Research Article

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Wood losses and economical threshold of *Btk* aerial spray operation against spruce budworm

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Abstract

BACKGROUND: Spruce budworm, *Choristoneura fumiferana* (Clem.), causes cumulative defoliation and hence annual growth loss of the balsam fir, *Abies balsamea* (L.) Mill, host tree. Annual growth increments of mixed balsam fir stands were measured by stem analysis over a 9 year period (1994–2002), when *Bacillus thuringiensis* ssp. *kurstaki* (*Btk*) was applied to control spruce budworm defoliation. With this approach, it was possible to quantify the change in stand volume growth after aerial spray applications of *Btk*.

RESULTS: Differences between the periodic volume increment of protected and unprotected plots were statistically significant, while differences between protected and budworm-free plots were not significant. After 9 years, the difference in periodic increment between protected and unprotected plots was 20 m^3 ha^{-1}, and the difference in periodic mortality was 20.5 m^3 ha^{-1}.

CONCLUSION: An economic assessment of *Btk* treatments indicates that biopesticide aerial spraying operations are justified, as they prevented substantial balsam fir mortality and growth losses over the 9 year study.
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Keywords: *Abies balsamea*; *Bacillus thuringiensis*; *Choristoneura fumiferana*; stem analysis; economical analysis; photosynthetic capacity

1 INTRODUCTION

The spruce budworm (SBW), *Choristoneura fumiferana* (Clemens) (Lepidoptera: Tortricidae), is one of the most important defoliators in North American coniferous forests.[1] During the past century, three major SBW outbreaks have occurred in the coniferous forests of eastern North America, beginning about 1909, 1938 and 1967.[2–4] In Quebec, the last outbreak started in 1967 in the southwestern part of the province and ended in 1992 in the east. During that outbreak, mortality losses were estimated at 238 million m^3 for spruces and balsam fir and probably an equal amount in reduced growth.[5]

Previous studies[6,7] have established that balsam fir, *Abies balsamea* (L.) Mill., is the most vulnerable species to SBW attack, followed by white spruce, *Picea glauca* (Moench) Voss, and black spruce, *P. mariana* (Mill.) BSP. Vulnerability to SBW is assessed as the probability of tree mortality that results from a given level of defoliation.[8,9] SBW larvae typically consume current-year foliage, but the insect can also eat older foliage at high larval densities (i.e. severe outbreaks).[10]

Progressive removal of foliage (photosynthetic capacity) and tree reserves by insect feeding can result, initially, in a reduction in radial and height growth, followed by top-kill (i.e. death of the aerial biomass), and eventually by death of the individual tree.[11] Indeed, numerous studies have reported on relationships between cumulative defoliation, growth losses and tree mortality across the boreal and other forested regions of North America.[12–14] For example, after 4 years of continuous defoliation caused by the western spruce budworm, *Choristoneura occidentalis* (Freeman), the growth of 80-year-old Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, stands declined by about 60 m^3 ha^{-1}, consisting of 40 m^3 ha^{-1} by tree mortality and 20 m^3 ha^{-1} by growth reduction in the surviving trees.[15] In New Brunswick, mortality caused by hemlock looper, *Lambdina fiscellaria* (Guen.), ranged between 14 and 51–119 m^3 ha^{-1} for plots with light and severe defoliation respectively.[16] SBW defoliation can likewise lead to major stand growth losses and tree mortality.[13,17–20] Losses can vary markedly with stand age. For example, Archambault and Beaulieu[21] reported radial growth losses of 55% in a young balsam fir stand and 25% in an old balsam fir stand after a 10 year SBW outbreak in the Ottawa River Valley of Quebec. Similarly, volume reductions can vary among individual hosts as well as over time. In New Brunswick, according to MacLean *et al.*,[13] reductions in specific volume increment over 6 years in a 35-year-old balsam fir stand ranged from 11 to 83%, paralleling cumulative defoliation ratings.

The bacterial insecticide *Bacillus thuringiensis* ssp. *kurstaki* (*Btk*) has been used for the last 20 years to control SBW defoliation.[22] Spraying operations have been aimed at maintaining tree survival and preserving the annual allowable cut, and in some instances at protecting wildlife habitat and recreation values. Over the past two decades of *Btk* utilization there has been some debate about whether aerial spraying with *Btk* reduces wood losses and whether the treatment is cost effective.

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The main objective of this study was therefore to quantify the stand volume growth saved from successive defoliation during an SBW outbreak after aerial spray applications of *Btk* and to document its cost effectiveness.

2 METHODS

2.1 Study area

Study was located in the Ottawa River Valley of Quebec, Canada (45°38′–46°01′ N and 75°33′–76°33′ W; 165 m above sea level). The climate is characterized by a mean annual temperature of 4 °C and 950 mm of precipitation.[23] The mixed stands in which the blocks were chosen were situated on rich, subhydric sites[24,25] that contained 35–45-year-old balsam fir and white spruce with a varying component of hardwoods. Balsam fir was the main host species in all sampling sites.

To evaluate the impact of SBW on wood production, 19 blocks were selected in 19 different stands. During this study, the outbreak evolved in certain parts of the Ottawa River Valley region. Inside this epidemic, protected and unprotected blocks were chosen, whereas the budworm-free blocks were chosen in the circumference of the epidemic. Inside this project, every block was separated by a 1 km buffer zone. In the center of each block, which averaged 18.4 ± 7.8 ha (mean ± SE) in area, one 0.05 ha plot was established and measured in 2003. Of the 19 plots, 12 were protected through aerial applications of *Btk* at one or two applications per year at 30 BIU (billion international units) per hectare during the period 1994–2002, while three were left unprotected from *Btk* aerial application. The remaining four plots had budworm-free populations during the outbreak period, and thus were considered as controls for tree growth evaluation as the epidemic progressed in the other plots. SBW impact was measured on balsam fir trees by cumulative visual defoliation assessments.[26] In this study, the 19 plots had 19 different defoliation chronologies.

2.2 Stand measurements and stem analysis

This study consists of a follow-up of annual spray operations and defoliation levels over a 9 year period (1994–2002), whereas stem analysis and collecting data analyses were made in 2003. Annual defoliation was estimated as the SBW epidemic progressed, using the 12-point Fettes scale (0, 0–10, 10–20, 20–30, ..., 90–100, 100, +100).[26,27] The Fettes method was used to estimate host shoot defoliation on all branches sampled from each plot. This is a quantitative defoliation estimate based on individual ratings in percentage classes of all or a subset of the current shoots on a branch, and calculation of mean defoliation per branch. In this method, branches were obtained from the mid-crown of 15 balsam fir trees per plot, where upon the percentage of needles that had been removed from each current-year shoot on the branch were visually estimated. These estimates provide a percentage defoliation for the whole branch.[27]

Balsam firs were harvested from the plots in 2003, following the SBW epidemic. First, distributions of height (m) and diameter at breast height (DBH) were compiled, the latter to determine the proportions of each species in every plot. Each individual was then classified as live or dead. A disk was cut at DBH from the bole of each dead balsam fir to determine its year of death and wood volume. Prior to the harvest, crown defoliation was evaluated for balsam fir with a DBH of 10–24 cm. The DBH classes used were the following: 10, 12, 14, 16, 18, 20, 22 and 24 cm. After felling of the live individuals we measured total stem length (m).

2.3 Tree growth assessment

Growth loss and mortality were analyzed both together and separately to determine their relative contributions regarding total losses in each balsam fir treatment category. Reduction in the annual volume increment of trees indicates the effects of previous defoliation through alterations in radial and height growth combined.[28] To evaluate changes in the annual growth of balsam fir, one tree for each of the 10–24 cm classes of DBH range was randomly selected in each plot. After taking a wood disk at stump height (30 cm), samples were cut from the bole at 0.8 m, 1.3 m, 2.3 m and subsequent 1 m increments to the top of the tree. All disks were sanded on one face, and, to facilitate the analysis, four cross-shaped radii were marked out using a binocular microscope to highlight annual growth rings. Annual ring widths were measured and cross-dated along these radii using an optical digitizing scanner (Epson Expression 1680, 200–400 dpi resolution) and WinDENDRO image analysis software.[29]

To evaluate the effect of spruce budworm and *Btk* on balsam fir increment, growth reduction estimates were based on the methods followed by Gross.[30] Calculating growth reduction caused by SBW defoliation was done by the comparison methods used by MacLean *et al*.[13] and Piene.[31]

2.4 Mortality

A chronology of annual growth patterns was constructed with disks (DBH) cut from the dead balsam fir trees and compared with those of living individuals in the same plot to identify the year of death. Flowering years and actual SBW outbreak were good landmarks to identify the year of each balsam fir death tree. As the SBW infestation began in 1994 in the experimental site, trees that died before 1994 were not considered in the volume calculation of mortality loss. During the study period (1994–2002), certain levels of natural mortality in free budworm plots occurred, and therefore this estimated natural mortality was removed from the volume estimates of the protected and unprotected plots.

2.5 Photosynthetic capacity

The impact of defoliation decreases photosynthesis capacity in balsam fir for more than 1 year because old foliage remains on the trees for long periods of time (>6 years).[32–34] Thus, the level of protection against SBW defoliation was related to cumulative defoliation in balsam fir using the following formula:

$$\begin{aligned}LP_n = 1 - \big[&(D_n \times 0.35) + (D_{n-1} \times 0.24) + (D_{n-2} \times 0.17)\\&+(D_{n-3} \times 0.10) + (D_{n-4} \times 0.07) + (D_{n-5} \times 0.05)\\&+(D_{n-6} \times 0.02)\big]\end{aligned}$$

where LP_n is the level of protection in year n, D_n is the defoliation in year n, D_{n-1} is the defoliation in year $n-1$, and so on.

To assess the threshold of *Btk* aerial operations, the cumulative volume was calculated at the beginning of the study period (1994) and at the end (2002). The difference between cumulative volumes of these two periods represented the earnings brought by the application of *Btk*. For values of periodic increment and mortality, the difference between unprotected and protected stands yielded

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Table 1. Characteristics of sprayed, unsprayed and budworm-free plots in balsam fir stands sampled in 2003

Stands	Plots	DBH (± SEM) (cm)	Height (± SEM) (m)	Age (± SEM) (years)	Proportion of stems (%)		Density[c] (stem ha^{-1})
					BF[a]	WS[b]	
Protected	1	15.2 (±0.5)	12.5 (±0.2)	34 (±0.2)	98.3	0.0	1580
	2	14.6 (±0.6)	12.7 (±0.4)	42 (±0.3)	90.6	3.8	1060
	3	15.4 (±0.6)	14.7 (±0.4)	42 (±0.3)	88.6	8.9	1580
	4	15.1 (±0.7)	15.4 (±0.4)	38 (±0.1)	52.7	33.0	1820
	5	18.1 (±0.9)	16.0 (±0.8)	41 (±0.3)	59.7	20.9	1340
	6	16.9 (±0.9)	15.7 (±0.5)	44 (±0.1)	77.8	4.2	1440
	7	14.8 (±0.5)	13.7 (±0.2)	29 (±0.2)	84.6	5.1	1560
	8	16.7 (±1.1)	14.4 (±0.6)	39 (±0.3)	50.8	41.5	1300
	9	16.1 (±0.7)	14.0 (±0.5)	40 (±0.2)	88.5	5.8	1040
	10	16.0 (±0.6)	13.7 (±0.3)	30 (±0.1)	75.4	20.0	1300
	11	14.5 (±0.8)	14.8 (±0.4)	44 (±0.1)	65.6	4.9	1220
	12	14.5 (±0.6)	12.8 (±0.3)	31 (±0.1)	79.7	8.9	1580
Unprotected	1	13.2 (±0.5)	13.4 (±0.4)	45 (±0.2)	75.4	2.9	1380
	2	14.1 (±0.6)	13.7 (±0.4)	40 (±0.2)	73.8	0.0	1680
	3	19.2 (±1.1)	18.0 (±0.6)	35 (±0.1)	62.3	23.0	1220
Budworm-free	1	17.1 (±0.7)	15.6 (±0.4)	40 (±0.2)	80.4	3.6	1120
	2	17.6 (±0.7)	15.4 (±0.4)	38 (±0.2)	71.0	22.6	1240
	3	17.2 (±0.6)	16.4 (±0.3)	33 (±0.2)	63.7	34.1	1820
	4	15.3 (±0.6)	14.7 (±0.5)	45 (±0.2)	63.5	1.4	1480

[a] Balsam fir.
[b] White spruce.
[c] All species present in the plot.

the volume saved through *Btk* applications. Further, a break-even point was calculated as

$$C_0 = \frac{C_n}{(1+i)^n}$$

where C_n represents the cost in year n, i represents interest and n represents the number of years. This threshold represents the value of the wood (m^3 ha^{-1}) at tree harvest. As the present study concerned young balsam fir stands (35–45 years old), harvesting would not occur before 10 or 20 years had passed; therefore, an economic break-even point was calculated for these two periods.

2.6 Data analysis

Growth data from the harvested trees were used to calculate a volume growth per hectare, assuming that the growth of trees sampled from each plot was representative of other trees in the same diameter class.[35] The data were normally distributed and homoskedastic. Repeated-measures analysis of variance (ANOVARM) was used to test differences in annual growth between protected, unprotected and budworm-free plots in the 1994–2002 period (PROC MIXED).[36] Stands (with three levels) were the between-plot factor, and time (9 years) was the repeated-measures factor. These were considered fixed effects, while plots were a random factor. The matrix structure of variance was autoregressive heterogeneous.

One-way analysis of variance (ANOVA) was used to test differences in the percentage of balsam fir mortality among protected, unprotected and budworm-free plots during two periods: pre-defoliation (before 1994) and the studied outbreak period (1994–2002). Regression analysis was used to test the relation between growth during the 1994–2002 period and annual average photosynthetic capacity. The error rate was referred to 5% as the threshold for significance.

3 RESULTS

3.1 Growth impact

In the pre-defoliation period, no significant difference was found between DBH classes ($F_{18,126} = 1.48$; $P = 0.1083$) and annual growth ($F_{2,144} = 0.01$; $P = 0.9922$) among protected, unprotected and budworm-free plots. Balsam fir and white spruce are the two main species in the 19 plots, with fir predominating. The average proportion (mean ± SE) of balsam fir was 76.0 ± 4.5%, 70.5 ± 4.1% and 69.7 ± 4.0% for the protected, unprotected and budworm-free plots respectively (Table 1). Annual surveys during the study period have indicated that average annual defoliation was 39.0 ± 5.6% for the protected plots, as opposed to 55.0 ± 8.6% for the unprotected plots (Fig. 1). Annual volume increments per tree for protected and budworm-free plots were usually higher than the 100% threshold over the 1994–2002 period (Fig. 2). In contrast, annual volume increments per tree for the unprotected plots were always under 100% over the same 9 year period, declining to 56.6 ± 11.5% in 1998 (Fig. 2). During the infestation period (1994–2002), annual growth was significantly different ($F_{2,21} = 4.43$; $P = 0.0251$). The contrasts of annual growth in protected ($F_{1,21} = 8.68$; $P = 0.0078$) and budworm-free ($F_{1,21} = 5.34$; $P = 0.0314$) plots were significantly higher than in unprotected plots. Futhermore, no difference between protected and budworm-free plots was observed for the same period ($F_{1,21} = 0.06$; $P = 0.8142$). These results revealed that, for a 9 year period of SBW outbreak in the Ottawa River Valley, this defoliator caused an average of 22.8%

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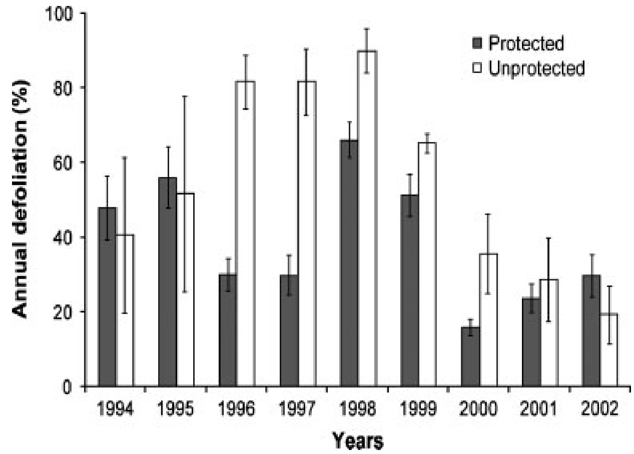

Figure 1. Spruce budworm annual defoliation (mean ± SE) in protected and unprotected balsam fir stands during the period 1994–2002.

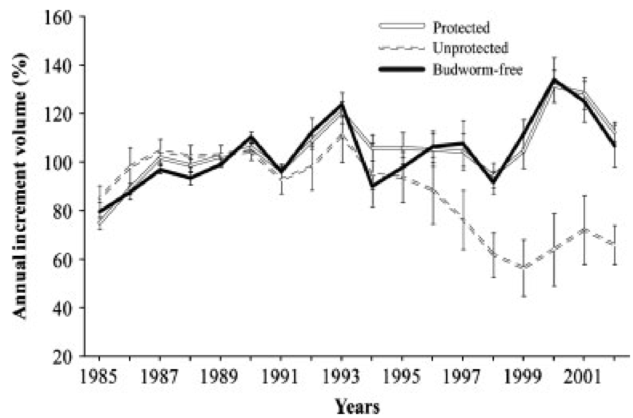

Figure 2. Annual volume increment (mean ± SE) for protected, unprotected and budworm-free balsam fir stands in southwestern Quebec. Protected trees were sprayed with *Btk* at least once between 1995 and 2001, while unprotected trees were not sprayed.

volume growth loss in balsam fir trees in the unprotected plots, compared with the average annual growth for the reference period. In contrast, volume growth increased by 14.0% in the protected plots and 4.7% in the budworm-free plots, respectively, compared with the reference period. For the protected plots, the average periodic volume was 46.2 ± 4.1 m^3 ha^{-1}, as opposed to 26.2±1.6 m^3 ha^{-1} for the unprotected plots. However, the average periodic increment was 57.1 ± 6.3 m^3 ha^{-1} in the budworm-free plots. Futhermore, periodic growth increment (1994–2002) was positively related to average annual photosynthetic capacity ($P = 0.0010$; $r^2 = 0.545$, $y = 2.083x - 123.1$). Ordinary least-squares regression of this relationship explained 55% of variation in the data.

3.2 Mortality impact

Before 1994, balsam fir tree mortality per hectare rate for the protected, unprotected and budworm-free plots was 2.0 ± 0.6%, 7.0 ± 2.0% and 6.0 ± 3.0% respectively ($F_{2,16} = 3.62$; $P = 0.0503$). During the outbreak, mortality percentage per hectare rate was significantly different ($F_{2,16} = 9.80$; $P = 0.00017$). In the unprotected plots (29.0 ± 6.0%), percentage mortality was significantly higher than in the protected plots (8.0 ± 2.1%, $F_{1,16} = 18.90$; $P = 0.0005$) and budworm-free plots (8.0 ± 3.0%, $F_{1,16} = 12.61$; $P = 0.0027$). Moreover, the average volume of tree mortality attributable to SBW was 0.9 ± 0.4 m^3 ha^{-1} in the protected plots, as opposed to 21.4 ± 7.3 m^3 ha^{-1} in the unprotected plots.

3.3 Economic benefits of *Btk* aerial spraying

With protection fixed at 50% of the annual foliage at the beginning of the project, every block received a different number of *Btk* applications over time. At the end of 9 years, the aerial treatment, with an average of seven applications, protected an average 66.0 ± 1.4% of the annual foliage. The costs (assessed in Canadian dollars) of such operations were estimated at \$42 ha^{-1} for one application and \$78 ha^{-1} for two applications (Chénard R, 2007, private communication). In the protected plots, the periodic growth increment was 46.2 ± 4.1 m^3 ha^{-1} and the mortality loss was 0.9 ± 0.4 m^3 ha^{-1}, as opposed to 26.2 ± 1.6 m^3 ha^{-1} and 21.4 ± 7.3 m^3 ha^{-1} in the unprotected plots. Under these considerations, the total volume saved by aerial application of *Btk* (increment and mortality) was estimated to be 40.5 m^3 ha^{-1}. With an average cost for aerial spraying operation of \$273.5±27.8 ha^{-1}, the cost effectiveness required for profitable operations was \$10.0 m^{-3} for a harvesting schedule of 10 years and \$14.8 m^{-3} for 20 years. With a minimum value for balsam fir fixed at \$25 m^{-3} (Martin M, 2008, private communication), the profit realized for this 9 year operation would be \$604 ha^{-1} for a harvesting schedule of 10 years and \$413 ha^{-1} in 20 years.

4 DISCUSSION

Results confirm not only that the aerial *Btk* microbial insecticide spray program, which was aimed at protecting an annual average of 66.0 ± 1.4% of tree photosynthetic capacity during an SBW outbreak, would have saved a significant quantity of balsam fir wood fibre, but also that such operations are cost effective. To the authors' knowledge, this is the first time that economic justification of a *Btk* aerial spray program against SBW has been documented.

Balsam fir photosynthetic capacity was used as a physiological characteristic to fix the annual level of protection in each block treated with *Btk*. Each year of defoliation has a persistent effect on the 7 year balsam fir foliage reservoir.[32,33] Balsam fir tree crown consists mainly of current-year foliage.[32] As it is highly nutritious, this is the first foliage chosen by the SBW.[37] Attacks made by this insect on the annual foliage can eliminate substantial balsam fir tree productivity.[33,38] However, reductions in growth are not proportional to losses of foliage,[33] which may not be visible on the annual rings along the stem during the first year.[18,39] Use of photosynthetic capacity allowed consideration of the impact of SBW defoliation over more than a year.

For the study period (1994–2002), annual volume increment was reduced in the unprotected plots compared with protected and budworm-free plots. Recently, numerous examples of reduction in annual increment caused by SBW defoliation have been documented, thus confirming the magnitude of volume losses.[12,13,20,33,40] The present study also confirms that balsam fir volume reduction reached 54% after 9 years of defoliation. These results are consistent with those of Archambault and Beaulieu,[21] who found a volume growth reduction of 49% in balsam fir over a 10 year period. Volumes in this study were estimated from a mathematical formula that considers only measures of DBH. In contrast, balsam fir volume calculations in the present study were

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made from stem analyses. By taking several discs from every tree, this method makes it possible to gain greater precision in the estimates, compared with taking only a DBH sample.[41]

Before 1994, balsam fir stem mortality was relatively low because SBW defoliation started in 1994. At the end of the study (2003), SBW killed 29% of balsam fir trees. These results were below the 55% mortality shown by Beaulieu and Hardy.[42] For the period 1967–1975, Blais[43] similarly found a high level of balsam fir tree mortality (44%) at the end of the last SBW outbreak in the Ottawa River watershed, but his result represented the average mortality for both coniferous and mixed stands. Moreover, in this particular study, mortality in young stands was almost as high as in mature fir stands. Mortality is observed when there are at least 4–5 consecutive years of severe defoliation (>75% of annual defoliation).[24,25,44] During the present study, balsam fir trees suffered only 3 years of severe defoliation. Also, it is known from the literature that balsam fir stands situated on very good sites during an SBW outbreak (moderate or imperfect drainages with seepage) have approximately 30% mortality.[24,25]

These results confirm that *Btk* may reduce growth loss impacts induced by SBW on balsam fir trees. Piene and MacLean[35] also reported a reduction in annual growth loss caused by SBW on balsam fir by the application of *Bacillus thuringiensis* in the Cape Breton Highlands, Nova Scotia. However, by having begun treatments in the fourth year of defoliation, the volume protected was lower than with the present results. As previously reported,[13,40] there is a positive relationship between periodic increment and photosynthetic capacity ($r^2 = 0.54$).

This study shows cost effectiveness of *Btk* foliage protection during an SBW outbreak. The Province of Quebec has been going through a major forestry crisis for approximately 6 years, so the break-even benefit point was calculated from a low balsam fir price with a percentage of interest of 4%, which is a conservative rate. Yet it is interesting to see that, even in times of crisis, this kind of silvicultural treatment is cost effective.

This study confirmed the importance of protection during an SBW epidemic. Annual increment reductions caused by SBW defoliation were significantly correlated with photosynthetic capacity. At the end of the outbreak, the projected goal of balsam fir foliage protection was achieved, with an average annual foliage protection of 66%. This foliage protection saved a total volume (periodic increment and mortality) of 40.5 m^3 ha^{-1}. Also, this study demonstrated that it was not necessary to protect 100% of photosynthetic capacity by *Btk* aerial applications, because this would save only an additional 10 m^3 ha^{-1}. These results suggest that, for a young balsam fir forest, the application of *Btk* is efficient and cost effective. Forest managers may decide to have a more intensive foliage protection, and these results provide a useful guideline for *Btk* applications. Further research should be pursued to determine the impact of *Btk* applications in other Quebec locations, in other tree species and against other lepidopteran pest species.

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