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SPRUCE BUDWORMS HANDBOOK REGIONAL CLIMATIC PATTERNS AND WESTERN SPRUCE
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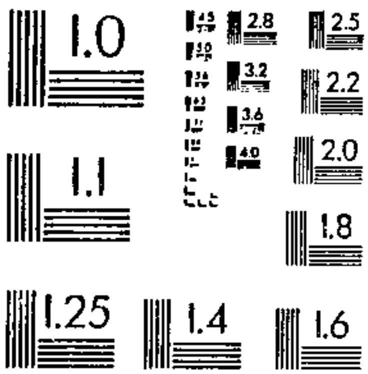

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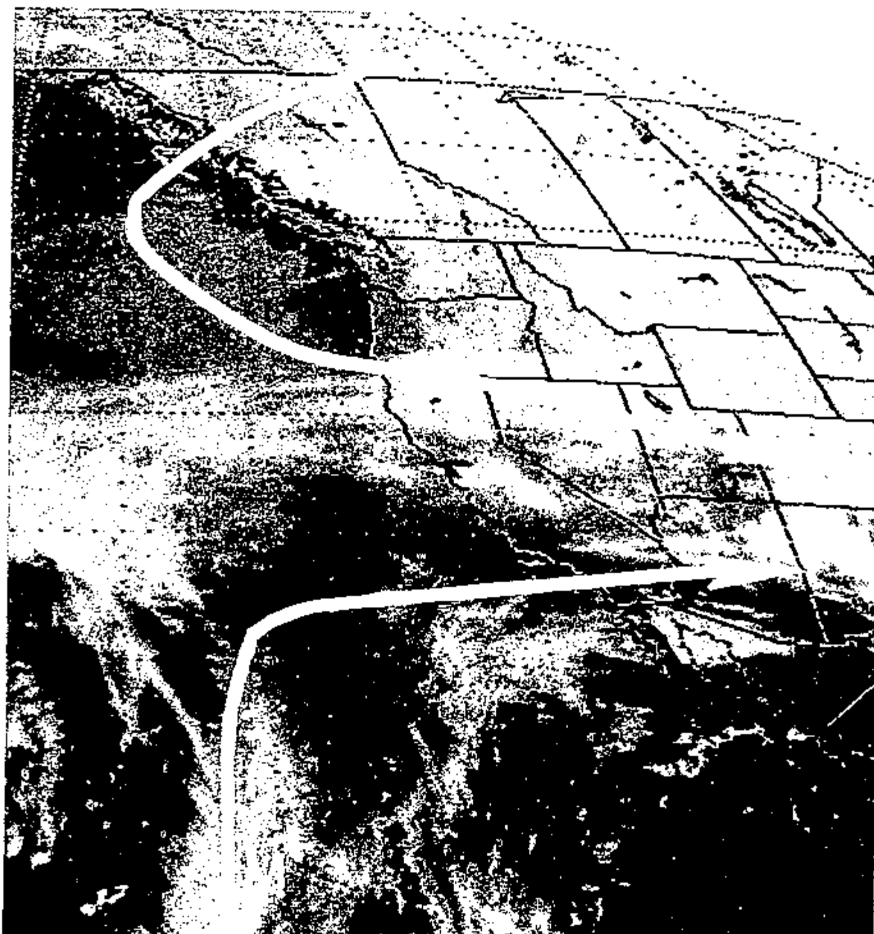
Spruce Budworms Handbook

Regional Climatic Patterns and Western Spruce Budworm Outbreaks



In 1977, the United States Department of Agriculture and the Canada Department of the Environment agreed to cooperate in an expanded and accelerated research and development effort, the Canada/United States Spruce Budworms Program (CANUSA), aimed at the spruce budworm in the East and the western spruce budworm in the West. The objective of CANUSA was to design and evaluate strategies for controlling the spruce budworms and managing budworm-susceptible forests, to help forest managers attain their objectives in an economically and environmentally acceptable manner. Work reported in this publication was funded by the Program. This manual is one in a series on the western spruce budworm.

canusa

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Spruce Budworms
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February 1985

Contents

Regional Climatic Patterns and Western Spruce Budworm Outbreaks

by William P. Kemp, Dale O. Everson, and W. G. Wellington[1]

Introduction

The western spruce budworm (*Choristoneura occidentalis* Freeman) has been reported in Western North America since the early 1900's, but only relatively recently have reasonably precise geographic locations been recorded (Dolph 1980; Fellin, personal communication;[2] Johnson and Denton 1975). The western spruce budworm reaches outbreak densities in only certain parts of its range, but the reasons for this pattern are still unknown.

Little information exists on budworm tolerance for climatic extremes. While evaluating the effects of late spring frosts on the spruce budworm (*C. fumiferana* [Clemens]) and its main host, balsam fir (*Abies balsamea* [L.] Mill.), Blais (1981) found that temperature extremes killed more host foliage than insects. Fellin and Schmidt (1973) found that unseasonably low temperatures in Montana (< 21 °F [−6 °C]) during June 1969 reduced western spruce budworm densities and subsequent defoliation.

Few studies relate specific climatic events to budworm physiology or behavior. Recently, scientists have investigated growth rates of budworm as a function of accumulated heat units or degree-days and have generated developmental curves for the spruce budworm and its hosts (Bean 1961, Bean and Wilson 1964, Cameron and others 1968, Ives 1974, Miller and others 1971). Similar procedures have yielded developmental curves for western spruce budworm (Wagg 1958).

On a larger scale (Provincewide), Ives (1974) found that population fluctuations in the spruce budworm were correlated with heat units above 39 °F (4 °C) and below 64 °F (18 °C) during the overwintering period and above 50 °F (10 °C) during the 6 weeks after peak third instar. Ives obtained data from 48 locations across Canada. In Quebec and New Brunswick, Blais (1957, 1968) associated dry summers and suitable host densities as generally predisposing forests to budworm infestations. Wellington and others (1950) described a predictable pattern of climatic events that consistently preceded spruce budworm outbreaks in Ontario during the previous 50 years. Clancy and others (1980) also correlated temperature and precipitation with jack pine budworm (*C. pinus* Freeman) populations and defoliation in Wisconsin.

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In northwest Montana and northern Idaho, Hard and others (1980) found that defoliation by the western spruce budworm during an infestation varied directly with mean maximum temperatures during May, June, and July of the previous year and inversely with the frequency of days with measurable precipitation during that same period. Twardus[3] found that warm, dry periods often precede western spruce budworm outbreaks and that such events appear to be required for outbreaks in north-central Washington. Reviews by Johnson and Denton (1975) and Ives (1981) also show the importance of direct climatic influences on outbreak development and collapse. After observing a specific western spruce budworm infestation in British Columbia, Silver (1960) suggested that infestation collapse is related to increased precipitation.

[3]Twardus, D. B. Evaluation of weather patterns in relation to western spruce budworm outbreaks in north central Washington. Unpubl. misc. rep. 1980. 16 p. On file at: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Portland, OR.

In relating climate to western spruce budworm outbreak frequency, little has been done to identify large-scale regions where outbreak behavior was similar, as has been done with other insects (for example, Cook 1924, 1929; Shelford 1926).

This study was designed to test the hypothesis that, if climatic characteristics are important to budworm development and survival, then regional outbreak frequency should be related to regional climatic conditions. The specific objectives were to

- Obtain historical weather and western spruce budworm defoliation records for Idaho, Montana, Oregon, and Washington;
- Develop an index to explain local variations in defoliation frequency (frequency of outbreaks) from about 40 sample locations;
- Compare selected climatic and forest-cover-type variables between western spruce budworm outbreak-frequency classes; and
- Develop a model to predict outbreak-frequency class of any point in the four-State area as a function of climatic characteristics of each point.

Methods

Development of Outbreak-Frequency Classes

Forty-three sample locations, distributed as evenly as possible through Idaho, Montana, Oregon, and Washington, subject to the proximity of proper forest-cover types, and completeness of data on defoliation (1948–78), were selected for analyses (fig. 1). Initial criteria for selection were locations of National Oceanic and Atmospheric Administration (NOAA) weather stations. At each point a "zone of influence" was established to assess annual defoliation patterns, consisting of the area within a 13.0-mi (20.9-km) radius of the selected location. The climate as measured at each weather station was considered to represent the general climatic features within each zone. This procedure was much more conservative than those in other studies (for example, Cramer 1962) and existing NOAA methods used to develop temperature and precipitation isoclines (NOAA 1968).

Within the zone of influence for each of the selected locations, the presence or absence of budworm defoliation was determined for each year where regional defoliation maps existed. This zone of influence provided a standardized assessment of defoliation around a point each

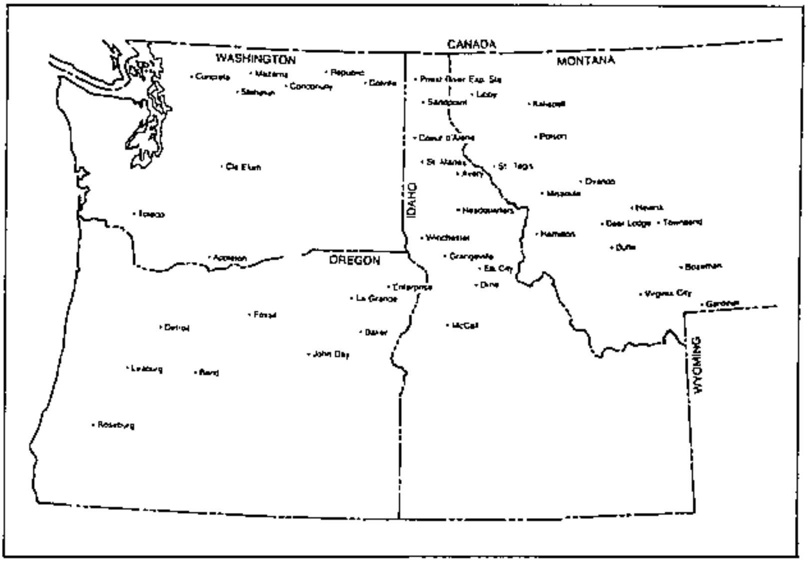

Figure 1—Location of 43 points in Idaho, Montana, Oregon, and Washington used to develop outbreak-frequency classes.

year. Most of the defoliation maps used were developed through aerial defoliation surveys. Aerial surveys are considered sensitive to defoliation in excess of 20 percent of the current foliage (Twardus, personal communication[4]). Budworm defoliation of less than 20 percent is likely to be missed by aerial surveyors. The zone of influence design therefore provides information on only those areas where the budworm populations have increased to densities causing more than 20-percent defoliation. For this analysis, if any area within the zone of influence in a given year had recorded defoliation, it was considered to be an "outbreak" year (that is, was recorded as 0 = no defoliation or 1 = defoliation) (fig. 2).

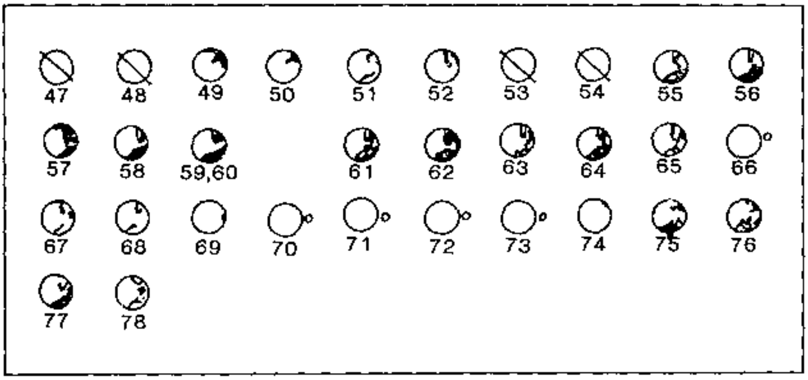

Figure 2—Historical western spruce budworm defoliation trace at Bozeman, MT, for the years 1947–78. ¢ = no data available. ○ = no defoliation. Blackened areas delineate defoliation as observed from the air.

Next, a defoliation-frequency index was developed for each point based on all years when defoliation was recorded. The following equation was used:

$$\text{Proportion of years with defoliation at a point} = \frac{\text{Number of years where defoliation occurred in the zone of influence}}{\text{Total number of years where defoliation was measured in the zone of influence}}$$

[4]Daniel B. Twardus, USDA Forest Service, Forest Pest Management, 180 Canfield Street, Morgantown, WV 26505.

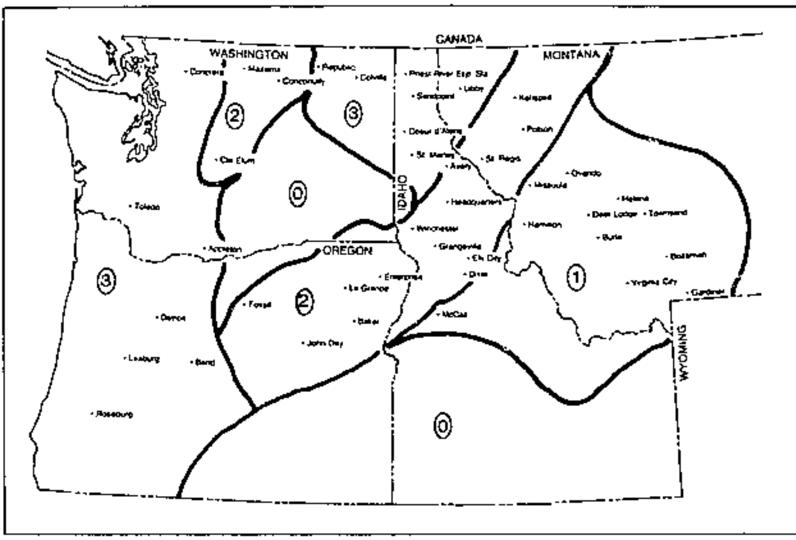

Figure 3—Three classes of outbreak frequency (1947–78) developed for forested areas of Idaho, Montana, Oregon, and Washington (high = 1, medium = 2, low = 3).

The defoliation index can thus range from 0 to 1.00. This value, developed for each point, served as a basis for classifying forested areas of Idaho, Montana, Oregon, and Washington into three arbitrary classes related to outbreak frequency (fig. 3). Points in outbreak region 1 (high outbreak frequency) had values between 0.60 and 1.00; areas classified as 2 or medium outbreak frequency had values between 0.07 and 0.48; and areas classified as 3, or low outbreak frequency, had values between 0 and 0.11 for the proportion of years when defoliation was recorded. The slight overlap in the ranges—of the proportion of years where defoliation was recorded between classes—is considered acceptable because the procedure was designed to give general class/region information.

Selection of Climatic Variables

To evaluate the general range of climates associated with the three classes of outbreak frequencies, a series of acetate map overlays was applied to a base map of the outbreak classes in the four States. These overlays were

- The Society of American Foresters (SAF) cover types (map from Eyre 1980);
- Mean annual precipitation isoclines (map from NOAA 1968);
- Mean maximum and minimum temperature isoclines for July (map from NOAA 1974); and

• Mean maximum and minimum temperature isoclines for January (map from NOAA 1974).

Next, 335 points were selected from a grid representing a systematic sample across the four States (each grid cell = 900 mi^2 [23 310 ha]). For each point on the grid, outbreak-frequency class (1–3, fig. 3), SAF forest-cover type, mean annual precipitation (inches), mean maximum and minimum temperatures for July (°F), and mean maximum and minimum temperatures for January (°F) were recorded. Those climatic variables selected were the ones generally used in regional climatological descriptions (NOAA 1968, 1974). Before any analyses, all 335 points were sorted by SAF forest-cover type. Any points located in nonforest-type areas (Eyre 1980) were flagged and omitted from further analyses.

Two types of analytic procedures were used. Climatic data by outbreak class were first compared using a Kruskal-Wallis nonparametric one-way analysis of variance (Siegel 1956). This step determined whether a significant difference occurred among the outbreak classes for each climatic variable. If the Kruskal-Wallis test was significant, a Mann-Whitney U-test was used to make all pairwise comparisons to determine which outbreak classes were significantly different by climatic variable (Siegel 1956). The second analytical procedure was discriminant analysis (Marriot 1974). This procedure, which is essentially a special case of multiple linear regression, was used to build a model to predict the outbreak classification (that is, high, medium, or low outbreak frequency) as a function of the climatic characteristics of a selected point.

Results and Discussion

Restricting the analysis to only those grid points that fell in forested areas reduced the total number of points to 169. Of these, 39 points fell within the high outbreak-frequency classification (class 1, fig. 3). Fifty-two points were in areas designated as medium outbreak frequency (class 2, fig. 3), and 78 points fell within the low outbreak frequency classification (class 3, fig. 3).

The first step was to identify differences, if any, between outbreak-frequency classes by examining the same climatic variables in each class. Figures 4 and 5 show frequency plots for January mean maximum and minimum temperatures for each of the outbreak-frequency classes. Medians and ranges for each variable by outbreak-frequency class are contained in table 1.

A progressive increase appears in both the January mean maximum and minimum temperatures from high to low outbreak-frequency

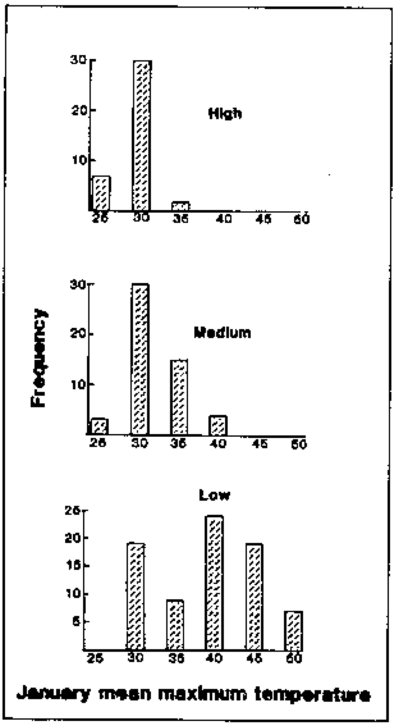

Figure 4—Distribution of January mean maximum temperatures for points in three outbreak-frequency classes (°F).

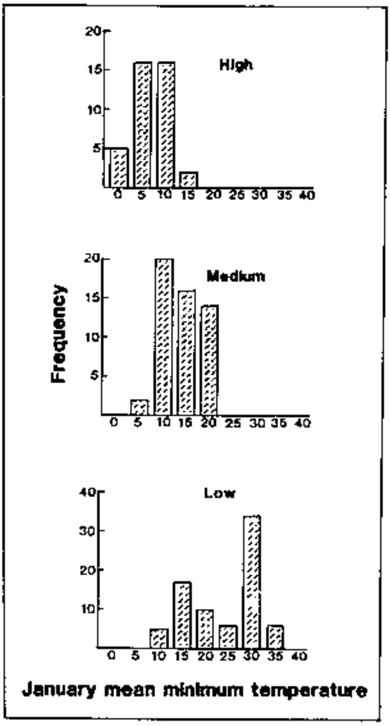

Figure 5—Distribution of January mean minimum temperatures for points in three outbreak-frequency classes (°F).

Table 1—Median values and ranges of five selected climate variables by outbreak-frequency class[1]

Variable	Outbreak class High (class 1)	Medium (class 2)	Low (class 3)
	°F		
January mean maximum temperature	Median = 28	32	40
	Range = 24–34	24–42	28–50
January mean minimum temperature	Median = 4	16	28
	Range = (−2)–14	4–22	10–36
July mean maximum temperature	Median = 80	84	80
	Range = 72–88	72–92	63–88
July mean minimum temperature	Median = 44	48	48
	Range = 36–54	40–56	36–54
	Inches		
Mean annual precipitation	Median = 20	24	40
	Range = 10–40	12–64	12–120

[1]To convert these temperatures to °C, subtract 32 from the °F and divide that figure by 1.8. To convert inches of precipitation to cm, multiply inches by 2.54.

classes. A Kruskal-Wallis nonparametric one-way analysis of variance showed significant differences between all variables by outbreak-frequency class (table 2). An all-pair Mann-Whitney U-test indicated that, with January maximum and minimum temperatures, all possible pairs were significantly different (table 3).

Forested regions that had the coldest January temperatures thus had the highest frequency of outbreaks (table 1). Conversely, forested areas that had significantly higher mean maximum and minimum temperatures were associated with reduced budworm activity.

Table 2—Results of a Kruskal-Wallis test (chi-square approximation). Tabular values are rank generated from a one-way nonparametric ANOVA design for each variable across budworm outbreak class.

Variable	Outbreak class[1]		
	High (class 1)	Medium (class 2)	Low (class 3)
January mean	Mean score = 38.31	73.39	116.75
maximum temperature	Rank = 3	2	1
January mean	Mean score = 25.31	74.17	122.06
minimum temperature	Rank = 3	2	1
July mean	Mean score = 85.33	106.43	70.54
maximum temperature	Rank = 2	1	3
July mean	Mean score = 54.24	88.18	98.26
minimum temperature	Rank = 3	2	1
Mean annual	Mean score = 53.74	71.01	109.96
precipitation	Rank = 3	2	1

[1]Classes within variable that are not significantly different are subscripted by identical letters ($\alpha = 0.05$).

Table 3—Results of an all-comparisons Mann-Whitney U-test (two-sample test). Tabular values show rank order (largest sum = 1, smallest sum = 3) from Kruskal-Wallis test (table 2). Pairwise comparisons were made within variables between classes.

Variable	Outbreak class[1]		
	High (class 1)	Medium (class 2)	Low (class 3)
January mean maximum temperature	3	2	1
January mean minimum temperature	3	2	1
July mean maximum temperature	2_a	1	3_a
July mean minimum temperature	3	2_b	1_b
Mean annual precipitation	[2]3_c	2_c	1

[1]Classes within variable that are not significantly different are subscripted by identical letters ($\alpha = 0.05$).

[2]Classes significantly different at ($\alpha = 0.06$).

Figures 6 and 7 show frequency plots for July mean maximum and minimum temperatures by outbreak-frequency class. Table 1 shows the median values for these variables by outbreak-frequency class. A Kruskal-Wallis test again showed significant differences between classes for both July maximum and minimum temperatures (table 2). A Mann-Whitney U-test selected for all paired comparisons showed no significant difference between July mean maximum temperatures in the high and low outbreak areas (table 3) and none between July mean minimum temperatures in the medium and low classes ($\alpha = 0.06$). Relations between outbreak class and July mean maximum temperatures were not as clear as with January variables (table 3). Outbreak frequency appears to increase, however, as July mean minimum temperatures decrease.

Figure 8 shows plots of precipitation frequency for each of the three regional outbreak-

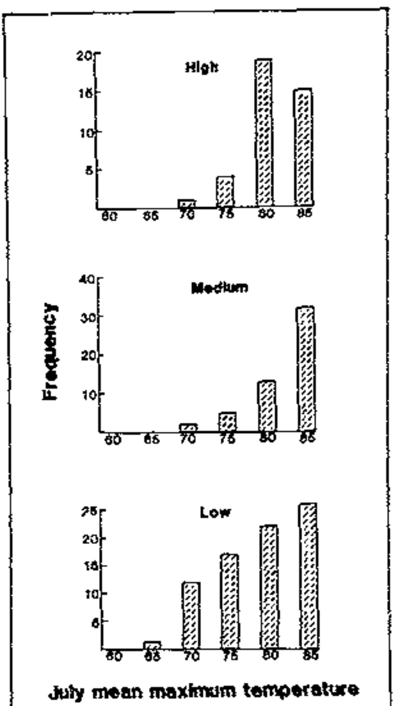

Figure 6—Distribution of July mean maximum temperatures for points in three outbreak-frequency classes (°F).

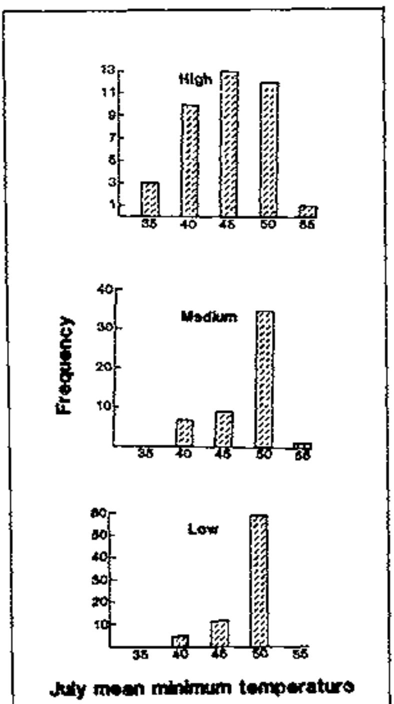

Figure 7—Distribution of July mean minimum temperatures for points in three outbreak-frequency classes (°F).

frequency classes. A Kruskal-Wallis test showed an inverse relation between annual precipitation and outbreak frequency (table 2). Mann-Whitney U-tests showed that annual precipitation was different in all classes (at the $\alpha = 0.06$ level) (table 3).

Although forest cover-types by outbreak-frequency class (fig. 9) were not tested for significance, these figures suggest a relation between forest conditions and a

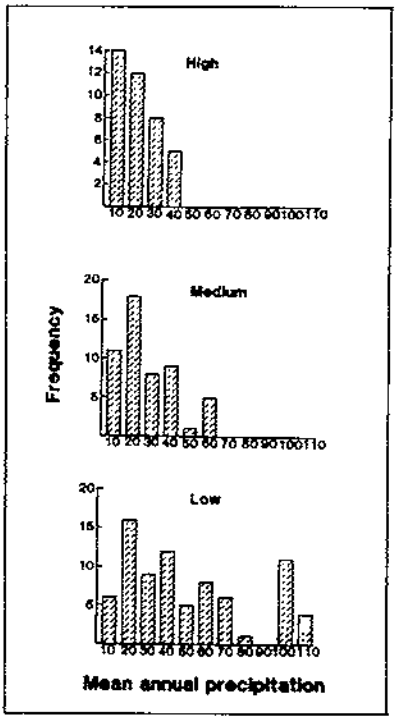

Figure 8—Distribution of the mean annual precipitation for points in three outbreak-frequency classes (inches).

decrease in precipitation from the low (3) to high (1) outbreak-frequency classes. Outbreak frequency class 1 points contained only Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), ponderosa pine (*Pinus ponderosa* Laws.), and lodgepole pine (*Pinus contorta* Dougl.) forest-cover types (figs. 3 and 9). Outbreak frequency class 2 points contained forest-cover types of fir–spruce (*Abies* spp.–*Picea* spp.), white pine (*Pinus monticola* Dougl.), larch (*Larix occidentalis* Nutt.), and pinyon–juniper (*Pinus* spp.–*Juniperus* spp.) (5 points) in addition to those forest types identified in class 1 (figs. 3 and 9). Lastly, a range of all cover types in this analysis was found in class 3, and a rather clear separation can be made between cover types based on mean annual precipitation (figs. 3 and 9). Douglas-fir and fir–spruce cover types were distributed throughout the precipitation range of outbreak class-3 points. Pinyon–juniper (only 2 points) occurred only in the lowest precipitation grouping. Ponderosa pine and lodgepole pine cover types were most common where annual precipitation was between 10 and 60 inches (25 and 60 cm). Larch and white pine cover types occurred where annual precipitation ranged between about 20 and 60 inches. The hemlock–Sitka spruce (*Tsuga* spp.–*Picea sitchensis*) cover type occurred

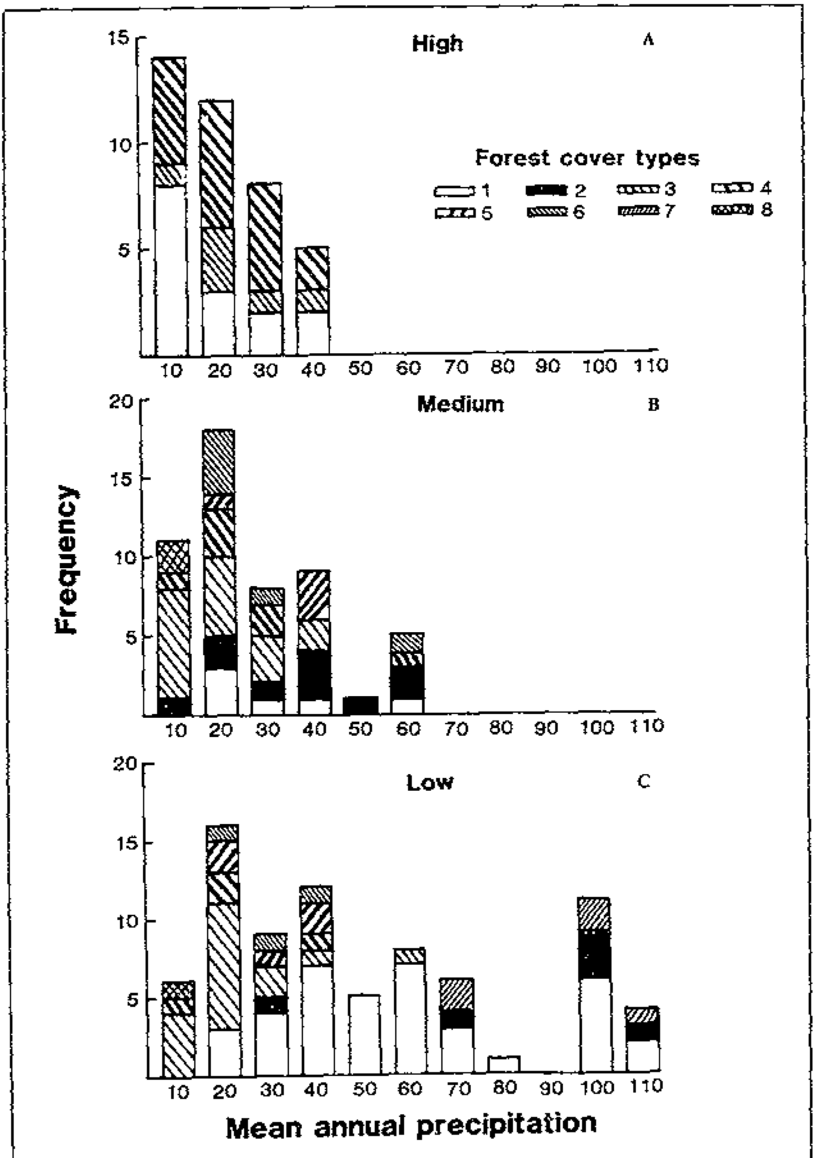

Figure 9—Distribution of the Society of American Foresters (SAF) forest-cover types for points in three outbreak-frequency classes (1 = Douglas-fir, 2 = fir-spruce, 3 = ponderosa pine, 4 = lodgepole pine, 5 = white pine, 6 = larch, 7 = hemlock-Sitka spruce, 8 = pinyon-juniper).

only at the wettest end of the scale, between, roughly, 70 and 110 inches (178 and 279 cm) annually.

The analyses suggest that the five climatic variables affected the outbreak frequency of the western spruce budworm in the four States evaluated (fig. 3). A discriminant analysis could thus be developed to predict outbreak-frequency class (1, 2, or 3) as a function of the five selected climatic variables: two discriminant functions were developed (table 4). A stepwise discriminant analysis design was used to select only the best predictors: four of the five possible variables were selected. In order of discriminating capability (from best to worst), the variables selected were January mean minimum temperature, July mean minimum temperature, January mean maximum temperature, and July mean maximum temperature. Mean annual precipitation, although significantly different by outbreak-frequency class (table 3), did not show sufficient discriminating power in the analysis conducted.

Table 4—Unstandardized canonical discriminant-function coefficients and summary statistics for a stepwise discriminant analysis developed to predict outbreak-frequency class as a function of climatic variables in Idaho, Montana, Oregon, and Washington

Unstandardized canonical discriminant-function coefficients

$$D1 = 3.110 + 0.024\,(JLMX) - 0.133\,(JLMN) - 0.098\,(JAMX) + 0.027\,(JAMN)$$

$$D2 = -13.766 + 0.152\,(JLMX) + 0.105\,(JLMN) - 0.142\,(JAMX) + 0.083\,(JAMN)$$

where JLMX = July mean maximum temperature
JLMN = July mean minimum temperature
JAMX = January mean maximum temperature
JAMN = January mean minimum temperature

Function	Eigenvalue	Percent of variance	Canonical correlation	Wilks' lambda	Chi square	Sig.
1	1.912	95.050	0.810	0.312	191.450	0.00
2	0.099	4.950	0.330	0.909	15.612	0.00

The discriminant functions were then used on the original data to develop a scatter diagram (fig. 10) that shows the separation between group centroids (1 = high outbreak frequency and so on). Although group points overlap, centroids show good separation. Table 5 shows the classification accuracy of the discriminant functions when used with original data. Of the actual 39 points in the high outbreak-frequency area (fig. 3), the discriminant functions correctly classified 31 in class 1 and classified the remaining 8 in class 2 (table 5). Forty of the actual 52 points from the medium outbreak-frequency areas were classed correctly and 9 and 3 were classed as high and low, respectively. The low outbreak-frequency area had 78 actual points, of which 56 were correctly classified as low and 22 were classified as medium (table 5).

One problem with the results in table 5 is that the accuracy of the prediction equation is tested with data used to develop the equations initially. In an effort to validate the

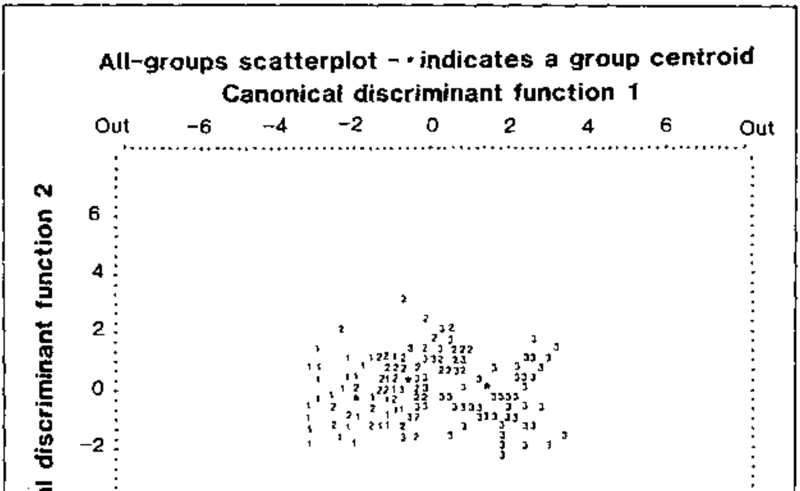

Figure 10—Scatter diagram developed when discriminant functions were used on the original data (outbreak frequency: 1 = high, 2 = medium, 3 = low).

Table 5—Classification results of a stepwise discriminant analysis developed to predict outbreak-frequency class as a function of climate variables in Idaho, Montana, Oregon, and Washington[1]

		Predicted outbreak-class membership		
Actual outbreak-frequency class	No. points	High (class 1)	Medium (class 2)	Low (class 3)
High (class 1)	39	31	8	0
		79%	21%	0%
Medium (class 2)	52	9	40	3
		17%	77%	6%
Low (class 3)	78	0	22	56
		0%	28%	72%

[1]The percentage of pooled cases correctly classified was 75 percent.

discriminant functions, the procedure of collecting data was repeated (see Methods) and a new set of 239 points was selected. From this validation set, climatic data were used with the discriminant functions in table 4 to predict outbreak frequency for each point. The estimates were compared to the classification of each point based on its location on the outbreak-frequency map (fig. 3). The discriminant functions correctly classified 74 percent of the points (table 6). Further, the percentage of correctly classified points (table 6) by outbreak-frequency class was similar to that found in table 5. The analyses suggest that the relations between

Table 6—Classification results using a validation-test data set with previously developed coefficients for discriminating outbreak-frequency class as a function of climate variables in Idaho, Montana, Oregon, and Washington[1]

		Predicted outbreak-class membership		
Actual outbreak-frequency class	No. points	High (class 1)	Medium (class 2)	Low (class 3)
High (class 1)	60	50	10	0
		83%	17%	0%
Medium (class 2)	75	9	56	10
		12%	74%	13%
Low (class 3)	104	1	31	72
		1%	30%	69%

[1]The percentage of pooled cases correctly classified was 74 percent.

outbreak-frequency classes (fig. 3) and climatic variables (table 3) are strong.

Because of the climatic differences identified between outbreak-frequency regions, two additional analyses were conducted. Data were collected from a subset of 17 NOAA weather stations that represented a sample from each of the three outbreak-frequency regions. Pooled within each region, data were collected on the number

Table 7—Median values and ranges for the number of days with temperatures of greater than 42 °F (5.5 °C) per month by outbreak-frequency class

Month	Outbreak class: High (class 1)	Medium (class 2)	Low (class 3)
January	Median = 4	3	14
	Range = 0–20	0–23	0–30
February	Median = 7	9	20
	Range = 0–22	0–27	0–29
March	Median = 12	21	25
	Range = 0–28	2–31	6–31
April	Median = 24	29	30
	Range = 5–30	6–30	21–30
May	Median = 30	31	31
	Range = 23–31	22–31	27–31
June	Median = 30	30	30
	Range = 27–30	29–31	25–30
July	Median = 31	31	31
	Range = 27–31	30–31	24–31
August	Median = 31	31	31
	Range = 28–31	28–31	19–31
September	Median = 30	30	30
	Range = 9–30	26–30	24–30
October	Median = 28	31	31
	Range = 16–31	22–31	21–30
November	Median = 14	16	25
	Range = 2–30	2–28	1–30
December	Median = 5	5	16
	Range = 0–19	0–26	0–30

of days above 42 °F (5.5 °C) and the accumulated number of degree-days per month.

Differences between the number of days above 42 °F throughout the year by region are shown for the subset of 17 stations in tables 7 and 8 and figure 11. For the months of June through September, essentially no regional differences occurred between the number of days where temperatures exceeded 42 °F (fig. 11, table 8). The two interesting parts of the year appear to be January through May and October through December. The region with highest outbreak frequency had the least number of days per month where temperatures exceeded 42 °F during the periods

Table 8—Results of an all-pairwise-comparisons Mann-Whitney U-test for 17 weather stations scattered throughout three outbreak-frequency regions. Variables compared between outbreak-frequency classes were the number of days per month that had recorded temperatures greater than 42 °F (5.5 °C). Tabular values are rank order based on Kruskal-Wallis tests (mean score values) within variable between class (3 = lowest, 1 = highest).

	Outbreak class[1]		
Month	High (class 1)	Medium (class 2)	Low (class 3)
January	3_a	2_a	1
February	3	2	1
March	3	2	1
April	3	2	1
May	3	2_b	1_b
June	3_c	2_c	1_c
July	2_d	1_d	3_d
August	2_e	1_e	3_e
September	3	2_f	1_f
October	3	2	1
November	3	2	1
December	3_g	2_g	1

[1]Within variable class ranks scored with like letter subscripts are not significantly different (α = 0.05).

January through May and October through December (fig. 11).

Differences between the number of accumulated degree-days (above 42 °F) per month throughout the year by region are shown in tables 9 and 10 and figure 12. Again, the region with the lowest outbreak frequency had the highest number of degree-days per month, September through December. Further, the region where outbreak frequency was the highest showed significantly lower degree-days during March through June.

Results of analyses presented in tables 7–10 and figures 11 and 12 suggest strong relationships between outbreak frequency and fall and spring temperature regimes. Warmer temperatures (October through May) in some way negatively affected outbreak frequency. Overwintering survival of second instars may thus be related to winter temperatures. If

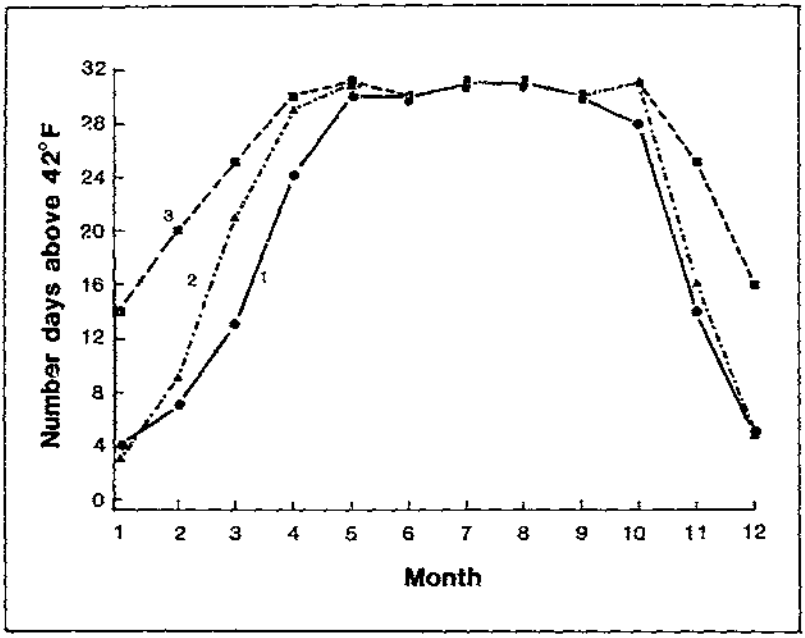

Figure 11—Number of days per month where temperatures exceeded 42 °F (5.5 °C) by outbreak-frequency class (1 = high, 2 = medium, 3 = low).

milder January temperatures, at or near the threshold for budworm development, were disruptive to diapausing larvae, reduced survival would be expected during the winter. This could occur through several theoretical pathways. Milder winter climates may result in the accumulation of fewer than the required number of chilling hours or degree-days for successful spring emergence (Hardman 1976, Ives 1981, Thomson 1979). Highly variable temperatures during the winter may initiate larval development too early as the result of a warming trend and cause increased mortality when temperatures fall below a critical level (Ives 1974, 1981; Thomson 1979). Lastly, milder winter temperatures may disrupt host–

Table 9—Median values and ranges for the number of degree-days (42 °F [5.5 °C] base) each month by outbreak-frequency class

Month	Outbreak class: High (class 1)	Medium (class 2)	Low (class 3)
January	Median = 0	0	0
	Range = 0–25	0–44	0–134
February	Median = 0	0	15
	Range = 0–22	0–75	0–178
March	Median = 2	10	36
	Range = 0–110	0–175	0-234
April	Median = 52	117	128
	Range = 0–223	0-263	2-373
May	Median = 241	296	332
	Range = 42–574	26–565	120–570
June	Median = 438	499	505
	Range = 207–788	57-734	222–732
July	Median = 687	717	686
	Range = 487–908	149–945	517–876
August	Median = 644	666	653
	Range = 401–906	305–999	447–992
September	Median = 347	402	475
	Range = 79–615	48–691	221–780
October	Median = 122	121	253
	Range = 12–333	1–394	29–438
November	Median = 6	8	55
	Range = 0–58	0–114	0–270
December	Median = 0	0	9
	Range = 0–32	0–32	0–137

insect synchrony in the spring and result in greater larval mortality (Eidt and Little 1968, 1970).

As noted, increases in mean annual precipitation were also associated with a reduction in outbreak frequency (table 3). The trend from low to high outbreak frequency was similar to that found with temperatures. This again suggests several possibilities. Host species in drier climates may be more prone to drought stress (Daubenmire 1968), and thus these areas will likely exhibit higher outbreak frequencies (Despain 1981, Sutherland 1983). Direct effects of increased precipitation on western spruce budworm at whatever stage may limit survival in a variety of ways and thus limit outbreak frequency (Ives 1981).

This discussion has dealt primarily with possible relations of individual climatic variables to outbreak frequency. The system is obviously not that simple. More likely, the climatic variables in tables 3, 8, and 10 give information on the large-scale differences between climates of the various regions depicted in figure 3. Much of the

Table 10—Results of an all-comparisons Mann-Whitney U-test for 17 weather stations scattered throughout outbreak-frequency regions. Variables compared between outbreak-frequency class were the number of degree-days per month (base of 42 °F [5.5 °C]). Tabular values are rank order based on Kruskal-Wallis tests (mean score values) within a variable between class (3 = low, 1 = high).

	Outbreak class[1]		
Month	High (class 1)	Medium (class 2)	Low (class 3)
January	3_a	2_a	1
February	3_b	2_b	1
March	3	2	1
April	3	2	1
May	3	2	1
June	3	2_c	1_c
July	2_{de}	1_d	3_e
August	3_f	1_f	2_f
September	3	2	1
October	3_g	2_g	1
November	3_h	2_h	1
December	3_i	2_i	1

[1]Within variable class ranks scored with like letter subscripts are not significantly different (α = 0.05).

high outbreak-frequency region (fig. 3) is considered to be influenced by continental air-mass movement (Arno 1970, USDA 1964, Wellington 1954). Low precipitation because of rain shadows—and cold winters—is characteristic of this region. Areas identified as low outbreak areas tend to have what is known as maritime climates and are associated with higher annual precipitation and milder winters (Arno 1970, USDA 1964, Wellington 1954). Though northern Idaho and the northeast corner of Washington are at the drier and cooler end of the maritime climate, they are still sufficiently different from harsher continental climates to the east and south. This fact is corroborated by the presence of white pine and grand fir (Daubenmire 1956). Lastly, the areas classified as medium outbreak frequencies fall into regions of convergence between major airmass types (that is, maritime versus continental) or in rain shadows in more northerly latitudes. These areas showed the most variability in outbreak frequencies and were correspondingly most difficult to

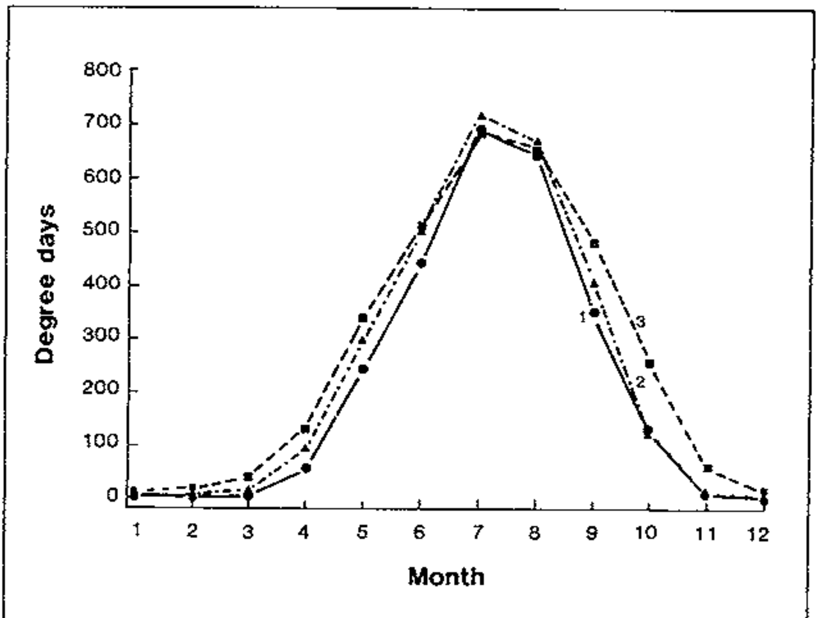

Figure 12—Number of degree-days (base 42 °F, 5.5 °C) per month by outbreak-frequency class (1 = high, 2 = medium, 3 = low).

classify in terms of climatic variables (tables 5 and 6).

From a managerial perspective, several relationships should be considered. Although regional differences noted above are mesoscale, they are a product of macroscale events that shift the complex of North American airmasses from time to time. This occurs as hemispheric circulation changes from virtually straight westerly flow to more meridional flow, adding more meanders in the upper westerlies and the associated midlatitude jetstreams. These deviations alter the size of the subcontinental areas dominated by polar maritime or continental air (figs. 13 and 14). Practically, searching for long series of historical examples is pointless. The current examples in figures 13 and 14 illustrate the important differences. Years have occurred—and will occur in the future—when the **seasonal** average position of the jetstream and its associated airmass regimes resemble the recent daily examples shown in figures 13 and 14.

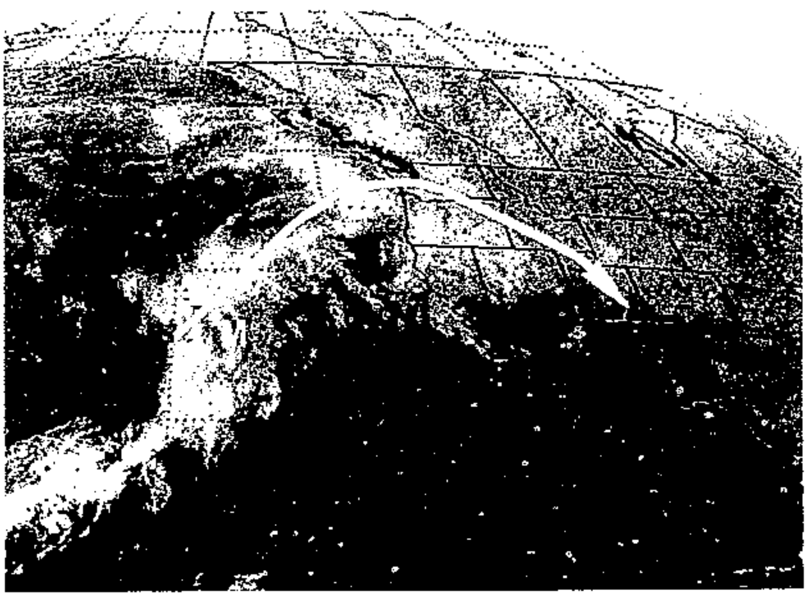

Figure 13—Satellite infrared imagery showing dominant maritime zonal airflow over the Pacific Northwest, December 29, 1983. The approximate position of the jetstream is drawn on the photograph. When the jetstream is in this position, a continual procession of maritime (M) airmasses is carried directly across the Pacific Northwest in the westerly circulation.

Although managers need at least a general understanding of the relations described above, monitoring winter and spring weather of their particular region is advisable (fig. 3) to keep track of the occurrence of relatively long periods (more than 2 weeks) of cold or dry weather. Such monitoring helps to translate upper air jetstream activity into biosphere temperature and precipitation data that can be used to assess the likelihood of increases or decreases in local western spruce budworm populations. If we combined such generalized weather information with present stand hazard-rating systems, we could measurably improve our present ability to forecast the onset of unacceptable defoliation by this insect.

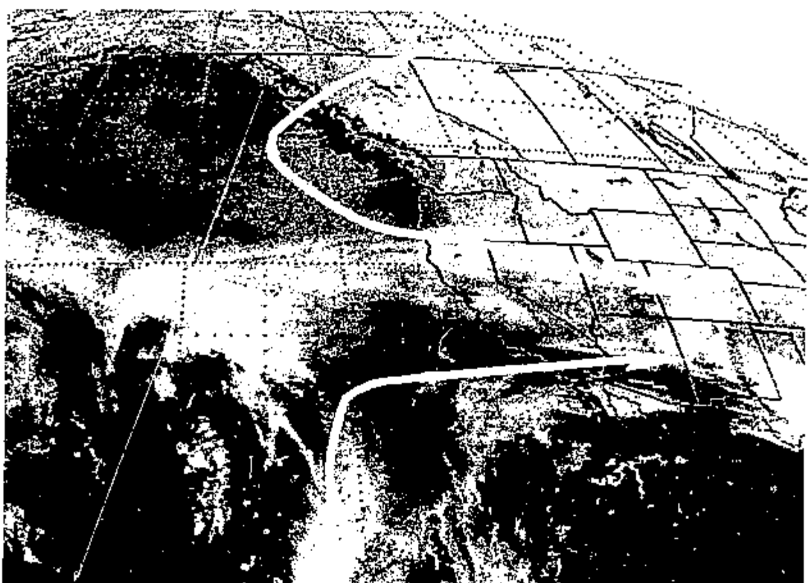

Figure 14—Satellite infrared imagery showing dominant continental arctic airflow throughout the Pacific Northwest, December 23, 1983. As before, the jetstream has been indicated on the photograph. Continental (C) air from the Arctic has invaded much of North America, preventing maritime (M) air from entering the Pacific Northwest. Instead the maritime air is deflected southward by this more meridional circulation pattern.

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To determine if the frequency of outbreaks of western spruce budworm (*Choristoneura occidentalis* Freeman) was related to selected climatic variables in Idaho, Montana, Oregon, and Washington, defoliation histories were collected for a sample of 43 points across the four States. Three broad regional compartments of differing outbreak frequencies were identified. Mean maximum and minimum temperatures for January and July, as well as mean annual precipitation data, were collected from a four-State, stratified sample of 169 points where susceptible hosts occurred. Significant differences in climate were found among the three classes of outbreak frequencies identified. A discriminant analysis was developed to predict the outbreak frequency of any point in the area as a function of the climatic characteristics of each point.

Keywords: Western spruce budworm, insect outbreaks, biometeorology, entomology, integrated pest management, forest management

END