MORTALITY AND TOP-KILL IN DOUGLAS-FIR FOLLOWING DEFOLIATION BY THE WESTERN SPRUCE BUDWORM IN BRITISH COLUMBIA

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ABSTRACT

Surveys of mortality and top-kill caused by the western spruce budworm, *Choristoneura occidentalis* Freeman, in 65 stands of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco are reported. Top-kill was detected in 85% of the stands and 25% of the trees surveyed. Mortality amounted to 8% and less than 1% of the trees examined in the Vancouver and Kamloops Forest Regions, respectively. Both frequency of top-kill and mortality were related to the number of years defoliation in the stand and were higher on suppressed trees than on dominant or codominant trees. Younger stands sustained a higher incidence of top-kill than older stands. Tree mortality was higher on steep slopes than on flat terrain. These results suggested that top-kill or mortality were the results of physiological stress on the trees, in addition to the debilitating effects of defoliation.

INTRODUCTION

The western spruce budworm, *Choristoneura occidentalis* Freeman, is a recurrent defoliator of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, in British Columbia (B.C.). The earliest documented infestation in B.C. occurred on southeastern Vancouver Island during the period 1909-1911 (Harris *et al.* 1985). Since then, six other infestations have occurred, mainly in the Pemberton, Fraser Canyon and Ashcroft areas.

The effects of budworm defoliation on tree growth in B.C. are recorded (Alfaro *et al.* 1982, 1984, 1985; Thomson *et al.* 1982; Van Sickle *et al.* 1983). Noticeable loss in diameter growth starts in the second year of defoliation; annual tree rings become progressively smaller with increasing duration of defoliation (Alfaro *et al.* 1982). Growth rate recovery to pre-infestation levels does not occur immediately after the decline of the infestation, but takes several years. Height growth is severely affected as well; repeated defoliation results in shorter or missing internodes or even in dieback or top-kill of the crown (Shepherd *et al.* 1977; Van Sickle *et al.* 1983). Depending on the severity of the top-kill (length and basal diameter of the dead part of the stem), large defects may develop in the bole, thus reducing its merchantability. The combined effect of height and diameter growth loss results in tree volume loss (Alfaro *et al.* 1985). Mortality is most frequent in trees of small diameter (Alfaro *et al.* 1982) and appears to be randomly distributed in the stand (Alfaro *et al.* 1984).

These previous studies were generally based on small samples in terms of the number of stands evaluated. Therefore, it was not possible to develop damage models of wide applicability. This report interprets damage surveys of top-kill and tree mortality on 65 Douglas-fir stands affected by the latest western spruce budworm epidemic in B.C. This infestation began in 1967, reached a maximum infestation area in 1976 and, on a reduced scale, continued in 1985. The surveys were conducted in 1979 by the Forest Insect and Disease Survey (FIDS) of the Canadian Forestry Service (Fiddick and Van Sickle 1979). Emphasis is on the study of the relationship between tree mortality or top-kill frequency on a stand basis *versus* defoliation history and stand characteristics.

METHODS AND MATERIALS

The areas of defoliation by the western spruce budworm were obtained from FIDS maps, then 65 stands of different duration and severity[1] of defoliation were selected throughout the infested area (Table 1). Thirty-seven and twenty-eight stands were in the Vancouver and Kamloops Forest Regions, respectively. About 100 trees were examined in each stand as follows: five sampling points, 20 m apart, were established along a transect line; at each point, about 20 trees, closest to the point, were selected. A total of 6594 trees were examined in all stands.

Each tree was examined to determine whether it was dead or alive. All trees that had died in recent years (as opposed to old kills and snags) were assumed to have been killed by the budworm. The length of top-kill, or severity, in each tree was estimated with the naked eye or with the aid of binoculars. Severity was classified as 0 (no top-kill), > 0 to 1 m, > 1 to 3 m, > 3 to 5 m, > 5 m. The percentage of dead trees (percent mortality) and percent-

[1]Aerial observers in B.C. classify defoliation severity according to the following criteria: *light*: discolored foliage barely visible from the air, some branch tip and upper crown defoliation apparent; *moderate*: pronounced discoloration, noticeably thin foliage, top third of many trees severely defoliated, some completely stripped; *severe*: bare branch tips and completely defoliated tops common, most trees more than 50% defoliated.

age of trees top-killed were calculated for each stand. The factors of slope, age, aspect, elevation, site quality (from forest cover maps) and number of years of defoliation were recorded for each stand.

Covariance and regression analysis were used to study the relationship between percent mortality and top-kill in the stand and the stand factors. For the analysis, the percent mortality and top-kill per stand were transformed to the arcsin (in radians) $\sqrt{p}$.

Regression model selection was based on examination of the data and residual plots, and on comparison of correlation coefficients. Only statistically significant correlation coefficients were reported. Differences in mean percentage top-kill and mortality by aspect and site quality were tested by covariance analysis (Dixon and Massey 1957), adjusting the means by the difference in number of years of defoliation among aspects or sites. One stand with high mortality (94% of the trees dead) was dropped from the analysis of top-kill data. The qualitative variables, site and aspect, were introduced in the regression as indicator or "dummy" variables (Wesolowsky 1976).

RESULTS AND DISCUSSION

Top-kill

Top-kill was detected in 85% of the stands. Forty-one percent of the stands had between 1 and 20% of the trees top-killed, 23% had frequencies between 21 and 40%, 12% had 41-60%, and 10% sustained greater than 60% top-kill (Fig. 1). Twenty-five percent (range 0 to 91%) of all trees examined in all stands showed top-kill.

Most of the damaged trees were in the > 0 to 1 m top-kill class (16% of the trees) (Table 2), 5% had top-kill in the >1 to 3 m length class, 3% in the >3 to 5 m class, and 1% in the > 5 m class. The proportion of trees in the different top-kill classes varied significantly among crown classes (Table 2) (χ^2 test, $P<0.01$). Percent top-kill was about the same among dominant and codominant trees, at 20 and 21%, respectively, but it was significantly higher (χ^2 test, $P<0.01$) for intermediate trees, at 25%, and much higher for suppressed trees, which had a 41% top-kill frequency. The higher incidence of top-kill among the suppressed trees is probably due to these

TABLE 1. Characteristics of 65 Douglas-fir stands defoliated by the western spruce budworm.

	Mean	Minimum	Maximum
Elevation (m)	782	300	1128
Slope (%)	21	0	80
Age (yrs.)	76	20	141
No. yrs. defoliation			
Light	3	0	5
Moderate	1	0	5
Severe	1	0	5
All Classes	5	2	8

TABLE 2. Percentages of Douglas-fir trees top-killed, listed by crown class and top-kill severity class (length of crown killed), in stands defoliated by the western spruce budworm.

Crown Class	Top-kill severity class (m)[1] > 0 - 1	> 1 - 3	> 3 - 5	> 5	All classes
Dominant	8	6	5	1	20 a
Codominants	10	6	4	1	21 a
Intermediate	20	4	1	0	25 b
Suppressed	37	3	0	1	41 c
All crown classes	16	5	3	1	25

[1] The percentage of top-killed trees varied significantly by top-kill severity and crown class (χ^2, P<0.01). Percentages within column followed by the same letter were not statistically different (χ^2, P>0.05)

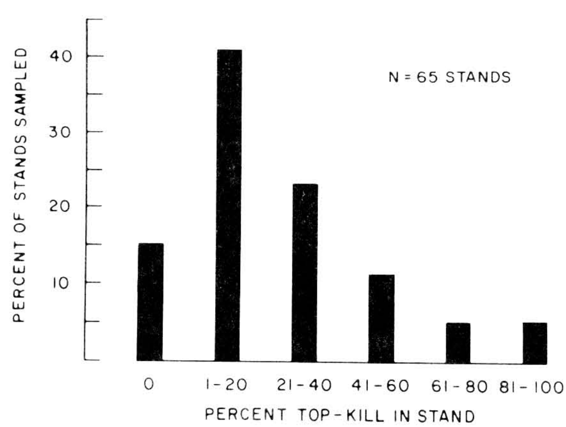

Fig. 1. Percentage of stands sampled by top-kill frequency class.

having smaller nutrient reserves than dominant or co-dominant trees and, therefore, being less able to withstand insect defoliation. Scott *et al.* (1980) arrived at a similar conclusion when studying top-kill frequency in Douglas-fir and Grand fir, *Abies grandis* (Dougl.) Forbes, in central Washington.

Percent top-kill in stands increased with the number of years of defoliation (Fig. 2). Regression analysis yielded the following model:

(1) ARCSIN $(\text{PTop-kill})^{1/2} = -0.16 + 0.12$ [No. years of defoliation]
$R^2 = 0.24$ and Se $= 0.29$, $F = 20.0$
where PTop-kill = percent top-kill in the stand/100.

This model indicated that, on average, with 2 to 7 years of defoliation, the expected top-kill levels in the stand were 1, 4, 10, 18, 28 and 39% respectively. Although the regression coefficient was significant, a considerable proportion of the variance remained unexplained. The regression did not improve when the number of years of severe defoliation in the stand was included instead of the number of years of defoliation.

Analysis of covariance indicated that, in addition to the number of years of defoliation, stand aspect and age explained a significant portion of the variability of top-kill percentage. Stands on North, West or South aspects had significantly lower percent top-kill (13 to 24%) than East (28%) aspects (Table 3). The reasons for this increased top-kill on East aspects are not clear. Top-kill had a significant negative correlation with stand age.

Although stands on poor sites had nearly double the percent top-kill (38%) of stands on medium (20%) or good sites (21%) (Table 4) the differences were not statistically significant. Stand elevation or slope did not influence the percent top-kill in the stand.

Average percentage top-kill was 27 and 18% in the Vancouver and Kamloops Regions, respectively. However, after adjustment by the difference in number of years of defoliation between the two regions, these two means were not statistically different (Table 5).

Mortality

Mortality was evident in 26 of the 65 stands sampled (40%) and averaged 4.9% of the trees in all stands sampled (range 0 to 94%). However, mortality was significantly higher in stands located in the Vancouver District, at 8%, than in stands located in the Kamloops District, which had less than 1% average mortality. Only three of the 28 stands in the Kamloops District sustained

TABLE 3. Percent top-kill and tree mortality, listed by aspect, in 65 Douglas-fir stands defoliated by the western spruce budworm.

Aspect	No. Stands	No. years defoliation	Top-kill[1] (%)	Tree mortality[1] (%)
North	8	4.4	13 (19)a	0 (2)a
West	4	5.0	23 (22)a	0 (0)a
South	42	5.2	24 (20)a	7 (6)a
East	11	3.9	28 (39)b	2 (5)a
All aspects	65	4.9	25	4.9

[1] Shown in brackets is the mean top-kill or mortality percent by aspect after removal of the effect of differences in number of years of defoliation by covariance analysis. Top-kill or mortality percentages within columns followed by the same letter were not statistically different.

TABLE 4. Percent top-kill and tree mortality, listed by site quality, in 65 Douglas-fir stands defoliated by the western spruce budworm.

Site	No. Stands	No. years defoliation	Top-kill[1] (%)	Tree mortality[1] (%)
Good	10	4.5	22 (25)a	1 (2)a
Medium	45	4.9	20 (20)a	5 (5)a
Poor	10	5.1	38 (37)a	7 (6)a
All classes	65	4.9	25	4.9

[1] Shown in brackets is the mean top-kill or mortality percent by site quality after removal of the effect of differences in number of years of defoliation, by covariance analysis. Top-kill or mortality percentages were not statistically different by site quality.

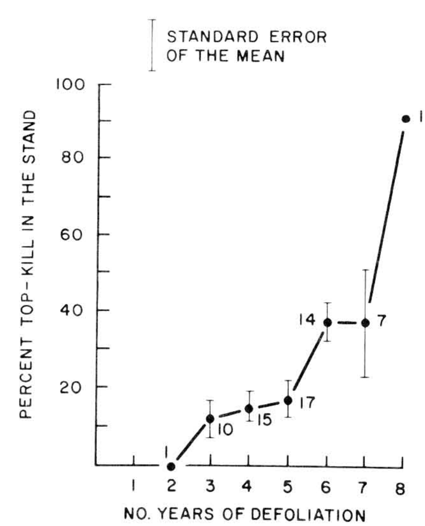

Fig. 2. Relationship between the percent top-kill in a Douglas-fir stand and number of years of defoliation by the western spruce budworm. Number of stands indicated beside each point.

mortality. The areas sampled in the Vancouver District included the steep slopes of the Fraser River Canyon which often coincide with poor sites and shallow soils. Trees growing under these conditions are probably under stress and are more prone to mortality.

Percent mortality also varied by crown class (χ^2 test, $P<0.01$, Table 6); suppressed trees suffered a significantly higher average mortality (8.4%) than other classes. Differences in mortality among intermediate (3.7%) co-dominant (4.7%) and dominant (5.2%) trees were not statistically significant. Increased mortality in both suppressed and intermediate classes was reported in 1982 by Alfaro *et al.* As with top-kill, the higher mortality in the suppressed trees is probably due to the fact that these trees are stressed from competition and are therefore unable to withstand defoliation.

The following models were developed:

(2) $\text{ARCSIN}(\text{PMORT})^{1/2} = -0.24 + 0.075$ [No. years of defoliation]
$R^2 = 0.20$ and $Se = 0.20$, $F = 15.6$
where PMORT = percent top-kill in the stand/100.

This equation indicated that mortality was expected if the stand was defoliated for more than 3 years. With 4 to 7 years of defoliation, the expected levels of tree mortality in the stand were 0.4, 1.8, 4.3 and 7.9%, respectively. This equation crosses the x-axis at No. years of defoliation = 3.2, therefore it is not defined for durations of defoliation less than or equal to 3 years. Although this relationship was significant, it explained only 20% of the variability in tree mortality in the stand. The correlation improved significantly when the number of years of severe defoliation was used as a predictor variable.

(3) $\text{ARCSIN}(\text{PMORT})^{1/2} = -0.004 + 0.133$ [No. years of severe defoliation]
$R^2 = 0.47$ and $Se = 0.16$, $F = 56.9$

This equation predicted that, with 1 to 7 years of severe defoliation, the levels of tree mortality were 2, 7, 15, 25, 38, 51 and 64%, respectively.

Percent mortality appeared to be higher on South (7%) or East aspects (2%) than on North or West aspects (negligible mortality) and also higher on medium (5%) or poor (7%) sites than on good sites (1%) (Tables 3, 4). However, after removal of the effects of different number of years of defoliation by covariance analysis, percent mortality did not differ statistically by site or aspect.

Stepwise multiple regression analysis between percent tree mortality in the stand and stand elevation, slope, aspect, age and number of years of defoliation, detected a significant effect only of slope and number of years of defoliation. Tree mortality was higher in stands with the steepest slopes.

CONCLUDING DISCUSSION

The fact that 85% of the stands and 25% of the trees sampled sustained top-kill suggests that top-kill is a major cause of growth loss and a source of stem defects in

TABLE 5. Percent top-kill and tree mortality in Douglas-fir stands defoliated by the western spruce budworm in two forest regions of British Columbia.

Region	No. Stands	No. Years Defoliation	Top Kill (%)	Mortality (%)
Vancouver	37	5.5	27	8.0
Kamloops	28	4	18	0.8
Total	65	4.9	25	4.9

TABLE 6. Percentage of Douglas-fir trees killed by western spruce budworm, listed by crown class, in stands defoliated by the western spruce budworm.

Crown Class	Total No. trees	No. dead trees	Tree mortality (%)[1]
Dominant	1394	72	5.2 a
Codominant	2208	103	4.7 a
Intermediate	2131	79	3.7 a
Suppressed	861	72	8.4 b
All trees	6594	326	4.9

[1] Mortality percentages within columns followed by the same letter were not statistically different (χ^2 test, $P>0.05$)

Douglas-fir defoliated by western spruce budworm. The negative correlation of top-kill with age, indicative of a higher susceptibility to top-kill in younger trees, is of particular importance since large defects in the lower bole may render any growth above the damaged point non-merchantable. Douglas-fir mortality averaged about 8% in the Vancouver District, with 5.2 and 4.7% of the dominant and codominant trees, respectively, killed by budworm (Table 6). Since these trees represent the future crop, mortality caused by budworm, although not so spectacular as that in eastern forests caused by the eastern spruce budworm, *Choristoneura fumiferana* (Clem.), should also be of concern to the western forest manager. Higher mortality was recorded among the supressed trees but because most of these trees would probably die before harvest, this volume loss can be considered unimportant.

The models presented could be used as a basis for the hazard rating of stand susceptibility to western spruce budworm damage and to calculate the possible outcome of infestations of different durations on particular stands. The high proportion of the variance that remained unexplained is not surprising in a study of this nature and suggests that other important factors are at work. Tree susceptibility to top-kill or mortality appears to be related to a stress condition. Other factors causing stress on trees, such as stand density, presence of other insects or diseases and climate during defoliation could also be important. Although this study did not provide statistical proof of top-kill or mortality variation by aspect or site quality, the data suggested that trees on steep, South and East slopes, and on poor sites are more susceptible (Tables 3 and 4). Further sampling is recommended to clarify this point.

ACKNOWLEDGEMENTS

I thank the Rangers of the Forest Insect and Diseases Survey, Pacific Forest Research Centre, Canadian Forestry Service, who collected most of the data.

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