Research Report

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Influence of past forestry practices on western spruce budworm defoliation and associated impacts in southern British Columbia

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Abstract

The western spruce budworm, *Choristoneura occidentalis* Freeman, is a native defoliator of interior Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in British Columbia. Repeated budworm defoliation causes tree mortality, reduction in growth rates, and reduced lumber quality. Eight hundred and fifteen (815) plots were established between 1992 and 2002 throughout chronically defoliated areas, and areas which until recently had never been defoliated, to assess defoliation and impact (growth reduction, top kill, tree mortality) in the Southern Interior of British Columbia. Stands within the Interior Douglas-fir (IDF) biogeoclimatic zone were most susceptible and suffered the greatest amount of chronic budworm activity. The driest, hottest ecosystems predominated by Douglas-fir had the greatest number of consecutive years of defoliation, as well as more frequent defoliation events (total years defoliation). Multi-storied stands with chronic budworm activity had on average 50% fewer Douglas-fir trees per hectare than stands with few or no budworm defoliation events. The understorey component (0.1–7.4 cm dbh and > 1.3 m height) of multi-storied and selectively harvested stands suffered substantial defoliation, often followed by tree mortality, due to intensive budworm feeding. Young, thinned stands and stands that had never been harvested suffered the least impact from budworm defoliation. In conclusion, changes in stand structure through harvesting have influenced the susceptibility of Douglas-fir to the western spruce budworm.

KEYWORDS: *impact,* Choristoneura occidentalis, Pseudotsuga menziesii, *stand structure, understorey mortality.*

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Introduction

The western spruce budworm (WSB), *Choristoneura occidentalis* Freeman (Lepidoptera: Tortricidae), is an important defoliator of interior Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, forests in southern British Columbia (BC). Budworm outbreaks have been recorded from coastal BC through the Central Interior into the western Kootenay Mountains. Outbreaks can have extremely devastating effects on Douglas-fir by reducing growth and yield and causing stem defects and tree mortality (Alfaro et al. 1982, 1985; Alfaro and Maclauchlan 1992), and can disrupt long-term term supplies (MacLean 1985).

According to historic records for BC (Forest Insect and Disease Survey, Pacific Forestry Centre, Canadian Forest Service (1916-1995); BC Ministry of Forests and Range, Kamloops Forest Region (1996-2002) Aerial Surveys), approximately 1 598 500 ha have been defoliated by WSB one or more times between 1916 and 2002. Most of this historic defoliation has occurred within the Southern Interior Forest Region (SIFR) (Figure 1), within seven biogeoclimatic zones (Table 1). Of all zones where western spruce budworm occurs in British Columbia, the Interior Douglas-fir zone (IDF) has seen the most widespread and sustained the longest outbreaks (Maclauchlan et al. 2006). Therefore, we decided to further investigate the impacts of western spruce budworm defoliation in this and other susceptible ecological zones, all of which contain a component of Douglas-fir. Approximately 450 000 ha within the Interior Douglas-fir zone that have not sustained past budworm defoliation are at risk (Maclauchlan 2003). Most western spruce budworm outbreaks have occurred in three IDF subzones which are common to southern BC: the IDFdk (dry cool interior Douglas-fir), the IDFmw (moist warm interior Douglas-fir), and the IDFxh (very dry hot interior Douglas-fir) (Lloyd et al. 1990). Infestations have extended into other less susceptible zones during outbreak years but duration and impact of defoliation is usually less.

Western spruce budworm larvae preferentially feed on developing buds and new Douglas-fir needles. Occasionally, they will also feed on interior spruce, true firs, and western larch. The larvae are capable of severely reducing or eliminating height and diameter growth during each year of defoliation. In addition, severe defoliation over several years can cause upper crown mortality, known as top-kill, which may lead to the formation of stem defects (Van Sickle et al. 1983; Alfaro and Maclauchlan 1992).

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Interior Douglas-fir forests in BC have a long history of intervention and management by humans. Before present-day management and intervention, insects, disease, climate, and fire were the major influencing disturbances in these Douglas-fir-dominated ecosystems, where they continue to play a major role (Thomson et al. 1984; Taylor et al. 1998). Past harvesting practices, access development, urban expansion, and fire suppression have greatly influenced the current stand structure in most interior Douglas-fir forests (Schmidt 1985; Vyse et al. 1991).

Eight hundred and fifteen (815) fixed-radius plots were established between 1992 and 2002 as part of a larger study that examined historic budworm occurrence using GIS analysis and dendro-chronology.

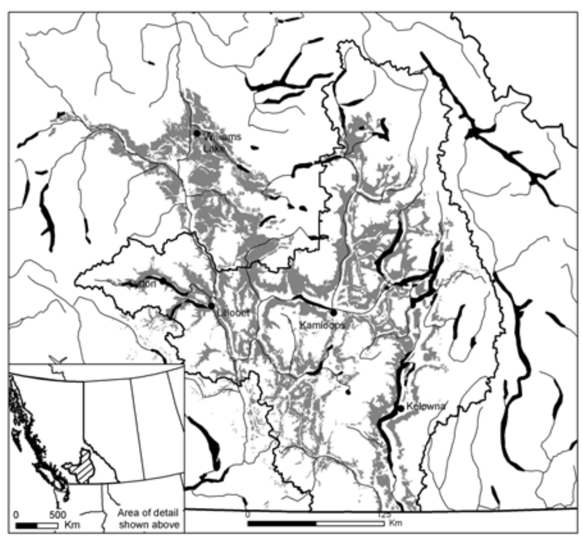

FIGURE 1. Historic areas of western spruce budworm defoliation in British Columbia (1916-2008) with inset showing the project study area.

TABLE 1. List of biogeoclimatic ecosystem classification (BEC) zones having records of western spruce budworm defoliation between 1916-2003 in the study area of southern BC. Also noted is the area defoliated in each zone and percent of total area defoliated (all subzones). The Biogeoclimatic zones are: Bunchgrass (BG); Engelmann spruce subalpine fir (ESSF); Interior cedar hemlock (ICH); Interior Douglas-fir (IDF); Montane spruce (MS); Ponderosa pine (PP); and, sub-boreal spruce (SBS).

Biogeoclimatic zone	Area defoliated (ha)	Total BEC area (ha)*	% total area defoliated (all BEC combined)
BG	13 360	229 708	0.2
ESSF	87 153	1 768 467	1.3
ICH	370 822	1 185 007	5.6
IDF	928 109	2 066 290	14.0
MS	108 399	1 036 920	1.6
PP	81 036	255 041	1.2
SBS	9 643	82 102	0.1
Total	1 598 522	6 623 535	

* Total BEC area determined from the Forest Cover Inventory Map database, BC Ministry of Forests, Victoria, BC.

Through plot evaluation, we assessed the influence of past harvesting practices, silvicultural treatments, and western spruce budworm defoliation on current stand conditions and future susceptibility to the budworm in southern BC. Understanding stand susceptibility will allow us to more accurately predict the occurrence and impact of disturbance agents such as the western spruce budworm.

The main objectives of this study were:

- To quantify the impact (% defoliation as total and maximum consecutive number of years defoliated, top-kill, and tree mortality) of western spruce budworm in different stand structures;
- To describe the resilience of certain biogeoclimatic zones and stand structures to western spruce budworm outbreaks and defoliation; and
- To determine the impact of defoliation in select biogeoclimatic zones and subzones.

Methods

A study was initiated in 1992 to describe and quantify damage caused by western spruce budworm defoliation. From 1992–2002, eight hundred and fifteen (815) fixed-radius plots (3.99 m², 0.005 ha) were established throughout areas of known historic defoliation (750 plots) and in susceptible forest biogeoclimatic zones (containing interior Douglas-fir) that had no records of previous western spruce budworm defoliation (65 plots). All field assessments were conducted by the authors, as well as by three forest health specialists. The plots were proportionately distributed across susceptible biogeoclimatic zones containing interior Douglas-fir within southern BC. Interior Douglas-fir is the preferred host of western spruce budworm, and therefore the Interior Douglas-fir ecosystem and other ecosystems containing a moderate to high proportion of Douglas-fir were selected for this study. The majority of plots were placed in the Interior Douglas-fir dry, cool (IDFdk) and the Interior Douglas-fir very dry, hot (IDFxh) ecosystems (340 and 420, respectively), with fewer plots established in the Interior Cedar –Hemlock moist, warm (ICHmw) zone and Ponderosa Pine very dry, hot (PPxh) zone (Lloyd et al. 1990) (33 and 14 respectively). Eight plots were deleted from the analysis due to uncertainty as to subzone placement.

Aerial photographs and forest cover maps (1:20 000) were used to select and stratify areas for plot establishment. The current level of defoliation, maximum consecutive years of defoliation, and total number of years of defoliation were taken into account during the stratification process. GIS overlay analysis provided the maximum consecutive years and total number of years of defoliation. Once preliminary stands were chosen, walk-through surveys were conducted to confirm suitability. The walk-through surveys were limited to stands that were accessible by vehicle. Initial reconnaissance was done to ensure that species typing through the mapping exercise was correct. Stand structure types (strata) for each selected stand were categorized by tree size (layers), spatial aggregations of trees (clumps), stem density, gaps or openings in the stand, and tree characteristics such as vigour (live or dead), percent live crown, and size of crown. Within each stand, three plots were randomly located and established. Plots were assessed and then assigned to one of the four strata described below:

- Stratum 1 – This stratum is composed of high-density (prior to tree mortality), multi-layered, closed-canopy stands. Overstorey trees are evenly distributed and form a relatively closed canopy. Understorey trees (0–7.4 cm dbh) have the highest stem densities in these stands (large understorey component). This stand structure is typically a result of past harvesting (1960–1970s) that removed single, large-diameter Douglas-fir from stands.
- Stratum 2 – This stratum is composed of low-density stands of primarily even-height and equally distributed stems. This structure is primarily a result of past thinning activity. Smaller trees have been removed, leaving a stand of intermediate-sized trees. Most of these stands were dense prior to thinning, and therefore tree crowns are small, resulting in open, low-density stands.
- Stratum 3 – This stratum is composed of stands with a history of selective harvesting (primarily in the 1950s). These stands are multi-layered, consisting of grassy or bushy openings with young regeneration, clumps of dense, small- and intermediate-sized trees, and scattered clumps or individual, large-diameter trees. Stand density is variable due to patchy stem distribution and canopy gaps (moderate density overall) often due to past selective harvesting.
- Stratum 4 – This stratum is composed of stands displaying little or no harvesting disturbance. These stand types are mature with a high crown closure. The understorey component is lacking or suppressed.

Trees were assigned into layers based on diameter at breast height (dbh) and tree height (BC Ministry of Forests 1992) as described in Table 2. All trees within each plot and within each layer were assessed. Data collected included: total number of trees, total number of live Douglas-fir, and total number of dead Douglas-fir (noting causal agent if possible). An analysis was not performed if the number of plots sampled per ecosystem in a stratum was less than 10.

Over the rotation of a stand, defoliation events can be quantified in different ways. Defoliation can be viewed as the number of times (years) that trees have incurred defoliation (total years defoliated), the number of consecutive years that defoliation has occurred, and the periodicity of outbreak periods.

TABLE 2. Description of tree layers, categorized by diameter at breast height (dbh) and tree height (BC Ministry of Forests 1992).

	Description of trees in each layer	
Layer	Diameter at breast height (cm)	Tree height (m)
1	≥ 12.5 cm	any, given dbh ≥ 12.5 cm
2	7.5 to 12.4 cm	any, given dbh 7.5–12.4 cm
3	0 to 7.4 cm	≥ 1.3 m
4	any, given height restriction of < 1.3 m	< 1.3 m

Each of these three factors could have a significantly different effect on the tree or stand in terms of growth response or mortality. To quantify western spruce budworm impact, by layer, the following attributes were visually estimated and averaged by plot: percent live crown (percent of bole with live branches to the nearest 5%), total tree defoliation (ocular estimate to nearest 5%), top-kill (estimate to nearest 0.1 m for small trees and to 0.5 m for overstorey trees), current defoliation using the Fettes scale (Fettes 1950), and total number of years of defoliation. Tests for normality were performed on the data. The data were then transformed and the analyses performed (arcsine for percent defoliation and percent Douglas-fir mortality, and square root transformation for stem density) to increase the trend toward normal data. Analysis of variance (using SYSTAT 10.2 (SPSS Inc. 2003)) comparing strata, biogeoclimatic zones and subzones, and tree layers was performed on percent mortality, percent defoliation, the maximum number of consecutive years of defoliation, and the total number of years defoliation. Stand density and percent defoliation by layer comparing historically defoliated versus non-defoliated areas were analyzed using t-tests.

Results

The quantitative data collected from the plots supported the original qualitative stratum descriptions (Figure 2). Strata 1 and 3 had significantly higher (Tukey's, $P < 0.05$) stems per hectare (sph) in layer 3, 1 846 and 946 sph,

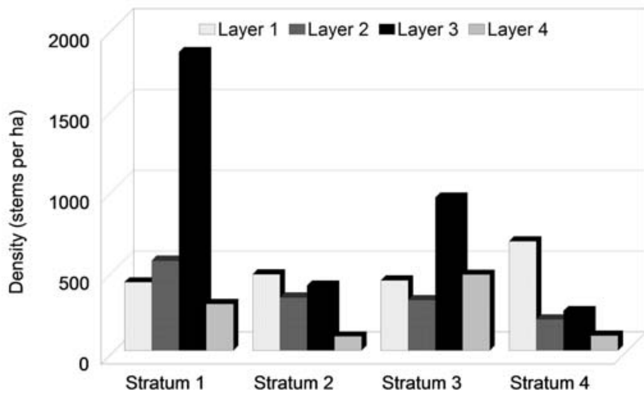

FIGURE 2. Douglas-fir density (live and dead) in plots, showing stems per ha in each stratum by layer. Similar letters above the error bars indicate no significant difference (Tukey's, $p > 0.05$).

respectively (Figure 1). Stratum 4 had significantly greater sph in the overstorey component (layer 1, 675 sph) than in the understorey, regeneration component (layers 3 and 4, Figure 2), 244 and 92 sph, respectively.

Top-kill and percent live crown estimates were collected from all plots; however, an analysis of these attributes showed no significant differences between layers, strata, or ecosystems. Top-kill ranged from 0–6 m with an average of 0.1 ± 0.01 m across all strata. Percent live crown varied among strata, with stratum 3 stands having significantly more live crown than the other strata. These attributes are not discussed any further.

Understorey trees (layers 3 and 4) were more severely defoliated in all strata with average total tree defoliation ranging from 20–45% (Table 3). Observed total tree defoliation on layer 1 trees was significantly less than the other layers, except in Stratum 2, ranging on average from 4–12% in all strata (Table 3).

When layers were compared, mortality was highest in understorey trees (layers 3 and 4) among all strata sampled (Table 3). Layer 3 and 4 trees in stratum 1 suffered the highest percent mortality on average (34.6% and 61.3% respectively) (Table 3). The lowest mortality, across layers 1 and 2 (the overstorey), was seen in stratum 2 stands (Table 3).

Using GIS overlay analysis (Maclauchlan et al. 2006), past occurrence of budworm was calculated within the interest area by biogeoclimatic zone (Table 1). The IDF and ICH accounted for 31.2% and 17.9%, respectively, of the susceptible forest types within the old Kamloops Forest Region. The Montane Spruce (MS), Engelmann Spruce–Subalpine Fir (ESSF), and Sub-Boreal Spruce (SBS) zones contain lower proportions of Douglas-fir and are near the elevational limits for western spruce budworm (Thomson et al. 1983; Lloyd et al., 1990). As such, the insect plays a minor role in these forest types. Therefore, the MS, ESSF, and SBS zones were not considered further in the plot analysis.

There was no significant difference in the mean number of live trees per plot (all layers combined) among the three biogeoclimatic zones compared (ICH, IDF, and PP) (Table 4). Significant differences (Tukey's, $P < 0.05$) in Douglas-fir mortality existed between the IDFdk and the IDFxh (Table 4). The highest Douglas-fir mortality (17%) was seen in the very dry IDFxh (Table 4).

Based on the overlay analysis, both the IDF and the PP zones were proportionally most affected by western spruce budworm (Maclauchlan et al. 2006). The average total years of defoliation varied little between the IDF and PP; however, the average maximum consecutive years of defoliation was consistently longer in the IDF zone (Table 4).

Although more than 30% of the total ICH area was defoliated (Table 1), the average percent defoliation and Douglas-fir mortality recorded in the plots were both 1% (Table 4). Only 14 plots were established in the PP zone, which occupies 255 000 ha (Table 1) in the study area. The average total tree defoliation in PP zone plots was 12% and mortality was 5% (Table 4). Douglas-fir trees within the IDF were the most susceptible to defoliation and subsequent mortality by WSB. Nearly half the total area occupied by the IDFdk, IDFxh, and IDFmw had records of budworm defoliation with 39%, 50%, and 58%, respectively, having been defoliated (Table 5).

Overstorey (layers 1 and 2) and understorey (layers 3 and 4) in each ecosystem sampled were compared by stratum (Tables 6a, b). The stem density of Douglas-fir in the overstorey component of all strata types did not vary as much as the density in the understorey component of the strata sampled. However, mortality and defoliation levels did vary among ecosystems. The IDFxh was the most profoundly affected ecosystem in all strata with a maximum average of 120 stems per hectare dead in stratum 1 plots (Table 6a). In contrast, there was virtually no impact (mortality) from budworm defoliation on ICHmw, PPxh, and IDFdk ecosystems in strata 1, 2, and 3.

TABLE 3. Density, described as stems per hectare (sph), percent mortality and percent defoliation by stratum and layer.

		Average				
Stratum	Layer	No. plots	Live Douglas-fir (sph)	Dead Douglas-fir (sph)	% Douglas-fir mortality ± SE*	% Defoliation ± SE*
1	1	118	381	41	3.7 ± 1.59*a*	12 ± 1.31*a*
(High density)	2		445	111	18.8 ± 2.88*b*	28 ± 2.40*b*
	3		1150	696	34.6 ± 3.28*c*	39 ± 3.34*c*
	4		97	191	61.3 ± 5.88*d*	37 ± 7.71*c*
2	1	107	471	0	0 *a*	11 ± 0.65*a*
(Juvenile spacing)	2		317	11	1.9 ± 0.97*a*	22 ± 1.39*b*
	3		300	102	14.2 ± 3.33*b*	45 ± 3.12*c*
	4		76	11	16.0 ± 7.06*b*	25 ± 6.09*ab*
3	1	416	430	4	0.7 ± 0.26*a*	9 ± 0.53*a*
(Selective harvesting)	2		278	34	8.9 ± 1.40*b*	19 ± 1.02*b*
	3		789	157	15.3 ± 1.42*c*	29 ± 1.32*c*
	4		432	37	12.9 ± 1.89*c*	26 ± 1.64*bc*
4	1	109	668	7	0.9 ± 0.51*a*	4 ± 0.68*a*
(No harvesting)	2		165	28	11.0 ± 3.69*b*	18 ± 2.78*b*
	3		182	62	26.5 ± 5.82*c*	25 ± 3.87*b*
	4		81	11	7.9 ± 3.65*ab*	20 ± 6.19*b*

*Means ± Standard Error (SE) followed by the same letter are not significantly different, Tukey's ($P > 0.05$).

TABLE 4. Description of Douglas-fir trees in plots within the Interior Cedar–Hemlock (ICH), Interior Douglas-fir (IDF), and Ponderosa Pine (PP) biogeoclimatic ecosystem classification (BEC) subzones. The density of live and dead trees is expressed as stems per hectare (sph).

		Average per plot					
BEC	No. Plots	Live trees (all species) (sph)	Live Douglas-fir (sph)	% Douglas-fir defoliation	% Douglas-fir mortality ± SE*	Max. consecutive years defoliation ± SE*	Total years defoliation ± SE*
ICHmw	33	664	176	1	0.7 ± 0.65*a*	1.3 ± 0.04*a*	1.4 ± 0.06*a*
IDFdk	272	502	501	22	4.0 ± 0.56*a*	2.7 ± 0.04*b*	4.1 ± 0.10*b*
IDFmw	56	405	296	13	12.2 ± 2.45*bc*	2.7 ± 0.11*b*	3.1 ± 0.13*c*
IDFxh	362	420	416	22	17.3 ± 0.95*b*	3.1 ± 0.04*c*	4.4 ± 0.07*b*
PPxh	14	521	489	12	5.0 ± 1.80*ac*	1.6 ± 0.08*a*	3.6 ± 0.34*bc*

*Means ± Standard Error (SE) followed by the same letter are not significantly different, Tukey's ($P > 0.05$).

TABLE 5. Area and percent area defoliated by western spruce budworm between 1916-2003 for each biogeoclimatic ecosystem classification (BEC) subzone of the Interior Douglas-fir (IDF) zone in the study area of Southern BC. The Interior Douglas-fir subzones are: dry, cool (dk); very dry, hot (xh); and, moist, warm (mw).

IDF subzone	Area defoliated (ha)	Total BEC area (ha)	% Area defoliated
dk	391 962	1 015 609	39
xh	315 511	628 724	50
mw	156 578	268 165	58

Defoliation and mortality of understorey trees (layers 3 and 4) also varied among ecosystems within strata. The IDFxh suffered the highest mortality level in all strata sampled (Table 6b) and very high levels of defoliation. Strata 1 and 3 had the densest understorey, whereas stratum 2 (juvenile spaced) and stratum 4 (never harvested) had the lowest number of stems per hectare, and were less affected by the budworm.

Twenty-one sites (65 plots) were sampled in 2001 in areas where there was no historic record of WSB defoliation. Some plots showed evidence of past and recent defoliation during the field assessment. Plots were established in two IDF subzones, the IDFdk and IDFxh. Since theoretically these stands had not incurred budworm defoliation in the past, site selection was stratified by ecosystem only and later assigned to a stratum. Fifty-three plots were located in stratum 3 (selective harvest). Stratum 3 stands consisted of areas with a history of selective harvesting; trees were clumped in distribution, both in the understorey and overstorey. Stand density tended to be variable due to patchy stem distribution and canopy gaps. As noted in Table 3, the majority of Douglas-fir sites selected, and having a history of budworm defoliation, were stratum 3 (416 plots) confirming this to be the most typical stand structure type in the IDF. Douglas-fir mortality ranged from 1.1–1.9% in historically non-defoliated areas (Table 7). Most understorey tree mortality was directly attributed to suppression (due to competition for limited site resources between the understorey trees,

TABLE 6a. The number of plots sampled by biogeoclimatic ecosystem classification (BEC) zone and subzone; density in stems per ha (sph) of live and dead Douglas-fir; and average percent defoliation separated by stratum. Layers 1 and 2 (overstorey) are combined. An analysis was not performed if the number of plots sampled was less than 10. The zones are: Interior Douglas-fir (IDF); Ponderosa Pine (PP); and Interior Cedar–Hemlock (ICH). The subzones are dry, cool (dk) and very dry, hot (xh) and moist, warm (mw).

			Average density (sph) ± SE*		
Stratum	No. plots	BEC	Live Douglas-fir	Dead Douglas-fir	Average % defoliation ± SE*
1	37	IDFdk	481.1 ± 62.30 *a*	5.4 ± 3.80 *a*	13.2 ± 1.11 *a*
	65	IDFxh	375.6 ± 25.74 *a*	120.6 ± 31.23 *b*	23.6 ± 2.12 *b*
2	35	IDFdk	405.7 ± 43.26 *a*	0 *a*	16.5 ± 1.15 *a*
	70	IDFxh	384.3 ± 25.24 *a*	8.6 ± 4.90 *b*	16.2 ± 1.15 *a*
3	12	PPxh	225.0 ±42.24 *a*	8.3 ± 8.3 *ab*	5.1 ±1.55 *a*
	24	IDFmw	404.2 ± 56.02 *a*	37.5 ± 18.50 *ab*	9.9 ± 1.73 *ab*
	177	IDFdk	366.7 ± 17.43 *a*	6.2 ± 2.69 *b*	15.6 ± 0.85 *bc*
	196	IDFxh	337.4 ± 13.88 *a*	27.5 ± 5.41 *ac*	11.8 ± 0.84 *a*
4	30	ICHmw	246.7 ± 38.14 *a*	0 *a*	0.3 ± 0.3 *a*
	23	IDFmw	452.2 ± 72.61 *b*	4.3 ± 4.34 *a*	7.4 ± 1.99 *ab*
	22	IDFdk	563.6 ± 71.31 *b*	22.7 ± 18.64 *a*	22.3 ± 3.38 *c*
	31	IDFxh	438.7 ± 49.50 *b*	41.9 ± 14.64 *b*	7.9 ± 1.64 *b*

*Means ± Standard Error (SE) followed by the same letter are not significantly different, Tukey's (P > 0.05).

TABLE 6b. The number of plots sampled by biogeoclimatic ecosystem classification (BEC) zone and subzone; density in stems per hectare (sph) of live and dead Douglas-fir; and average percent defoliation separated by stratum. The layers 3 and 4 (understorey) are combined. An analysis was not performed if the number of plots sampled was less than 10. The zones are: Interior Douglas-fir (IDF); Ponderosa Pine (PP); and Interior Cedar–Hemlock (ICH). The subzones are: dry, cool (dk); very dry, hot (xh), and moist, warm (mw).

			Average density (sph) ± SE*		
Stratum	No. plots	BEC	Live Douglas-fir	Dead Douglas-fir	Average % defoliation ± SE*
1	37	IDFdk	961.1 ± 144.52 *a*	52.8 ± 16.78 *a*	21.2 ± 2.84 *a*
	65	IDFxh	533.3 ± 68.67 *b*	745.7 ± 76.01 *b*	49.2 ± 4.39 *b*
2	35	IDFdk	242.9 ± 39.44 *a*	20.0 ± 9.24 *a*	36.0 ± 3.34 *a*
	70	IDFxh	164.3 ± 31.23 *a*	70.0 ± 28.52 *a*	42.9 ± 4.26 *a*
3	12	PPxh	741.7 ± 336.32 *a*	58.3 ± 25.48 *a*	6.2 ± 1.72 *a*
	24	IDFmw	295.8 ± 60.43 *b*	83.3 ± 30.27 *a*	19.8 ± 4.25 *ab*
	177	IDFdk	636.1 ± 43.91 *a*	32.1 ± 6.28 *b*	30.1 ± 1.29 *b*
	196	IDFxh	614.3 ± 42.79 *a*	145.3 ± 15.62 *a*	27.1 ± 1.69 *b*
4	30	ICHmw	90.0 ± 53.87 *a*	0 *a*	0 *a*
	23	IDFmw	63.8 ± 23.64 *a*	8.5 ± 5.95 *a*	18.0 ± 5.93 *a*
	22	IDFdk	300.0 ± 66.47 *b*	59.1 ± 21.15 *ac*	44.2 ± 4.97 *b*
	31	IDFxh	116.1 ± 27.80 *a*	80.6 ± 27.77 *bc*	15.8± 5.02 *a*

*Means ± Standard Error (SE) followed by the same letter are not significantly different, Tukey's ($P > 0.05$).

with no sign of root disease or insect activity) or, in the case of older trees, laminated root disease, *Phellinus weirii* (Murr.) Gilbertson. Western spruce budworm did not play a large role in Douglas-fir mortality at these sites despite some evidence of defoliation (Table 7).

Discussion

Observed total tree defoliation on dominant, overstorey trees (layer 1 trees) was significantly less than the other more vulnerable understorey layers. Layer 1 trees have a greater amount of foliage than the less dominant trees in the canopy and therefore can sustain higher budworm densities with less manifestation of damage. Magnussen et al. (2005) found trees sprayed with *Bacillus thuringiensis* var. *kurstaki* Berliner had an extended period of protection against the eastern spruce budworm, *Choristoneura fumiferana* (Clem.) because these trees retained proportionally larger crowns than did unprotected trees. They hypothesized that this apparent effect was due to the treated trees having larger, healthier crowns, thus sustaining less damage for a given budworm population. Understorey trees (layers 3 and 4) in our study were more severely defoliated in all stand structure types (strata). The understorey, or suppressed component of trees, has proportionally less new foliage and, therefore, far fewer budworm larvae are needed to cause serious defoliation. More severe and/or prolonged periods of defoliation can result in tree mortality. The larger, overstorey canopy trees will often support increased budworm populations (Magnussen et al. 2004), but are able to sustain higher insect densities before defoliation causes mortality (Alfaro 1986; Alfaro et al. 1984). As with eastern spruce budworm populations, stands comprised of older, larger trees and thus containing a higher biomass of needles are more likely to sustain defoliation than younger stands (Magnussen et al. 2004). This increase in budworm population may have a profound effect on the suppressed understorey trees within these multi-storied stands as numerous larvae drop down from the canopy trees onto the understorey.

TABLE 7. Summary statistics including stand density in stems per hectare (sph), percent Douglas-fir mortality and percent defoliation, for stratum 3 plots in the Interior Douglas-fir dry, cool (IDFdk) and the Interior Douglas-fir very dry, hot (IDFxh).

		IDFdk (± SE)*		
		Live Douglas-fir (sph)	% Douglas-fir mortality	% Defoliation
Layers 1 & 2	Defoliated	366.7 ± 17.43 *a*	1.3 ± 0.56 *a*	13.2 ± 0.80 *a*
	Non-defoliated	678.1 ± 81.60 *b*	1.3 ± 0.81 *a*	1.4 ± 0.39 *b*
Layers 3 & 4	Defoliated	636.1 ± 43.91 *a*	7.1 ± 1.37*a*	24.8 ± 1.29 *a*
	Non-defoliated	1484.4 ± 256.10 *b*	1.9 ± 1.37 *b*	3.0 ± 0.93 *b*
		IDFxh (± SE)*		
Layers 1 & 2	Defoliated	356.8 ± 25.13 *a*	6.3 ± 1.94 *a*	10.1 ± 2.27 *a*
	Non-defoliated	795.3 ± 115.76 *b*	1.1 ± 0.75 *b*	4.0 ± 1.19 *b*
Layers 3 & 4	Defoliated	702.3 ± 95.46 *a*	23.6 ± 3.59 *a*	22.6 ±4.17 *a*
	Non-defoliated	1087.8 ± 191.41 *a*	1.4 ± 0.79 *b*	7.3 ± 2.54 *b*

*Means ± Standard Error (SE) followed by the same letter are not significantly different, Tukey's (P > 0.05).

Consistent with higher levels of defoliation, layer 3 and 4 trees suffered the highest mortality among all the strata sampled. Multi-storey stands (strata 1 and 3) were particularly susceptible to budworm-induced mortality. The understorey in stratum 1 was the most susceptible to budworm feeding. This increased level of mortality can be attributed in part to higher stem density and crown closure, combined with defoliation and understorey tree suppression. We noted differential impacts from budworm defoliation on the four canopy layers within this stand type. During outbreak periods, understorey tree mortality was common (L.E. Maclauchlan, personal observation, 1994) when larval densities were very high, causing 100% defoliation of trees in a single season.

The lowest percent mortality within each biogeoclimatic subzone, across layers 1 and 2 (the overstorey), was observed in low-density stands, of primarily even height and equally distributed stems having small crowns (stratum 2). High comparative understorey mortality (i.e. regeneration), particularly in these low-density stands (stratum 2) could negatively impact future harvest schedules and volume expectations. Although understorey mortality was very high in stratum 1 stands, this stand structure could be regarded as more resilient to chronic budworm events due to the greater stem density in all layers. The high-density, multi-layered stands (stratum 1) experienced patchy tree mortality and the remaining stems were not necessarily of good quality or vigorous in nature (L.E. Maclauchlan, personal observations).

Insect outbreaks appear to be increasing in extent, severity, and duration (Swetnam et al. 1995; Maclauchlan et al. 2006). In 1987, southern BC experienced the most extensive western spruce budworm outbreak ever recorded, covering approximately 821 360 ha (Erickson and Loranger 1987; Maclauchlan et al. 2006). During this outbreak, the budworm expanded into areas where it had never previously been recorded. A GIS overlay analysis examining past occurrence of budworm in the study area (former Kamloops Forest Region) revealed that the IDF biogeoclimatic zone was most affected by WSB (Maclauchlan et al. 2006) and where Douglas-fir occurs within the PP biogeoclimatic zone, defoliation was very severe and sustained. In the PP ecosystem, Douglas-fir has been encroaching due to fewer fire events (Taylor and Baxter 1998). The PP zone is often typified by very dense understorey and intermediate regeneration, the two layers most susceptible to WSB. However, this zone does not represent a significant proportion of the Douglas-fir dominated land base in the Kamloops Forest Region (255 000 ha).

The average total number of years of defoliation did not vary greatly between the IDF and PP zones; however, the average maximum consecutive years of defoliation was consistently longer in the IDF. This observation substantiates the fact that Douglas-fir is the primary host tree species in this ecosystem and thus is able to sustain longer and more intense budworm events than the Ponderosa Pine biogeoclimatic ecosystem where ponderosa pine predominates (Miller and Maclauchlan 1998). Douglas-fir occurs in mixes with other tree species within the ICH biogeoclimatic zone, thus preventing the budworm from reaching the high population densities seen in pure Douglas-fir stands typical of the IDF biogeoclimatic zone. There may also be differences in foliage quality for feeding budworms within these ecosystems (MacKinnon and MacLean 2003). Douglas-fir stands in the ICH zone tend to be more even-aged with a single canopy rendering them susceptible to budworm (Magnussen et al. 2004) but able to sustain larger populations without incurring significant impact. The moister climatic conditions of the ICH zone are less conducive to extended budworm outbreaks than the drier conditions of the IDF zone (Brookes et al. 1985).

Specific subzones within affected biogeoclimatic zones were more impacted by the western spruce budworm than others. The IDFdk, IDFxh, and IDFmw all had high levels of defoliation, whereas only the IDFxh suffered very high mortality levels, even in the overstorey trees. The very high levels of defoliation in the IDFdk, did not cause mortality but could have long-term impacts due to repeated defoliation events. These results confirm many anecdotal observations that have been made regarding the impact of budworm in multi-storied stands made by foresters and entomologists working in Douglas-fir forests in southern interior British Columbia. Most of the stands categorized as stratum 3 were partially harvested in the 1950s. This period of logging was typified by the removal of the largest overstorey trees with little regard for the remaining stand and future understorey regeneration.

Specific subzones within affected biogeoclimatic zones were more impacted by the western spruce budworm than others. The IDFdk, IDFxh, and IDFmw all had high levels of defoliation, whereas only the IDFxh suffered very high mortality levels, even in the overstorey trees.

Consequently, resultant stands were often of poor quality and vulnerable to budworm.

Multi-layered stands can support high budworm populations and thus may cause elevated levels of defoliation, particularly in the understorey layers. Multi-layered, high-density stands have an abundance of available new foliage for budworm larvae. As larvae feed, they descend via silken threads from overstorey branches to lower canopy foliage. Budworm larvae are more likely to encounter suitable host resources in these structurally diverse stands than in juvenile spaced or single-structure stands where they more typically fall to the ground and die (Fellin 1985).

Differences in Douglas-fir density became clear when stratum 3 (selectively harvested) plots from historically defoliated sites were compared to those without recorded defoliation. Douglas-fir density was 50% less in the IDF subzone with known western spruce budworm outbreaks than in the same subzone with no recorded history of WSB. This could be explained in part by higher volumes being removed by selective harvesting, as evidenced by remaining stumps in budworm-affected stands.

The majority of stands classified as having no recorded history of budworm were located in the southwest portion of the region between Princeton and Merritt, BC. The IDFdk is quite fragmented in this area and is intermixed with other species such as spruce and lodgepole pine (Lloyd et al. 1990). Over the past few years, WSB has been active in these stands. The outbreak periodicity of WSB may be different in this geographic region (Shepherd 1985; Cooke and Lorenzetti 2006) or the mixture of species has obscured past outbreaks from aerial detection. Cooke and Lorenzetti (2006) found outbreaks of forest tent caterpillar, *Malacosoma disstria* Hubner, recurred periodically in Quebec and were not perfectly synchronized across the province. Alternately, the budworm may simply be expanding its range due to more favourable climate, recent drought conditions, and available and more susceptible hosts.

Future management of these susceptible forest types should consider changing climate regimes and how this may affect both the host, in terms of increased susceptibility, and the insect. Managing for lower densities through thinning or harvesting could ensure more resilient forest structure.

Management implications

Both western spruce budworm and selective harvesting have lasting effects on stand structure and forest health. Data derived from the plots demonstrated that the degree of damage caused by budworm was dependent upon several factors, in particular ecosystem, climate, and availability of susceptible host. The drier, hotter, Douglas-fir-predominated ecosystems suffered the most severe impacts from budworm and sustained longer and more frequent episodes of defoliation (Wulf and Cates 1985). The IDF ecosystem provides the climate most conducive to the success and fitness of western spruce budworm populations. This, combined with harvesting and silviculture practices that have encouraged dense understorey regeneration, has led to substantial areas of highly susceptible forests.

Future management of these susceptible forest types should consider changing climate regimes and how this may affect both the host, in terms of increased susceptibility, and the insect. Managing for lower densities through thinning or harvesting could ensure more resilient forest structure.

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Test Your Knowledge . . .

Influence of past forestry practices on western spruce budworm defoliation and associated impacts in southern British Columbia

How well can you recall some of the main messages in the preceding Research Report? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. Which ecosystems have the highest hazard for budworm defoliation and damage?
   - A) Moister ecosystems with predominantly single canopy structures dominated by Douglas-fir, such as the ICH
   - B) Dry, hot, multi-storied stands predominated by Douglas-fir, such as the IDF
   - C) Young, thinned stands in the IDF predominated by Douglas-fir

2. Compare stands that have never experienced a budworm event to stands with chronic budworm defoliation—what is the difference in stems per hectare of Douglas-fir between these two stand types?
   - A) Multi-storied stands with chronic budworm activity had on average 50% fewer Douglas-fir trees per hectare than stands with no budworm defoliation events
   - B) Stands with chronic budworm activity had on average 50% more Douglas-fir trees per hectare in the understorey than stands with no budworm defoliation events
   - C) Even-aged stands with chronic budworm activity had on average 50% fewer Douglas-fir trees per hectare than stands with no budworm defoliation events.

3. What are some "best management practices" for mitigating the effects of western spruce budworm impacts?
   - A) Manage drier Douglas-fir ecosystems for lower densities through thinning or harvesting, reduce structural components of the stand, and promote mixtures of species
   - B) Remove mature Douglas-fir overstorey to reduce the "raining" effect of budworm larvae on susceptible understorey Douglas-fir regeneration
   - C) Maintain a multi-structured stand with moderate to high layer-3 density to ensure a resilient stand structure

ANSWERS

1. B 2. A 3. A