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ARTICLE

Stand breakdown and surface fuel accumulation due to spruce budworm (*Choristoneura fumiferana*) defoliation in the boreal mixedwood forest of central Canada

Graham A. Watt, Brian J. Stocks, Richard A. Fleming, and Sandy M. Smith

Abstract: Spruce budworm (*Choristoneura fumiferana* (Clemens)) defoliation has been shown to increase the likelihood of large forest fires in central Canada. However, the time frame of heightened risk based on the duration of spruce budworm defoliation has not yet been quantified. In this article, we document the extent of stand breakdown and surface fuel accumulation after a period of spruce budworm defoliation that occurred between 1972 and 1976. Data on stand characteristics were derived from previous studies at three different locations in the boreal mixedwood forests of central Canada: Aubinadong (B.J. Stocks. 1987. For. Chron. **63**: 8–14), Gogama, and Gowganda in Ontario. Stand breakdown was measured using a series of transects set in plots 7 years following aerially mapped defoliation (1977–1983). Results show that during the 4 years following 5 years of defoliation, crown breakage, a typical symptom of defoliation, increased by nearly 200%, and surface fuel increased by 145% from predisturbance levels. The high correlation between crown breakage and surface fuels linked defoliation to fuel buildup. We begin to solve the challenge of measuring fuel structure over the expansive scale of spruce budworm outbreaks by quantifying the relationship among stand breakdown, time since the end of defoliation, and the duration of defoliation so that the expected fuel structure can be modelled from annual defoliation surveys.

Key words: spruce budworm defoliation, crown fire, forest fire management, forest structure, natural disturbance.

Résumé : Il a été démontré que la défoliation causée par la tordeuse des bourgeons de l'épinette (*Choristoneura fumiferana* (Clemens)) augmente la probabilité que de vastes feux de forêt surviennent dans la partie centrale du Canada. Cependant, la période de risque accru fondée sur la durée des défoliations causées par la tordeuse des bourgeons de l'épinette n'a pas encore été quantifiée. Dans cet article, nous documentons l'ampleur de la détérioration des peuplements et de l'accumulation des combustibles de surface à la suite d'une période de défoliation survenue entre 1972 et 1976. Les données sur les caractéristiques des peuplements ont été extraites d'études précédentes réalisées à trois endroits différents dans les forêts boréales mixtes du centre du Canada : Aubinadong (B.J. Stocks. 1987. For Chron. **63**: 8–14), Gogama et Gowganda, en Ontario. La détérioration des peuplements a été mesurée à l'aide d'une série de transects établis dans des parcelles 7 ans après une défoliation cartographiée par la voie des airs (1977–1983). Les résultats montrent que durant les 4 années qui ont suivi 5 années de défoliation le bris des cimes, un symptôme typique de défoliation, a augmenté de près de 200 % et les combustibles de surface de 145 %, relativement aux niveaux existants avant la perturbation. La corrélation étroite entre le bris des cimes et les combustibles de surface relie la défoliation à l'accumulation de combustibles. Nous commençons à relever le défi que représente la mesure de la structure des combustibles considérant l'ampleur croissante des épidémies en quantifiant la relation entre la détérioration des peuplements, le temps écoulé depuis que la défoliation a cessé et la durée de la défoliation, de telle sorte que la structure anticipée des combustibles puisse être modélisée à partir des relevés annuels de défoliation. [Traduit par la Rédaction]

Mots-clés : défoliation causée par la tordeuse des bourgeons de l'épinette, feu de cime, gestion des feux de forêt, structure de la forêt, perturbation naturelle.

Introduction

Spruce budworm (*Choristoneura fumiferana* (Clemens)) outbreaks and forest fire are two important natural disturbances in Canada's boreal forests; however, the relationship between these two ecological drivers has not been fully explored (Weber and Flannigan 1997; Fleming 2000; James et al. 2017; Candau et al. 2018). Increasing evidence suggests that greater fire hazard, particularly the occurrence of explosive crown fires, can be linked to fuel restructuring in stands that have been previously defoliated by insects such as the spruce budworm (Stocks 1987; Fleming et al. 2002; James et al. 2017; Watt et al. 2018). If this is the case, then this raises serious concern for fire management because both large-scale spruce budworm outbreaks (Candau et al. 1998; Volney and Fleming 2000) and forest fire activity (Flannigan et al. 2000) are expected to rise across Canada in the near future. The combined impact of these two disturbances and their interaction with changing climate puts considerable pressure on the development of more effective management strategies. A deeper understanding of fuel structure dynamics in forests defoliated by spruce budworm, in terms of chronology, duration, and severity, is needed to address this growing challenge.

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G.A. Watt and S.M. Smith. Faculty of Forestry, University of Toronto, 33 Willcocks St., Toronto, ON M5S 3B3, Canada.
B.J. Stocks. BJ Stocks Wildfire Investigations Ltd., 128 Chambers Ave., Sault Ste. Marie, ON P6A 4V4, Canada.
R.A. Fleming. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON P6A 2E5, Canada.
Corresponding author: Graham Alexander Watt (email: Graham.Watt@mail.utoronto.ca).

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The spruce budworm defoliates its favoured host species, balsam fir (*Abies balsamea* (L.) Mill.), and to a lesser extent white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.), during periodic, large-scale events that occur approximately every 35 years (Fleming 2000). Although the length and severity of these outbreaks may vary (Morin et al. 1993), stand mortality generally occurs (MacLean 1980) when budworm defoliation lasts 5–15 years (MacLean 1980), with pure balsam fir stands being particularly susceptible, showing 30%–100% tree mortality under such conditions (MacLean 1980). Mortality rates of host trees increase with host species abundance (Campbell et al. 2008) and tree age, as trees with larger diameters (older) are most susceptible (Bergeron et al. 1995).

As stand mortality increases over time following defoliation, dead crowns, branches, and needles of host trees accumulate in the lower strata of the forest, and this dead organic matter substantially changes the forest fire fuel complex, essentially increasing the overall fire hazard rating (Stocks 1987). Small-scale field sampling is required to measure such changes in fuel characteristics following defoliation (Stocks 1987), yet this is logistically impossible at the large landscape scale over which spruce budworm defoliation usually occurs. Although aerial defoliation maps describe large-scale insect activity, they provide little information about the fine-scale changes in fuel structure. Thus, fire management would be greatly facilitated by developing a model that could infer the fine-scale fuel characteristics using large-scale information such as that readily available from aerial defoliation surveys (Fleming et al. 2002).

In Ontario, Canada, aerially mapped spruce budworm defoliation has been shown to be linked with the increased likelihood of crowning fires (Stocks 1987; Fleming et al. 2002; James et al. 2017). Stocks (1987) showed that crown fire hazard peaks 5–8 years following a severe spruce budworm outbreak, and more recent work has reported a distinct "window of opportunity" in the likelihood of such large (>200 ha) fires, one that lags 3–9 years after moderate to severe budworm defoliation (Fleming et al. 2002). James et al. (2017) found that the risk of ignition, a key aspect for forest fire development, decreased in the short term following defoliation (i.e., 1 year) but increased over longer periods (i.e., 8–10 years), lending further support to a delayed window of opportunity between defoliation and fire. The relationship between spruce budworm defoliation and subsequent crown fire has been explored both at the local level (Stocks 1987) and at a larger, province-wide scale (Fleming et al. 2002); however, these studies used different approaches, and neither study quantified the physical mechanisms that might directly determine the relationship between defoliation and fire activity. In the present study, we examine key aspects of this relationship to help understand how accumulated spruce budworm defoliation can alter the fuel complex, leading to fire occurrence in the boreal forest.

Variation in forest characteristics, weather conditions across the landscape, and frequency of defoliation are contributing factors to the relationship between spruce budworm defoliation and fire. Fleming et al. (2002) analyzed this interaction across three independent defoliation zones in Ontario (central, western, and eastern as described by Candau et al. (1998)) and found that the highest rates of fuel decomposition occurred in the relatively cool, wet eastern zone compared with the warm, dry western zone, leading to an increased likelihood of crown fire earlier after the end of defoliation in the east (i.e., 3 years) than in the west (i.e., 6 years). Work by James et al. (2017) examining variation in the climate, geomorphology, and forest composition of eastern and western Ontario provided further support for this conclusion.

More recently, Candau et al. (2018) showed how the frequency of spruce budworm defoliation (along with climate, hardwood, and host tree species content) was a significant predictor of the likelihood of subsequent large (>200 ha) fires; at least 9 years of moderate to severe defoliation had occurred in areas where the interaction was most probable. An increase in vertical fuel continuity was suggested as a factor to explain this interaction, and this was shown to increase significantly after 8 successive years of defoliation in Ontario's boreal mixedwood forest, with the highest occurring after 16 years of defoliation (Watt et al. 2018). Relating changes in the fuel complex to the time since defoliation (as in the present study) and to the duration of defoliation (Watt et al. 2018) are the initial steps in developing a model that can infer fuel characteristics and fire hazard from aerial defoliation surveys.

Fig. 1. Map showing the three study sites (black stars): Aubinadong, Gogama, and Gowganda. Black lines denote provincial boundaries. Map was created with QGIS Geographic Information System 2.18 (QGIS Development Team 2016). Geographic features on the main map are adapted from Natural Resources Canada (2019). Contains information licensed under the Open Government Licence – Canada. Inset © OpenStreetMap contributors (https://www.openstreetmap.org/copyright; Haklay and Weber 2008).

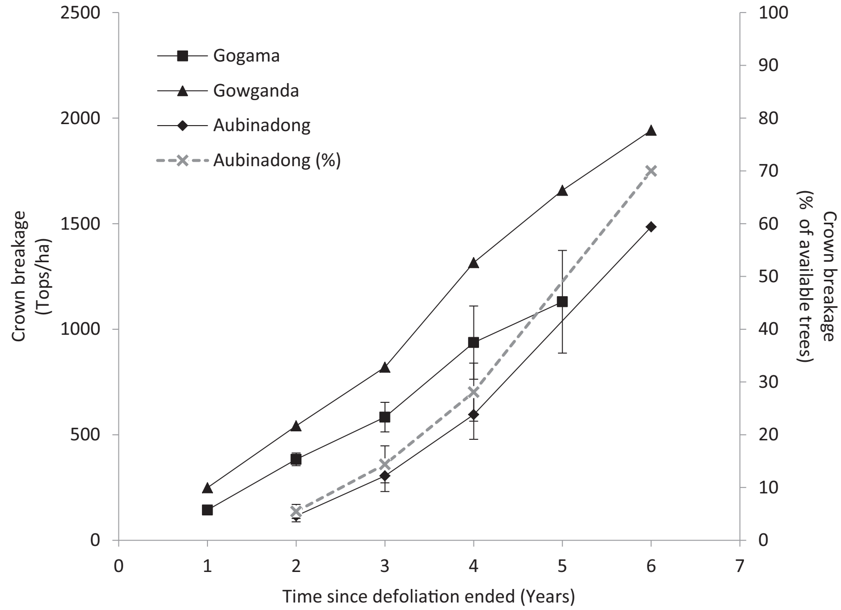
In this study, we investigate the dynamics of fuel accumulation and stand breakdown and their relevance to potential fire activity in the years following spruce budworm defoliation by leveraging historical fuel measurements obtained at one site (Stocks 1987), along with data from two additional sites. Specifically, we document changes in crown breakage and surface fuel accumulation by fuel size class in terms of the number of years of continuous defoliation and the number of years since defoliation ended for the boreal mixedwood forest in central Canada. Our main objectives were to capture the time period when the processes of stand breakdown (caused by spruce budworm) and surface fuel accumulation begin, how those processes progress, and to what extent they occur throughout and after a period of continuous spruce budworm defoliation.

Methods

Site selection

To measure stand breakdown and surface fuel accumulation, we selected three sites across northern Ontario where spruce budworm defoliation had occurred in the recent past: (*i*) Aubinadong (46°53′N, 83°24′W; 80 km northeast of Sault Ste. Marie), (*ii*) Gogama (47°40′N, 81°43′W; 120 km northeast of the Aubinadong site), and (*iii*) Gowganda (47°39′N, 80°46′W; 90 km east of the Gogama site) (Fig. 1). All three sites were classified as boreal mixedwood forest and consisted of a rich overstory and understory of balsam fir, although spruce (*Picea* A. Dietr.), pine (*Pinus* L.), and birch (*Betula* L.) were also sparsely present in the overstory. Overstory trees had a diameter at breast height (DBH; breast height = 1.30 m) of ≥3 cm and a mean stem density of 2652 stems·ha^{-1}. Over 80% of the overstory trees were dead balsam fir that had been killed by

Fig. 2. Crown breakage by time since defoliation ended following 5 years of continuous spruce budworm defoliation (1972–1976). Measurements were taken from boreal mixedwood forest at Aubinadong (n = 7), Gogama (n = 2), and Gowganda (n = 1). Error bars show the standard error of the mean (SEM).



spruce budworm (Stocks 1987); these trees had a mean DBH of 9.6 cm and a mean height of 8.2 m.

All three study sites were located within the zone of eastern Ontario where historical spruce budworm defoliation was recorded (Candau et al. 1998). Each site had experienced moderate to severe defoliation and had 40%–100% loss of new foliage, as aerially mapped by the Forest Insect and Disease Survey (FIDS) (Canadian Forest Service (CFS) and Ontario Ministry of Natural Resources and Forestry (OMNRF)) (Scarr et al. 2012).

FIDS data showed that the most recent budworm outbreak had occurred in the region between 1972 and 1981 (Stocks 1987), providing a minimum study period of 10 years of continuous defoliation at all three sites. Because it was difficult to assess the precise start date for defoliation at the Gogama and Gowganda sites (i.e., it may have begun up to 2 or 3 years prior to 1972, when defoliation was mapped), we used 1972 as the starting point for defoliation in both locations. Ground sampling was conducted during the years of spruce budworm defoliation (1972–1976), as well as into the years after (1977–1983) even though no new defoliation was reported. Sampling confirmed that budworm defoliation ended by 1977 at all sites; thus, we considered all three sites to have been continuously defoliated for 5 years (1972–1976) prior to our study's starting point.

Fleming et al. (2002) referred to the postoutbreak period, part of the "time lag" between the last year of defoliation and the year during which the effect of defoliation was realized, as a period of a statistically significant increase in the likelihood of large fires. During this time lag, the breakdown of stand structure continues, and thus our measurements on the three sites were carried out for 6 years following the original 5 years of continuous spruce budworm defoliation.

Data collection and analysis

Plot size varied slightly among the three sites because of their different origins. At Aubinadong, forest fire personnel from the Great Lakes Forestry Research Centre (now the Great Lakes Forestry Centre (GLFC)) had created seven 2 ha (141.2 m × 141.2 m) experimental burn plots, each containing sampling transects and (or) subplots to assess fuel loads (Stocks 1987). GLFC established two 0.3 ha plots at the Gogama site and one 0.45 ha plot at the Gowganda site to compare the additional measurement of fuel accumulation over time with the Aubinadong site. The primary goal at that time was to determine the effect of changes in stand structure and surface fuel accumulation on fire behaviour. In our study, the point-centered quarter method (PCQM) (Cottam and Curtis 1956) was used to inventory overstory trees (DBH ≥ 3 cm) at 36 points within each 2 ha plot at the Aubinadong site. Understory trees were inventoried using a series of fixed plots, each having a radius of 2 m. Crown breakage was estimated by measuring all broken tops of trees within each plot and was reported as the number of tops per hectare. The line-intersect sampling technique (Van Wagner 1968) was used to determine the volume of downed wood and assess balsam fir surface fuel accumulation in each plot at all three sites: thirty-six 15 m transects at Aubinadong, ten 15 m transects at Gogama, and fifteen 15 m transects at Gowganda. These downed-wood transects were remeasured yearly by size class to quantify surface fuel accumulation in kilograms per square metre. Surface fuel fraction (unitless) was calculated by dividing the quantity of balsam fir surface fuels in a given size class by the total quantity of balsam fir surface fuels.

Linear regression was used to test the relationship between total surface fuel (i.e., the response) and crown breakage (i.e., the predictor) for different years after the end of defoliation. Data used for analysis, specifically those of crown breakage, balsam fir surface fuel, and surface fuel fraction, were normally distributed (Shapiro–Wilk test) and of similar variance (Levene's mean test). An analysis of covariance (ANCOVA) was performed to test the difference in the parameters estimated from the linear regression of surface fuel accumulation with crown breakage for the years after the end of defoliation. More specifically, the ANCOVA tested whether there were significant differences among the estimated slope and intercept terms for each measured year and study site. A one-way, repeated-measures analysis of variance (ANOVA) was also used to determine differences among the fuel fractions over time.

Results

Crown breakage was quantified to determine how much of stand breakdown was due to continuous defoliation by spruce budworm. We found that crown breakage increased progressively in the years following the end of defoliation (Fig. 2). At Aubinadong, crown breakage increased from under 6% in year 2 after

Fig. 3. Balsam fir surface fuel quantity by time since defoliation ended following 5 years of continuous spruce budworm defoliation (1972–1976). Measurements were taken from boreal mixedwood forest at Aubinadong (n = 7), Gogama (n = 2), and Gowganda (n = 1). Error bars show the SEM.

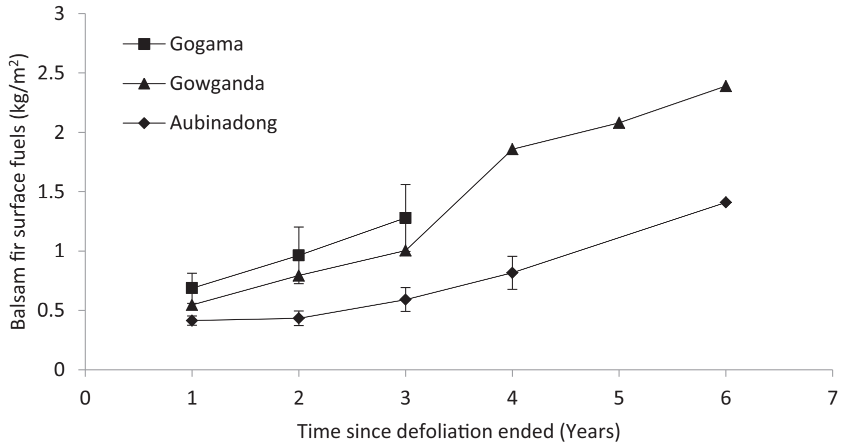
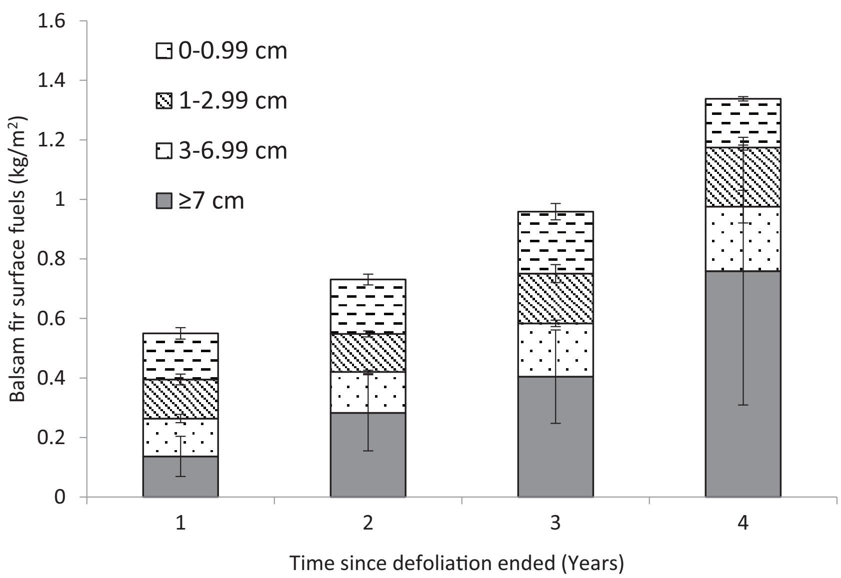


Fig. 4. Mean balsam fir surface fuel quantity in each size class (n = 3 for years 1–3, n = 2 for year 4) by time since defoliation ended following 5 years of continuous spruce budworm defoliation (1972–1976). Measurements were taken from boreal mixedwood forest at Aubinadong, Gogama, and Gowganda. In year 4, fuel data were available only from Aubinadong and Gowganda. Size classes refer to diameter of surface fuel. Error bars show the SEM.



defoliation ended to more than 70% in year 6 after defoliation ended. Total balsam fir surface fuels also increased at each location for all years measured (Fig. 3).

Balsam fir surface fuel quantity, averaged over all locations (n = 3), increased with time since the end of defoliation (Fig. 4). Fuels in each size class also tended to increase, with the exception of the smallest size class (diameter = 0–0.99 cm), which tended to increase over the first 3 years and then decrease after 4 years since the end of defoliation.

The fraction of total balsam fir surface fuels with a diameter of 0–0.99 cm decreased in the years following defoliation (Fig. 5). Results from a one-way, repeated-measures ANOVA showed significant differences in the fraction of those fuels to total fuels over time ($F_{[3,5]}$ = 6.399, p < 0.05).

On average, crown breakage increased from 196 ± 53 tops·ha^{-1} (mean ± standard error of the mean (SEM)) 1 year after defoliation ended to 569 ± 149 tops·ha^{-1} 3 years after defoliation ended. Crown breakage reached 949 ± 207 tops·ha^{-1} 4 years after defoliation ended (Fig. 6). At Aubinadong, approximately 70% of the balsam fir trees had broken crowns by year 6 after defoliation ended. Similarly, balsam fir surface fuels increased from 0.55 ± 0.08 to 0.96 ± 0.20 kg·m^{-2} 1–3 years after the end of defoliation and 1.90 ± 0.49 kg·m^{-2} 3–6 years after the end of defoliation (Fig. 6).

Crown breakage was found to be positively correlated with the total amount of fuels (Table 1; Fig. 7): more fuel was associated with greater crown breakage. The ANCOVA tested whether there were significant differences among the estimated slope and intercept terms for each measured year and study site. The slopes of the three regression lines (slopes for 2, 3, and 4 years since the end of defoliation) were not significantly different ($F_{[3,25]}$ = 0.975, p = 0.333); however, the intercept terms were significantly different, likely because of variation in local site history, forest composition, and climate ($F_{[3,25]}$ = 7.83, p = 0.01).

Discussion

Stand breakdown and surface fuel accumulation with respect to continuous defoliation

Knowledge of stand and fuel dynamics in forests defoliated by spruce budworm is limited. Although studies have documented

Fig. 5. Mean fraction of surface fuel (by mass) with a diameter < 1 cm (n = 3) by time since defoliation ended following 5 years of continuous spruce budworm defoliation (1972–1976). Measurements were taken from boreal mixedwood forest at Aubinadong, Gogama, and Gowganda. Error bars show the SEM.

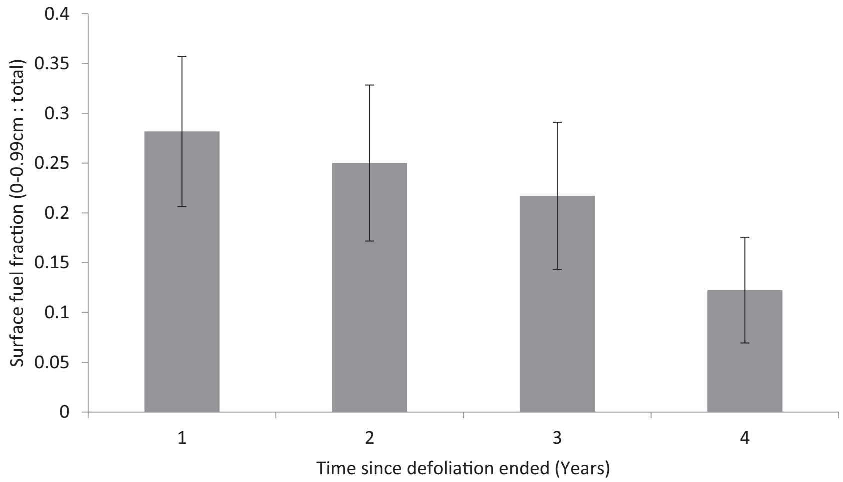


Fig. 6. Mean selected components of stand breakdown by time since defoliation ended following 5 years of continuous spruce budworm defoliation (1972–1976): (*a*) crown breakage (n = 2 for years 1 and 6, n = 3 for years 2–5) and (*b*) balsam fir surface fuels (n = 3 for years 1–3, n = 2 for years 4 and 6, n = 1 for year 5). Measurements were taken from boreal mixedwood forest at Aubinadong, Gogama, and Gowganda. Error bars show the SEM.

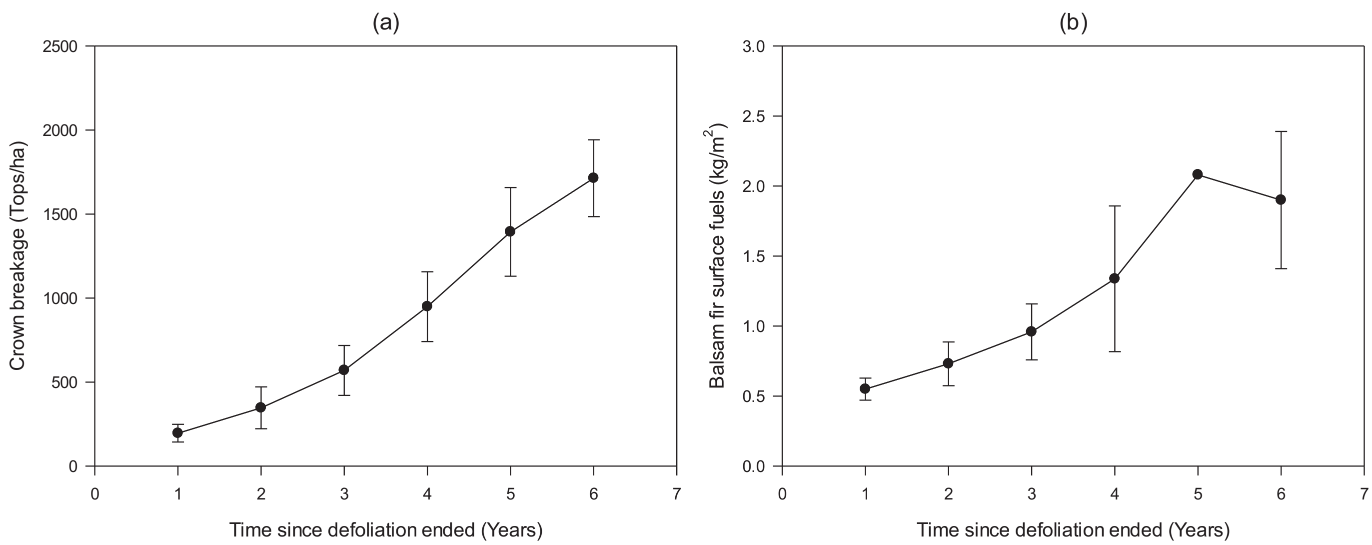


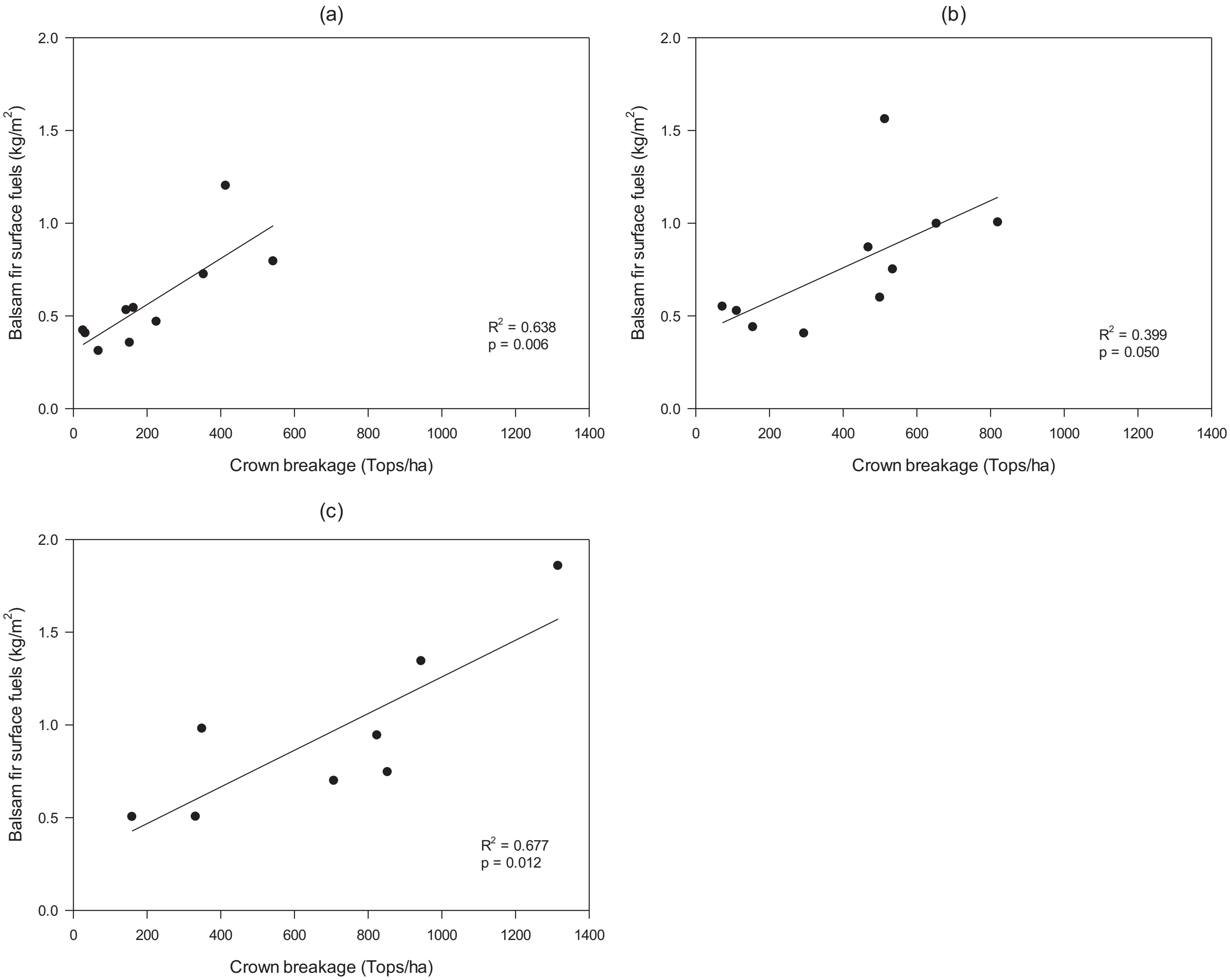
Table 1. Estimated simple linear model for the relationship between crown breakage and balsam fir surface fuels for the time since defoliation ended following 5 years of continuous spruce budworm defoliation (1972–1976) in the boreal mixedwood forest at Aubinadong, Gogama, and Gowganda.

Time since defoliation ended (years)	Parameter	Estimate	Multiple R/R^2	SEM	t	p
2	Intercept	0.3128	0.80/0.65	0.0886	3.53	0.01
2	Slope	0.0012		0.0003	3.75	0.01
3	Intercept	0.3971	0.63/0.40	0.1861	2.13	0.01
3	Slope	0.0009		0.0004	2.31	0.05
4	Intercept	0.2702	0.82/0.68	0.2154	1.26	0.26
4	Slope	0.0010		0.0003	3.55	0.01

Note: Multiple R, coefficient of multiple correlation; R^2, coefficient of determination; SEM, standard error of the mean.

tree mortality caused by spruce budworm, surface fuel accumulation, and their relationship with fire (Stocks 1987; Péch 1993), to our knowledge, no studies have considered these processes in terms of their relationship to the duration of continuous defoliation nor the number of years since the end of defoliation. Our study shows that stand breakdown and surface fuel accumulation following a spruce budworm outbreak increase steadily in the years after defoliation. More specifically, a surge in stand break-

Fig. 7. Linear relationship between balsam fir surface fuels and crown breakage in the time since defoliation ended following 5 years of continuous spruce budworm defoliation (1972–1976) in boreal mixedwood forest at Aubinadong, Gogama, and Gowganda: (*a*) 5 years of continuous defoliation + 2 years since defoliation ended (n = 10), (*b*) 5 years of continuous defoliation + 3 years since defoliation ended (n = 10), and (*c*) 5 years of continuous defoliation + 4 years since defoliation ended (n = 8). The slopes of the three regression lines were not significantly different ($F_{[3,25]}$ = 0.98, p = 0.33). The intercept terms were significantly different ($F_{[3,25]}$ 7.83, p = 0.01). R^2, coefficient of determination.



down appears to begin 1–3 years after defoliation ends and continues up to 6 years beyond this point, thereby generating a pulse consisting of large volumes of flammable woody debris in the boreal mixedwood forest in central Canada.

Many stand characteristics determine the vulnerability of balsam fir to spruce budworm defoliation, including density and age-class distribution. Generally, pure, mature balsam fir stands are expected to have higher overall mortality following a budworm outbreak than mixed stands of young balsam fir (MacLean 1980). Our sites were almost entirely balsam fir, and following the 5 years of moderate to severe spruce budworm defoliation (e.g., at Aubinadong), the trees were almost all (>80%) dead (Stocks 1987). This high rate of mortality is not surprising for severely defoliated, mature, and virtually pure balsam fir stands in eastern Canada (MacLean 1984), but it does represent an extreme. Because our study makes use of one of the same sites as Stocks (1987), our results should be interpreted cautiously. It is possible that the rate and extent of stand breakdown and surface fuel accumulation that we observed here peaked earlier than would be expected in a stand that had less tree mortality.

Our data provide insight into some of the factors that drive the start and duration of the window of opportunity described by Fleming et al. (2002) — a window that begins approximately 3 years after spruce budworm defoliation ends and lasts until 6 years after defoliation ends (i.e., the 3- to 6-year lag) in eastern Ontario. Prior to spruce budworm defoliation, mid- to late-successional boreal mixedwood forests dominated by balsam fir contain about 175–325 surficial tree crowns per hectare (i.e., the fallen part of a standing snag) (Angers et al. 2010). Initially, all of our sites fell within this range; however, 4 years after defoliation ended, crown breakage approached a level 200% higher than the maximum predisturbance levels reported by Angers et al. (2010). This is important because many broken crowns will fall and accumulate as surface fuels on the forest floor. Other broken crowns may be caught by lower overstory and understory branches and be held suspended within the lower crown and ladder fuel regions, thereby supporting a potentially higher likelihood of surface fire crowning. The timing of this fuel redistribution corresponds with the beginning of the window of opportunity.

Much of the increase in surface fuels is due to an increase in piece size, and our results suggest that this increase is due to the smaller pieces from a tree (e.g., needles) falling to the ground before the larger pieces (e.g., trunks). With many trees, there will be overlap in this process in that smaller pieces from a standing tree may fall after the trunk of an already fallen tree; however, it is evident from our work that there is an overall pattern of smaller pieces falling before larger pieces. As most decomposition happens on the ground, small pieces of woody debris have generally been subjected to decomposition for a longer period of time than larger pieces in the same stand. Thus, even if piece size has no bearing on decomposition rate (higher rates are generally expected for smaller pieces because of their greater surface to volume ratio), we would generally expect smaller pieces to decompose before larger pieces during stand breakdown because of differences in the length of time each has been exposed to contributing microenvironments.

According to Van Wagner (1977), the initiation of a crown fire above an active surface fire occurs when the intensity of the surface fire surpasses a critical value. Critical surface fire intensity is a function of crown foliage moisture and the vertical distance of fuels from the base of the overstory tree crown to the surface. Additional fuel loads in the surface region produce greater flame heights (Hummel and Agee 2003) and consequently facilitate the transfer of fire from the surface through the ladder region and into the crown (Menning and Stephens 2007). Stocks (1987) showed that, unlike crown fires that mainly consume foliage and fine branches in healthy forests, entire trees can be combusted in stands killed by spruce budworm because of the flaming front passage and (or) smoldering that results from the reduction in crown foliage moisture during the years following defoliation (i.e., moisture of fine fuel decreased to 5%–10% of dry mass, moisture of medium-sized branches decreased to 15%–20% of dry mass, and moisture of tree boles decreased to 30% of dry mass). The combination of additional fuel loads and decreased fuel moisture suggests a reduction in critical surface fire intensity and greater likelihood of crown fire initiation, as was demonstrated through controlled burns at the Aubinadong site, which also saw an increased probability of a surface fire crowning after stand mortality caused by spruce budworm (Stocks 1987).

The impacts of fuel redistribution and moisture on the window of opportunity are likely seasonal. Stocks (1987) showed that the opening of the canopy due to stand breakdown led to the proliferation of moist herbaceous and deciduous understory vegetation in the years following spruce budworm defoliation at the Aubinadong site. The extent to which the herbaceous and understory vegetation proliferate is, in part, driven by canopy openness, which can generally be expected to increase following spruce budworm defoliation (D'Aoust et al. 2004). Before leaf flush in the spring, increased solar radiation can facilitate the drying of standing dead crown fuels, as well as elevated ladder and surface fuels. This could cause an increase in the amount of fuel consumed and thus facilitate a surface fire more capable of surpassing Van Wagner's (1977) critical intensity for crown fire initiation. After spring flush, a more prevalent layer of vegetation would shield the forest floor from solar radiation. Surface fuels lying below this layer would hold more moisture (i.e., be less flammable) and decompose faster as a result (Péch 1993). Therefore, after spring leaf flush, increased moisture of surface fuel likely has a negative effect on surface fire intensity and consequently crown fire initiation over the short term, as was hypothesized by James et al. (2017). It is likely that the moist leaves of the spring understory vegetation directly inhibit the vertical spread of fire, as was suggested by Stocks (1987), and this was not explicitly accounted for in Van Wagner's (1977) model. Seasonality must therefore be considered when extending models of the relationship among surface fuel accumulation, duration of defoliation, and time since the end of defoliation to fire hazard.

Although Stocks (1987) found that fire hazard increased following spruce budworm defoliation in central Canada, Péch (1993) did not see similar results in eastern Canada. The discrepancy may be due to the differences in forest characteristics and climate between the zones, in that fuel decomposition rates are climatically driven (Harmon et al. 2004; Gould et al. 2008) and any additional risk of fire in a fuel complex disrupted by spruce budworm may be greatly mitigated by climate. Péch (1993) suggested that the wetter and cooler climate of eastern Canada led to faster fuel decomposition and reduced fire hazard in the stands of Nova Scotia killed by spruce budworm compared with those of northern Ontario (Stocks 1987). Such climatic divisions exist not only across Canada, but also across Ontario, as observed by Fleming et al. (2002), who suggested that warm, dry climates in western Ontario may limit fuel decomposition rates compared with those of the cool, wet climates of eastern Ontario. If true, then this in turn would produce a window of opportunity for large fires that begins and ends earlier in eastern Ontario than in western Ontario during those years following a spruce budworm outbreak.

The duration of defoliation and time since the end of defoliation are important considerations that must be used to interpret our results in light of previous work. Although Stocks (1987) measured surface fuel accumulation for 6 years following 5 years of defoliation, defoliation maps show that Péch (1993) measured surface fuel accumulation for 7 years following 8 years of continuous defoliation. Péch's (1993) measurements describe the years following a longer period of spruce budworm defoliation than that of Stocks (1987); the fuel complex in Péch (1993) had an additional 3 years within the period of defoliation to restructure and decompose. This additional decomposition time may provide further explanation as to why the findings of Stocks (1987) and Péch (1993) differed and supports the importance of considering both the duration of defoliation and time since the end of defoliation in estimating stand breakdown from aerial defoliation maps.

The drastic increase in crown breakage and surface fuel accumulation in the 3–6 years after the end of defoliation supports the concept of the window of opportunity identified by Fleming et al. (2002). Although the duration of spruce budworm defoliation was not a factor in Fleming et al.'s (2002) analysis, we have seen here that it does lead to stand mortality and fuel complexes that promote crown fire initiation. More specifically, estimates of the fuel complex with respect to duration of defoliation and time since the end of defoliation may clarify the impact of sustained spruce budworm defoliation on crown fire initiation. This warrants future investigation.

Aside from fire management activities (e.g., detection, initial attack, and suppression efforts), the probability of a large fire (>200 ha) occurring is the product of two probabilities that are not completely independent: the probability of ignition and, once ignited, the probability of the fire spreading to a large size. Fire management efforts are generally focused on reducing the latter. However, climate and the nature of the fuel complex likely affect both probabilities (Stocks 1987; Fleming et al. 2002; James et al. 2017). The nature of the fuel complex depends on many factors such as species composition, age, tree density, topography, moisture levels, history of disturbance (e.g., spruce budworm outbreaks), and management (e.g., logging and prescribed burns). Each factor likely has a unique "window of maximum effect"; however, that window may be constrained by other factors that push it away from the maximum to some degree. For instance, as far as moisture is concerned, desert-like conditions may be the most conducive to fire, but they are unlikely to support the growth of a spruce–fir forest vulnerable to spruce budworm defoliation.

In this study, our focus was to examine the nature of the fuel complex in the boreal mixedwood forest of central Canada following 5 years of continuous spruce budworm defoliation. Stand breakdown increased steadily in the time following defoliation and peaked sometime after 5 years. Watt et al. (2018) found that the fuel complex window following a budworm outbreak that is less severe than the one considered here likely occurs after 8 years of continuous defoliation. Because additional factors affect the overall window for actual fires, it likely differs to some degree from the fuel complex window. For instance, the window of opportunity found by Fleming et al. (2002), which incorporated actual frequency of large fires, could represent the combined effect of all factors in their historic context of occurrence. It is notable that the window proposed by Fleming et al. (2002) also varied in width (duration) and start time depending on geographic region, which was associated with differences in climate and forest composition (i.e., more white spruce and less balsam fir are found in western Ontario than in eastern Ontario).

Correlation of crown breakage with surface fuels

We found a strong and positive correlation between crown breakage and balsam fir surface fuel quantity for the years measured in this study. Figures 2 and 6*a* both show relationships between crown breakage and time since defoliation ended (range = 1–6 years) for stands defoliated for 5 years. Although this strictly applies to only stands defoliated continuously for 5 years, one could estimate the breakage from these relationships by estimating the number of years since defoliation ended according to defoliation survey maps. For other durations of defoliation, refer to Watt et al. (2018).

Although the positive correlation between crown breakage and balsam fir surface fuel quantity is not surprising, as fallen crowns can still hold branches (fuel size classes < 3 cm in diameter) and crown breakage is common in budworm-killed stands (Taylor and MacLean 2007), this is the first time an association between crown breakage and aerially mapped defoliation has been reported. Previous studies have indirectly estimated crown breakage or the abundance of downed woody debris from stand age, composition, and disturbance (Sturtevant et al. 1997) or by using stand mortality (Taylor and MacLean 2007). The correlation we have developed (Fig. 7) provides a means of estimating fuel loads in boreal mixedwood forests in central Canada defoliated by spruce budworm based on a measurement of crown breakage that could be applied elsewhere at the stand level.

Conclusion

Our work quantifies stand breakdown through crown breakage and surface fuel accumulation in boreal mixedwood forest in central Canada defoliated continuously by eastern spruce budworm. Large increases were found in crown breakage and fuel loads 4–6 years after the end of defoliation, with annual increases in total balsam fir surface fuels at all sites. Crown breakage and surface fuel loads were positively correlated, offering a new way to estimate crown breakage and fuel load in these defoliated forests. However, our findings should not be extended to the spruce budworm outbreaks in western Canada because of many contributing factors, including climate and forest characteristics, all of which are likely predictors of the relationship among the duration of aerially mapped defoliation, crown breakage, and surface fuel accumulation.

Fortunately, the relationships among the time since the end of defoliation, crown breakage, and surface fuel accumulation will enable us to develop a viable framework using estimates of budworm-caused stand breakdown and surface fuel accumulation on a large scale. There are three key components: (*i*) the nature of the defoliation, (*ii*) climatic conditions and associated fuel decomposition rates, and (*iii*) forest characteristics (i.e., species composition, age, and density). The frequency, severity, and time since the end of budworm defoliation can be characterized using large-scale maps of spruce budworm defoliation, and these metrics can then be integrated with other components to estimate the horizontal fuel profile. Additional components such as the vertical fuel profile (Watt et al. 2018), risk of ignition (James et al. 2017), likelihood of large fires (Stocks 1987; Fleming et al. 2002; Candau et al. 2018) (as well as risk of spread), weather (including lightning strikes), and topography can also be considered to extend the applicability of the defoliation maps to fire risk.

At a deeper level, the process of stand breakdown and surface fuel accumulation that occurs during and after the years of spruce budworm defoliation outlined here provides insight into the work of Fleming et al. (2002). More specifically, the timing of the surge in crown breakage and surface fuel accumulation aligns with their proposed window of opportunity for large fires across Canada. Although the relationship among aerial defoliation maps, forest structure, and surface fuel accumulation must be further developed to be widely applicable, our work foreshadows the development of a landscape-scale tool to assess the horizontal fuel profile following budworm defoliation. When refined by including parameters that account for current and future climate variation, stand breakdown, and surface fuel accumulation from different defoliation events across a range of forest types, a model to predict fuel structure and fire hazard from annual defoliation surveys can be developed to help forest fire managers in the challenge of quantifying fire hazard over the expansive area of budworm outbreaks.

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