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# Spatial variability of spruce budworm defoliation at different scales

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ABSTRACT

Aerial survey records of defoliation by spruce budworm (*Choristoneura fumiferana* (Clem.)) in New Brunswick, Canada taken annually from 1965 to 1992, were analyzed at four scales (66 × 66 km, 10 × 10 km, 2 × 2 km, 1 × 1 km) to determine patterns and spatial variability of defoliation. Spruce budworm defoliated 92% of the 7.4 million ha study area in at least one year. Cluster analysis was used to group similar defoliation patterns, and 51% of the variation in the 28-year record was described by 28 representative defoliation patterns, at 1 × 1 km cell size. Individual defoliation patterns were grouped into five spruce budworm outbreak classes (termed A–E), which each covered 12–27% of the area. These differed substantially in defoliation duration and severity: classes A–B had only 1–3 years of moderate–severe defoliation and 42–75% cumulative defoliation; class C had 8 years and 127% cumulative defoliation; and classes D–E had 13–16 years and 170–208% cumulative defoliation. Given the degree of 'averaging out' of high defoliation occurrences that cause the largest impacts, larger 10 × 10 km and 66 × 66 km cells were inappropriate for impact analysis. Defoliation variability was highest at 20–60% mean defoliation than at lower or higher defoliation levels. Distributions of area in each class in 1 × 1 km cells for 66 × 66 km areas throughout the province showed that with the exception of several small coastal areas, four or five of the above outbreak classes occurred in all areas. The wide variation in spruce budworm outbreak patterns is important in making management decisions that differentiate insecticide or salvage treatments based on defoliation severity, and emphasizes the importance of accurate annual aerial survey or remote sensing-based defoliation assessment.



## 1. Introduction

Spruce budworm (*Choristoneura fumiferana* (Clem.)) outbreaks severely defoliate balsam fir (*Abies balsamea* (L.) Mill.) and spruce (*Picea* spp.) approximately every 35 years, resulting in extensive host growth loss and mortality over large areas of eastern North America (MacLean, 1980; Royama, 1984; Batzer and Popp, 1985). The resulting volume losses can dramatically reduce merchantable spruce-fir timber supply, by an estimated 44 million $m^3$/year in Canada from 1977 to 1981, at the peak of the last outbreak (Sterner and Davidson, 1982). A spruce budworm outbreak has been building in eastern Canada, with the area of moderate–severe defoliation in Quebec increasing to over 3.2 million ha from 2005 to 2013 (QMRNF, 2013). Potential impacts of an impending spruce budworm outbreak on 3 million ha of Crown land in New Brunswick have been estimated at an 18–25% reduction in timber supply (Hennigar et al., 2013) and a total provincial economic output decline of $3.3 billion to $4.7 billion CDN, depending upon outbreak severity (Chang et al., 2012).

Models and a Spruce Budworm Decision Support System (SBWDSS) have been developed to estimate the effects of budworm defoliation on forest yields (MacLean et al., 2001; Hennigar et al., 2007). The SBWDSS can be used to prioritize management actions to mitigate the wood supply impacts of defoliation by spruce budworm (Hennigar et al., 2007; McLeod et al., 2012) by using optimization-based projections. Projections of spruce budworm outbreak scenarios for Crown forest in New Brunswick from 2012–2052 demonstrated that up to 30–50% of the projected timber supply reduction could be avoided through *Bacillus thuringiensis* (*Bt*) insecticide foliage protection treatments, and that salvage and harvest schedule re-planning could mitigate harvest losses by up to an additional 20% (Hennigar et al., 2013).

Management decisions about where and when to use insecticides, salvage, or harvest rescheduling to reduce spruce budworm impacts require data about the cumulative defoliation level of forest stands. At the landscape scale, aerial sketch mapping is the only operational method to provide annual defoliation data over large areas (MacLean and MacKinnon, 1996). Aerial sketch mapping during spruce budworm surveys was 82% accurate compared to

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ground survey data using three defoliation classes and was concluded to be an operationally acceptable technique for both surveys and SBWDSS input (MacLean and MacKinnon, 1996; Taylor and MacLean, 2008). However, aerial survey defoliation data suffers from several issues (MacLean and MacKinnon, 1996), including (1) observer ability to accurately identify defoliation 'polygons' on the survey map (spatial issues, including georeferencing errors, sketch mapping biases, and errors in edge delineation, given that budworm population processes and dispersal are continuous processes in space and time); (2) survey precision and lack of bias, which vary across observers and landscape types; and (3) homogeneity of survey effort through time and space in New Brunswick. Accuracy is influenced by weather conditions (rainfall, wind) prior to and during observations. Survey effort documented in annual NBDNR reports (e.g. Carter and Lavigne, 1993) was consistent spatially but did vary over time, especially in precision in 'poor weather' years. Nevertheless, overall accuracy was high using three defoliation classes (MacLean and MacKinnon, 1996).

At present, the SBWDSS uses past aerial survey defoliation data to determine current stand condition, and a user-specified future defoliation scenario to project future damage (Hennigar and MacLean, 2010; McLeod et al., 2012). However, using a single deterministic defoliation scenario ignores spatial variation resulting from different budworm population levels, and variation in budworm population processes resulting from host species, site characteristics, and hardwood content. Knowledge of distributions of defoliation severity within spatially defined areas could be used to alter the current deterministic defoliation scenario into a stochastic input, permitting more realistic distributions of spatiotemporal defoliation patterns based on historical variability.

Several studies have analyzed patterns of spruce budworm outbreaks. Blais (1983) delineated several distinct outbreak areas in eastern North America where outbreaks differed in time of onset or severity, with outbreaks historically tending to begin earlier in southwestern Quebec and extending north and east. Using cluster analysis, Gray et al. (2000) divided past budworm defoliation in Quebec into 25 representative patterns that differed in duration and severity. Royama et al. (2005) used spruce budworm population data to divide New Brunswick into three zones – north, middle and south – with differing outbreak patterns. Gray and MacKinnon (2006) analyzed spruce budworm outbreak dynamics across Canada, using $2 \times 2$ km spatial resolution, and delineated 27 representative outbreak patterns. In Ontario, Candau et al. (1998) showed that spruce budworm defoliation has occurred in three zones of frequent defoliation separated by longitudinally oriented corridors of lower frequency; and Candau and Fleming (2005) developed two empirical statistical models to describe spatial variation in defoliation that revealed several relationships with bioclimatic conditions over the landscape.

This paper consists of (1) a spruce budworm outbreak pattern analysis, (2) an impact estimation exercise, and (3) an analysis of the degree of association between backcast impacts and stand conditions. We use GIS and spatial statistics to determine spatial variability of spruce budworm defoliation in New Brunswick from 1965 to 1992 at four scales. We extracted defoliation data at a $0.1 \times 0.1$ km scale and clustered patterns at four alternative spatial scales ($66 \times 66$ km, after Royama et al., 2005 zones; $10 \times 10$ km; $2 \times 2$ km cells, after Gray and MacKinnon, 2006; and $1 \times 1$ km). We expected that spatial variability in defoliation would be related to outbreak stage (increasing, peak, decreasing populations) as a result of budworm population level (lower spatial variability at peak outbreak) and natural enemies (higher natural enemies in decreasing populations) and also related to host species and hardwood content (e.g., Su et al., 1996). Objectives were to: (1) determine effects of scale on temporal defoliation patterns derived from cluster analysis; (2) quantify defoliation variability (proportions of area with different outbreak classes) in regional $66 \times 66$ km cells, and seek relationships with outbreak stage and with balsam fir and hardwood content; and (3) estimate budworm-caused mortality that would result from use of several outbreak metrics to group geo-referenced classes derived from cluster analysis into classes, estimate probable resulting tree mortality levels, and evaluate use in SBWDSS projections.

## 2. Methods

### 2.1. Spruce budworm outbreak data

Annual spruce budworm defoliation data obtained from aerial surveys from 1965 to 1992 conducted by the New Brunswick Department of Natural Resources (NBDNR) (Carter and Lavigne, 1993) were used to characterize defoliation patterns. Because aerial application of insecticides occurred on up to 50% of the moderate–severe defoliated areas in some years, it significantly reduced the defoliation that would have occurred without foliage protection (Kettela, 1995). As a result, spatially-referenced "without protection" defoliation estimates for New Brunswick from Gray and MacKinnon (2007; available in ArcInfo format at http://www.atl.cfs.nrcan.gc.ca/internal/dgray/index.html) were used to account for the application of insecticide. These data adjusted for aerial spraying effects by increasing defoliation by an amount representative of the mean foliage protection obtained by that insecticide-year combination (Kettela, 1995; Gray and MacKinnon, 2007), in order to conduct spruce budworm pattern analysis uninfluenced by insecticide application.

Aerial defoliation surveys were conducted during a 1–2 week period, immediately following the completion of spruce budworm feeding. At this time, a distinct reddish-brown coloration of dry foliage appears, as a result of budworm severing and webbing together needles in the process of feeding. Areas with noticeable reddish-brown coloration of foliage were recorded on 1:190,000 scale maps in light (11–30%), moderate (31–70%), and severe (71–100%) defoliation classes (Carter and Lavigne, 1993). Areas with no noticeable defoliation were assigned to a nil (0–10%) class. Aerial sketch mapping of spruce budworm defoliation is a viable technique that can be used for both surveys and SBWDSS applications (MacLean and MacKinnon, 1996; Taylor and MacLean, 2008), but the primary error consists of misidentifying nil and light classes, so these were combined in analyses.

Forest composition data were obtained from a GIS-based forest inventory in 1986 using 1:12,500 aerial photography interpreted to determine species composition and stand maturity class for individual stand polygons (NBDNR, 1987). These inventory data are at least 80% representative of forest cover data verified in on-the-ground sampling (Province of New Brunswick, 2001) and represent roughly the mid-point of the 1965–1992 budworm outbreak.

### 2.2. Determination of temporal spruce budworm outbreak patterns

Aerial defoliation data each year from 1965 to 1992 were spatially intersected with a raster of $0.1 \times 0.1$ km grid cells using the Arc Info GIS. Mean defoliation was then calculated for cells at four scales ($1 \times 1$ km, $2 \times 2$ km, $10 \times 10$ km, and $66 \times 66$ km), weighted by area of the three defoliation classes using class midpoints (nil-light 0–30%; moderate 31–70%; severe 71–100%). Cells with no defoliation from 1965–1992 were excluded because their pattern was obvious with 0% current defoliation, 0% cumulative defoliation, and 0% estimated mortality in every year.

We then used standard methods to calculate multi-year defoliation metrics per cell: (1) summed current annual defoliation from