kill trees?**

The EHL is more wasteful in its feeding than the ESBW. The budworm feeds more systematically from needle to needle on current shoots and it eats a greater proportion of the needle than the EHL. The looper damages more needles and it also feeds on old foliage regularly which greatly reduces the capacity of defoliated trees to survive. Generally trees die after 1 to 3 years of severe EHL defoliation (93), compared to 5 to 7 years of severe ESBW defoliation (55, 100). The EHL is a more efficient tree-killer.

11. **Is tree mortality likely to occur without spraying in 1995?**

Much tree mortality occurred in previous EHL outbreaks, and it is likely that additional tree mortality will occur without spraying. The high density of eggs in many fall egg-samples means we should prepare for extreme population levels within infested areas, and subsequent severe tree mortality exceeding 100 000 m^3.

12. **Is the EHL a serious problem in other parts of North America?**

The EHL is a serious problem only on Anticosti Island in Quebec and in Newfoundland. Outbreaks on the mainland are usually small and confined to river banks and lake edges (101). Newfoundland's climate and forest composition are particularly suitable to outbreaks of this insect.

13. **Why are two applications of the insecticide sometimes used against the EHL?**

Not all larvae hatch at the same time and the second application is aimed at the late arrivals that are not hatched at the time of the first spray. The EHL adult lays many of its eggs on the branches of fir, but some also in the cooler habitats of the forest, such as on birch-bark crevices, and in mosses on the forest floor (17). Thus, some eggs are exposed to the sun and warm air, and these hatch early, but the eggs laid in cool places hatch late. This extended hatching period sometimes requires two applications of the insecticide.

14. **Will the spray decrease EHL populations so no spraying will be necessary in the following year?**

Not normally. Spraying will be done only in portions of the total outbreak area including those with the highest population levels. Enough moths survive outside the spray areas to repopulate much of the spray area. The purpose of the spray operation is to keep trees alive and prevent severe defoliation that would kill trees within 1-3 years (93).

15. Will spraying in 1995 necessitate long term annual spray operations?

No. EHL populations at outbreak levels in Newfoundland last only a few years (93) and the objective of the spray program is to keep trees alive. Spraying is not likely to prolong the outbreak, as was demonstrated by the collapse of the last two outbreaks (92), in spite of extensive spray operations.

16. Can we use any chemical or biological product to spray a forest pest?

No. The use of pesticides is highly regulated and controlled by the Pest Control Products Act administered by Health Canada in cooperation with other federal departments such as Agriculture and Agri-Food Canada, Environment Canada, Natural Resources Canada/Canadian Forest Service, and Department of Fisheries and Oceans (4). A pesticide has to be registered before operational use is permitted (43). In addition to meeting federal regulations, any pesticide use must also be approved by provincial government agencies.

17. Who applies for the registration of a pesticide and what is the registration process?

The manufacturer of the pesticide applies for registration. The Pest Control Product Act demands that applications contain extensive laboratory and field data on the effectiveness and all environmental side effects of the pesticide. The applications are critically reviewed by Health Canada and other cooperating departments before full registration is granted (43).

18. Can a pesticide be used without full registration?

Yes, Health Canada may grant temporary registration for pesticides which are effective and safe but require additional field data especially in terms of foliage protection before full registration can be granted. Temporary registration is valid for one year only but may be renewed upon request by the manufacturer.

19. What biological or chemical insecticides are available that can be used against the EHL?

Several formulations of *B.t.* are registered for forest use against the EHL. In addition the chemical fenitrothion is registered until December, 1998 for forest use against this insect with certain restrictions (see "Question 46").

20. What is *B.t.*? How does it work?

B.t. is the common abbreviation of the scientific name of a bacterium, *Bacillus thuringiensis* Berliner. The strain var. *kurstaki* is a microbial insecticide widely used in agriculture and forestry to control caterpillars (94). It selectively kills caterpillars and does not harm birds, fish, mammals or beneficial insects such as bees and parasites (15, 35, 79). It kills caterpillars by producing a toxin and by a spore that multiplies within the insect. *B.t.* needs to be ingested to be effective (49), and is considered one of the safest insecticides.

21. How is *B.t.* manufactured?

B.t. is manufactured by growing it in large vats called fermentors, where air-resistant spores are harvested in large quantities and formulated for operational use.

22. Why are *B.t.* sprays not used exclusively?

The use of *B.t.* in direct forest pest management has increased steadily in the last few years in all provinces of Canada. Its advantage is that by its very nature it is environmentally more benign than chemicals, and its disadvantage is that it has a rather narrow set of criteria to meet for successful application (127). The narrow set of criteria can not always be met in operational sprays, therefore the use of *B.t.* does not always give the best protection per unit-cost of application.

23. Is *B.t.* environmentally benign, or does its use have detrimental side effects?

After reviewing the literature on the side effects of *B.t.* Otvos and Vanderveen concluded: "During more than 35 years that *B.t.* has been in use in forestry, agriculture and domestic situations, no cases of harmful side effects to humans, mammals, or vertebrates, including fish, have emerged." (94).

24. Can a chemical insecticide be used to control the EHL ?

Yes. The chemical fenitrothion is currently registered for use against several forest insect defoliators, including the EHL (56) (see "Question 46").

25. What type of insecticide is fenitrothion and how does it work?

Fenitrothion is an organophosphorous insecticide (16). It kills on contact as it is absorbed by the insect and also when ingested (16, 109, 125). All organophosphorous insecticides act by interfering with the cholinesterase (ChE) activity necessary for transmission of nerve impulses within the nervous system. A major decrease in ChE activity causes a loss of muscular control and eventual death (80, 81, 82, 85, 109). Fenitrothion has been demonstrated to be effective against the EHL (102, 103, 104).

26. Did the Royal Commission on Forest Protection and Management examine the possible use of fenitrothion for forest spraying in Newfoundland?

The Royal Commission reviewed all registered and potential control methods against the ESBW in 1981 (100). The use of Matacil, *B.t.* and fenitrothion was approved by the Commission based on all aspects of environmental impact including human health and effectiveness. The Royal Commission's conclusion concerning human health was based in part on reports by the Newfoundland Medical Association (86, 87).

27. Why not use Matacil against the EHL?

Matacil is effective and registered against several forest insects but not against the EHL (79). The Canadian Forestry Service tested the effectiveness of Matacil in laboratory and field experiments in 1985 and it was ineffective even at 180 g ai/ha, twice the dosage registered against the ESBW (97). Furthermore, Matacil is no longer being manufactured.

28. What is the persistence of fenitrothion in the environment?

Persistence of fenitrothion in lake water is dependent upon the acidity of the water, temperature, and amount of sunlight received. Under Newfoundland conditions the half-life in water is probably between 20 and 50 hours (73). However, in streams fenitrothion is rapidly diluted and effectively disappears within 12 to 24 hours (28, 29, 75). In aquatic plants fenitrothion degrades within 2-4 days to extremely low levels of 0.0005 to 0.15 ppm (73). Fenitrothion does not persist in the air, water, moss, soils, aquatic sediment, aquatic plants or in fish (114, 116, 118, 120, 121).

The half-life of fenitrothion in upland and submerged soils is about 2-5 days depending upon temperature, light condition, and degree of microbial degradation (73, 78, 115).

Surface residues of fenitrothion persist only a few days on conifer needles and hardwood foliage (104, 119). Small amounts of fenitrothion (less than 300 ppb) may also persist in the forest litter and in forest soils for five days (119).

Pond water, pond sediments, mineral soil and balsam fir foliage were tested for fenitrothion in sites sprayed for one, two and three years. Residues above the detection limits were found only in balsam fir foliage, and ranged from 0.02 to 0.41 ppm of foliage. Residues tended to persist and accumulate with each additional year's spray (5).

Aspects of the fate of fenitrothion in the environment and their ecological side affects have recently been reviewed by the World Health Organization (109).

29. What is the effect of fenitrothion sprays on the safety of drinking water?

Fenitrothion is not applied over drinking water supplies, reservoirs and inhabited areas and thus most sources of drinking water would not be exposed. People in the forest who may use water from sprayed areas would have to drink thousands of litres within hours of the spray to have any effect. Fenitrothion in water breaks down very rapidly within two days. It is of interest that caffeine is equally toxic to humans as is fenitrothion, assuming the lethal dose of fenitrothion to rats equals the lethal dose to humans (67). The highest concentration of fenitrothion in waters sprayed with conventional dosages was 50 parts per billion (ppb). The amount of caffeine in a cup of instant coffee is about 260 000 ppb. Therefore the amount of fenitrothion in a cup of instant coffee prepared using water sprayed with fenitrothion is 5 200 times less than the amount of caffeine.

30. Are blueberries from sprayed areas safe to eat?

Blueberries exposed to a normal dosage of fenitrothion spray contained an average of 2.1 ppm of the insecticide. A person of average weight (70 kg) could eat at least 400 kg of blueberries at one sitting without reaching the no-effect level of 7 ppm for humans (90). Fenitrothion residues disappeared from blueberry foliage and fruit in 15 days (117). Since forest spraying occurs in June or July, blueberries picked in August and September in sprayed areas would not be contaminated.

31. What is the effect of fenitrothion sprays on browsing forest mammals?

Browsing forest mammals, such as rabbit and moose rapidly excrete fenitrothion at the low doses used in spray operations without any apparent side effects (25, 67, 85).

32. Is fenitrothion detrimental to bird populations?

Studies of operational and experimental applications have noted behavioural changes (reduced singing, less movement, increased bill wiping) at dosages of 210 g ai/ha. Mortality of crown-inhabiting birds (Canada warblers, and ruby crown kinglets) and white-throated sparrows have been observed at dosages greater than 280 g ai/ha (9, 96, 98). Other bird species are apparently unharmed at dosages as high as 1240 g ai/ha (80, 81, 83, 85). Breeding populations of any songbird species have not been reduced by application of fenitrothion at dosages of less than 280 g ai/ha (96). Other authors report that bird populations are not reduced even after 10 years of spraying with fenitrothion (11). The most detailed study on the effect of fenitrothion on birds was done in Quebec (63). They experimentally overdosed 336 ha with fenitrothion at 1400 g ai/ha, a dosage almost seven times the normal dose of 210 g ai/ha. Intensive searching by a team of 12 ornithology students located only two dead birds and relatively few birds showing behavioural changes. Furthermore, no significant differences were found in changes in numbers of birds, breeding territories or fledgling birds netted between treated and control plots (63). Inferences from these results (63) agree with many other monitoring studies at conventional dosages of 210 or 280 g ai/ha that birds are not killed, behavioural changes are not common even if birds regularly show temporarily reduced ChE activity (6, 7, 8, 12, 40, 41, 42, 44, 58, 61, 72, 108, 112, 113,).

In laboratory studies fenitrothion force-fed to zebra finches at a dose of 1.04 and 3.80 mg/kg of body weight reduced their activity on the day they were treated. Activity patterns returned to normal after 2 days (51). A 5-year study of bird populations in sprayed and unsprayed areas concluded that birds returned to sprayed areas at a lower rate, but that changes in insect larval densities [the collapse of the outbreak] influenced bird population more than the fenitrothion treatment (70). Three indicator species: White-throated sparrows, magnolia warblers, and chestnut-sided warblers did not abandon sprayed areas, but the first two bird species moved away from canopy regions with higher spray deposits. The fenitrothion spray affected foraging behaviour of these species of song birds but had no long-term effect on populations (70).

Fenitrothion sprays may cause a large and immediate kill of arboreal arthropods (69, 129), and thereby can indirectly affect bird populations. However sufficient refugia remain in sprayed areas where arthropods are not killed. In addition, mobile arthropods invade empty niches, and recuperation is generally rapid. Therefore birds tend to find sufficient food for themselves and their young, although a change in foraging sites is required (69, 129).

Markedly different results were reported by researchers with the Canadian Wildlife Service in Atlantic Canada, following application of 630 g ai/ha (420 g + 210 g several days later) or three times the recommended dosage (14, 97). Several adult white-throated sparrows could not be found after spraying and were assumed to have died. Birds showing intoxication were common, reproductive success was reduced, 11 of 16 males abandoned their territories (1 died, 2 missing, 1 deserted, and was overtaken by another male), 2 out 16 females deserted their nests, and ChE activity of birds in sprayed areas was reduced by an average of 29% with a maximum of 66% (14). In another study the percent of birds that exhibited 50% or more ChE inhibition was 17% in one plot and 18% on another plot (10). These levels were about equal to those of the previous study (14).

Reports of injury to birds in past sprays have generally been associated with overswathing and overdosing (80), and these reports have persisted in the literature. Improved application technology, including computerized control of flight lines has greatly reduced the chances of overswathing.

33. How much can ChE activity decrease without harmful effects on birds?

Several authors (13, 45, 46, 59, 71) have reviewed the complex subject of how ChE activity can be interpreted. In general, a greater than 80% decrease in ChE activity is likely to cause death, greater than 50% may be at least temporarily debilitating or at times life-threatening, and between 20% and 50% is not detrimental (48, 96, 137). Zinkle *et al.* (137) and Busby *et al.* (11) found living birds with greater than 50% ChE inhibition in treated plots. Most of these birds were behaving normally. ChE inhibition of 50% or greater is reversible and birds recover after exposure (37, 46). Recovery occurs after a single oral dose or prolonged dietary doses (36). Initial recovery to the 50% of normal levels is rapid and further recovery proceeds at a slower rate (36). Zinkle *et al.* (137) suggest that a ChE depression of 50% is "life-threatening". This phrase has often been repeated. However, Fleming (36) feels 50% is the minimum effect level. Birds acting normally with ChE depression levels of 50% and greater do not necessarily die (45, 46, 50, 64, 72). Miyamoto (72) reported that Japanese quail showing over 50% ChE reduction showed no behavioural effects or weight loss but egg production was temporarily reduced. The few dead birds found in fenitrothion-treated areas had ChE inhibitions of about 50%; no greater than many birds that survive such levels of inhibition. The poor understanding of the relationship between reduced ChE activity and short-term or chronic behavioural changes, lethal and sublethal effects, limits the use of ChE analysis and conclusions reached should be viewed with caution (1, 45, 57, 64).

34. **Is it true that birds receiving a lethal or potentially lethal dose of fenitrothion become inactive and secretive and are therefore almost impossible to find? Is this the reason why so few, if any, intoxicated or dead birds are found after a spray?**

When phosphamidon, an insecticide more toxic to birds than fenitrothion, has been sprayed, dead and intoxicated birds were readily found by crews of only a few persons (98). However extensive searching by crews, of up to 12 qualified persons, in several years and in several provinces, have found relatively few birds and then almost exclusively in areas of deliberate overdosing (6, 44, 61, 63). The lack of severely affected or dead birds in fenitrothion-sprayed areas appears to reflect the true condition.

Nevertheless scientists from the Canadian Wildlife Service in Atlantic Canada felt that birds affected by fenitrothion sprays have decreased activity and are therefore less likely to be sampled, and thus induce a bias towards less effect of sprays (14). However, exposure of birds to insecticides and their recovery is complicated by several factors, including that exposure in a forest tends to be prolonged, and not by an initial oral dose. Therefore decreased activity may not be pronounced within the first hours after the spray, and both exposure and recovery take place simultaneously over a period of a few days. This tends to remove the bias towards less-affected birds in sampling (51).

35. **Some people claim that trout and salmon might starve to death if fenitrothion is used in forested areas. (The insecticide will kill those aquatic insects which are the food source for these fish.) Is this true?**

The evidence is contrary to this conclusion. There may be increased drift of aquatic insects after spraying this insecticide (44). Both salmon and trout may gorge themselves on this drift on the first day without harmful effects to them (124, 130) but then switch back to their main food - immature dragonflies (39, 107). These do not form a large part of the drift, and are not reduced by the spray. Drift pattern after fenitrothion sprays are erratic and increased drift has been occasionally recorded (23, 25, 47). However, the standing crop of stream inspects (= insects that remain) is barely affected by the spray or recover rapidly (22, 23, 77, 123, 130). However, one study concluded that bottom dwelling insect species were temporarily reduced (44). Peak levels of fenitrothion are far below levels of 4 000 to 5 000 ppb toxic to fish (133) and usually below levels of about 66 ppb toxic to fish food organisms, including drangonfly nymphs; important fish food items in Newfoundland (134). Trout were not killed by fenitrothion when ponds were deliberately sprayed with operational dosages (30, 31, 32, 62), although water flea populations, a major food of small trout may be reduced (32).

Even if we assume a worst case effect that many aquatic insects are killed, then salmon and trout become better searchers for the remaining food, or both switch to alternate food sources (such as midge larvae, or terrestrial insects that drop into streams, etc.). Also both fish species are mobile predators that can move to new areas where food density is normal (130).

In experimental tests using the insecticide permethrin, where almost all stream insects had been deliberately killed (with permethrin) to test the effect on trout, no fish mortality was observed. However, some temporary slowing of growth was recorded until the insect species replenished their populations within one year. Such high aquatic-insect mortality is impossible to attain with the dosage of fenitrothion used (60, 62). In one study unusual high water temperatures caused temporary slowing of growth in both treated and untreated streams (62).

Juvenile Atlantic salmon exposed to sub-lethal concentrations of fenitrothion in the laboratory caused a significant decrease in ChE activity of about 50% at the highest concentration, and this decrease persisted for about 6 weeks (74) Sublethal dosages also decreased the efficiency of attack on prey. The re-action distance to prey, the number of prey ingested, and the frequency of attack were reduced (75). Field studies of salmon confirmed the decrease in re-action distance by juvenile salmon, however the foraging sequence by the salmon exhibited only minor effects of exposure and the number of ingested prey was not affected. However the decline in re-action distance persisted and was still evident for six weeks after exposure (76). Therefore, modifications of some behavior patterns of salmon and trout exposed to fenitrothion in the field are possible, although no effect on populations of such fishes have been measured in spite of intensive studies.

36. Why are there persistent reports on kills of aquatic insects, reduction of salmon in streams and growth reduction in salmon and trout caused by the lack of food (aquatic insects) following aerial application of fenitrothion?

Some early studies implied reduction in aquatic insects and salmon growth (30, 122, 123). However, most monitoring in those early years and more recent studies have not been able to repeat these results. One of the frequently cited reports calculated the reduction in aquatic insects and reduced salmon growth based on tentative conclusions drawn from the literature (123). Subsequent studies did not corroborate these projections. In general, most scientists have concluded that the safety margin of the use of fenitrothion for the growth of fish is large and for aquatic invertebrates it is intermediate and the effect only temporary (22, 23, 24, 27, 29, 66, 68, 77, 126). Relying only on isolated or outdated studies or on studies that create conditions quite different from a spray situation gives a biased picturestated a scientist in a critical review of the issue (128).

37. Are fish from sprayed areas safe to eat?

Human volunteers given 20 mg of fenitrothion (approx. 7 ppm for a person weighing 70 kg) exhibited no measurable effect and all chemical was excreted in the urine within 24 hrs (90). To reach this level of 7 ppm, a person weighing 70 kg would have to eat within 24 hrs at least 160 kg of trout containing 0.306 ppm of fenitrothion, the maximum concentration ever recorded (52). This maximum concentration of fenitrothion in fish was achieved by direct overdosing a body of water. The maximum concentration of fenitrothion recorded in trout in Newfoundland was 0.04 ppm (44). A person weighing 70 kg may eat within 24 hrs at least 1 225 kg of trout without measurable effect from fenitrothion.

38. Does the use of fenitrothion adversely affect aquatic invertebrates in small ponds?

Two recent studies report decreases of aquatic invertebrates in small acidic ponds that may be scattered on forested lands (32, 33, 34). In general the insect fauna was reduced from 20% to 77% depending upon the type of insect (33, 34), and population reductions were evident up to one year after treatment with fenitrothion (34). Adult-insect emergence was reduced for 6 to 12 weeks after treatment (34) and this caused a retention of nutrients within ponds and resulted in an increase of populations of Hydrachnellae [water mites], Oligochaeta [aquatic worms], and Nematoda [nematodes] (34). However this lack of insect emergence may temporarily affect predators that depend upon flying insects. The number of a water flea species (*Daphnia magna*) was greatly reduced when placed in water from one of the sprayed ponds (32), and although the credibility of the study has been questioned (110), the results indicate a need for caution.

39. What are the effects of fenitrothion on pollinators?

Non-target insects which appear to be significantly affected by aerial applications of fenitrothion include honey bee workers, wild pollinating bees, and bumble bees. Population sampling and mortality of caged bumble bees demonstrated a significant reduction in sprayed areas when sprayed with 210 g ai/ha (135). However, monitoring has shown that substantial recovery of bumble bees is possible within the same year of exposure to spraying, provided there is favorable (warm, dry) weather (99). Such recovery is aided by immigration of bees from unsprayed areas.

Counts of wild bees in low-bush blueberry fields adjacent to forests sprayed against the ESBW were also reduced. Crop reductions have occurred in these fields and lack of pollination may have contributed to this failure (135). Wild bee populations in forested areas may also be adversely affected, though pollination in the forest is not drastically changed by long-term application of insecticides at conventional doses (131).

Honey bees are also highly sensitive to fenitrothion and worker bees are affected within 2-3 days of the spray (134). However, total hive mortality, averaging about 1% of the workers, is insufficient to affect total bee populations (80). The subject of pesticide-pollinator interactions has been recently reviewed (83).

The above results pertain to the effect of fenitrothion in sprays against the ESBW. Spraying against the EHL with fenitrothion in Newfound-land may have some effect on blueberry pollinators because blueberries bloom from mid to late June when spraying against the looper may commence. However, blueberries are common on barrens and not in productive forests which are sprayed.

The evidence indicates that populations of bumble bees, solitary wild bees, and honey bees are at times greatly reduced following aerial application of fenitrothion, and that full recovery may take up to three years. However, the significance of this temporary reduction in the life of forest plants is not known. Reduced pollination by bees should increase the degree of self-pollination of understory flora for 1-3 years (136). The effect of this on the forest flora is probably negligible. Furthermore, most forest plants in Newfoundland are pollinated by wind rather than by insects.

40. Were the effects of fenitrothion use in forestry reviewed by a department of the federal government?

Yes. Staff of he Atlantic Region of Environment Canada initiated a review of the literature of the impact of fenitrothion as used in forest spray operations. This review was published in 1989: "Environmental effects of fenitrothion use in forestry - impacts on insect pollinators, songbirds and & aquatic organisms" (31). The editors of the review recommended: "...that an early re-evaluation of registered fenitrothion use pattern be undertaken." Based on that review the Government of Canada in October 1990 initiated a re-evaluation of the registration of fenitrothion, taking both positive and negative factors into account.

41. What were the major findings of the review by the Atlantic Region of Environment Canada on the use of fenitrothion in forestry?

The editors of the review (31) concluded that: "... an early re-evaluation of the registered fenitrothion use pattern be undertaken." Because:
a) small lentic (= surface or sub-surface water) systems are sensitive to fenitrothion contamination.
b) fenitrothion is detrimental to pollination, and sublethal effects on pollinators, especially as they relate to the reproductive success of forest flora, need further study.
c) the biological significance of avian cholinesterase inhibition is not fully understood.
d) that the implications of aquatic invertebrate depletions in small bodies of water for the survival of certain wildlife needs investigation.
e) no clear relationships have been established among fenitrothion spray technology, spray dosage rate, localized insecticide deposit and exposure pathways in non-target fauna.

42. Were the conclusions reached by the editors of the review accepted by all scientists who participated in the review?

No. A number of scientists, including several in the Canadian Forest Service, were critical of many conclusions, and disagreed with the recommendations of the review document (38). Scientists within the Canadian Forestry Service concluded that: "The accumulated evidence contained in the three technical reviews (see 31) does not support the conclusion that large-scale spraying of fenitrothion at registered dosage rates is so environmentally undesirable as to warrant a re-evaluation of its current forestry use pattern. It is the opinion of Canadian Forest Service scientists that an unbiased review of the literature would show that forest spraying with fenitrothion has slight, but acceptable, environmental impacts. The Canadian Forest Service will, however, support and participate in the federal review as part of a balanced approach to finalizing a regulatory position on future fenitrothion uses" (38).

43. Was there an attempt made to document the economic benefit of forest insect management, which included the use of fenitrothion ?

Yes. Numerous benefits stemming from protecting forests from pests were documented that included timber volumes, forest productivity, employment, and several non-timber values. The ratio of benefits to costs in one representative forest pest control program (the ESBW) was 5 to 1, resulting in a net benefit of $100 million (20). Since the EHL is a more potent tree killer than the ESBW, the benefit ratio is likely to be greater than that for the ESBW.

44. As part of the re-evaluation process, did Agriculture and Agri-Food Canada initiate an inter-departmental risk assessment of forestry use of fenitrothion and what were the conclusions ?

Yes, as part of the registration review of fenitrothion, the Canadian Wildlife Service, at the request of Agriculture and Agri-Food Canada, commissioned a team of four specialists to review the literature and present a consensus. The consensus (95) included:

> "Long-term effects of the spray on songbird populations are difficult to determine. Available census data for maritime songbirds do not allow an evaluation of population trends in the areas where fenitrothion has been used most heavily, and other potential influences on songbird population sizes are difficult to factor out".
>
> "The available data indicate that effects on songbirds ranging from behavioural alterations and reduced reproductive success to mortality may occur following operational fenitrothion applications. To obtain a measure of the extent and frequency of potential effects on songbirds, brain ChE activities have been monitored. The ChE monitoring data indicate that exposure of songbirds to the spray can be highly variable and unpredictable. However, the data also indicate that a large proportion of the songbird population may receive a significant exposure to the spray".
>
> "The weight of evidence accumulated .... supports the conclusion that the large-scale spraying of fenitrothion for forest pest control, as currently practiced operationally, is environmentally unacceptable".

45. Did Agriculture and Agri-Food Canada invite discussion on the "Fenitrothion Risk Assessment"?

Yes. Several reports were submitted to Agriculture and Agri-Food Canada, including some that were critical of the Risk Assessment (65) and the resulting Discussion Document (111)., and conversely, some reports stated that the Risk Assessment was not critical enough. Criticism generally centered around incorrect representation of the literature on ecological side effects.

46. What is the status of the re-evaluation of the registration of fenitrothion?

Several government departments, including Agriculture and Agri-Food Canada, Health Canada, Environment Canada, Natural Resources Canada/Canadian Forest Service, Department of Fisheries and Oceans, and other stakeholders contributed to the Decision Document released on April 13, 1995 (56). The decisions reached are hard-won compromises by all stakeholders to ensure a fair and balanced package, and are summarized as follows (56):

a) The registration for broad-scale aerial application of fenitrothion for control of ESBW and EHL will not be extended beyond December 31, 1998. Use will be phased out over a four-year period.
b) The aerial application of fenitrothion for minor pests such as the Swaine jack pine sawfly, jack pine budworm and fall cankerworm, and for minor uses such as seed orchards, is acceptable.
c) Beginning with the 1995 field season and until December of 1998, any broad-scale use of fenitrothion for ESBW or EHL will employ the following mitigative measures:

- fenitrothion applications will be restricted to areas where ESBW or EHL populations are forecast to be high; where it can be demonstrated that commercially valuable timber supplies are at risk, and where alternatives are unlikely to provide adequate protection, as determined by provincial authorities.
- all aerial applications for fenitrothion must be conducted using light (up to 12 500 lb) fixed-wing aircraft or rotary-wing aircraft, or using aircraft equipped with electronic guidance systems;
- buffer zones are required around all specified aquatic habitats. No direct applications of fenitrothion are to take place within 400 m upwind or 100 m downwind of these specified aquatic habitats.
- the dosage rate for any single application of fenitrothion can be no more than 210 g ai/ha with no more than two applications of fenitrothion per year; - no area can be treated with more than a total of 420 g/ha of fenitrothion in two consecutive years;

47. What insecticides are available for use against the EHL in addition to fenitrothion and *B.t.*?

None, However the Canadian Forest Service has been conducting laboratory and field experiments to improve the effectiveness of *B.t.*, and to provide alternative methods. These potential alternatives include biological control by imported parasites (132), and the development of a native fungus that is at times important in reducing populations of the EHL (89). A new insect growth regulator, called 'MIMIC', has also been tested for use against the EHL.

48. What kind of insecticide is an insect growth regulator and how does it work?

An insect growth regulator affects the developing larval stages of insects. It prevents moulting to the next larval instar, and the larva dies while attempting to shed its old skin. It has to be ingested like *B.t.* to be effective. It does not affect adult insects (105). Growth regulators are naturally occurring substances, manufactured in large quantities, and are being used against many insect pests (106).

49. What is the objective of the 1995 experimental spray program?

To provide field efficacy data contributing to registration of two new aqueous formulations of *Bacillus thuringiensis* (*B.t.*) (ABG6387 and ABG6414) and one aqueous formulation of MIMIC® (240LV); an insect growth regulator. If these new products prove to be effective, they then could be registered for operational use to minimize damage by EHL outbreaks.

Properties of the new *B.t.* formulations include improved potency, rainfastness and decreased rate of degradation by sunlight. These could contribute to better performance than formulations presently in operational use. The strain of *B.t.* in the new formulations, *Bacillus thuringiensis* var. Berliner *kurstaki*, is the same as currently in use operationally.

MIMIC 240LV® may become a realistic alternative to *B.t.* and fenitrothion. It has a narrow target range similar to that of *B.t.* but could be more efficacious than *B.t.*, because it acts quickly and persists longer on sprayed foliage (2). This attribute would improve control of species such as the looper that hatch over a prolonged period. It could be as efficacious as fenitrothion, but only to a narrow spectrum of species. Generally only larval lepidoptera are susceptible. Operational treatments with MIMIC 240LV should be competitive because only one treatment, rather than two, is likely to be required. The registration of MIMIC 240LV for the control of the ESBW is possible in 1995. Adding the EHL to the registration label depends on the outcome of the experiment in 1995.

50. Where will the experimental spray program be located in 1995?

Two 250-ha spray blocks, near the town of Pasadena, will be treated with MIMIC, and two nearby 250-ha spray blocks will be treated with *B.t.*

51. What are the environmental side-effects of MIMIC?

At the recommended rate of 70 grams of ai/ha sprayed once or twice a year, MIMIC has no significant effect on birds (Bobwhite quail and mallard duck tested), fish (bluegill sunfish, rainbow trout, fathead minnow and sheepshead minnow), aquatic organisms (algae, shrimp, oysters, stoneflies, water fleas [except for one species -*Daphnia magna*], caddis flies, mayflies, dragonflies, blackflies and lacewings), or their habitat. Honeybees were treated at a dosage equivalent to 1800 times the recommended rate of 70 g.ai./ha and showed no effect. No effect at 71 times the expected environmental concentration was demonstrated for predatory mites, a predatory stinkbug, 5 species of spiders, a beetle and tadpoles. Earthworms showed no effect when exposed to thousands of times the recommended dosage (2). Extensive field-testing in Canadian ponds indicated complete population recovery of the water flea, *Daphnia magna*, after 70 days (2).

52. Why are fungus sprays not used?

Scientist have been successful in mass-producing the spores of the fungus that can be important in reducing populations of the EHL (21, 88, 89). Further work is needed to develop and then to test formulations of fungal spores. In addition, technological problems of storage and maintaining virulence need to be solved. Furthermore, any new product must meet the rigorous standards of the Canadian registration process before it can be used.

53. Are fungal sprays likely to be safe to the environment and to humans.

The native fungi that infect and kill EHL larvae are detrimental to a very limited range of insect defoliator species. They are innocuous to all other forms of life, including most insects, soil organisms, fish, birds, and mammals; including humans.

54. What can be used to control the damage caused by the EHL larvae on ornamental trees?

Several insecticides are readily available from garden-supply stores. Formulations of *B.t.*, a biological insecticide, and several chemical insecticides, including Malathion and Diazinon, are effective at dosages recommended on the label. The labels of all insecticides should be carefully read and directions strictly followed. **Disclaimer**: The mention of any chemical, or formulation, does not imply endorsement, approval or permission for use, nor does the omission of any name imply the opposite or an inferior efficacy.

ACKNOWLEDGEMENTS

The contributions of several scientists in various disciplines, by providing references and discussing the content of this report, are gratefully acknowledged.

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