Variation in Surface and Crown Fire Hazard With Stand Age in Managed Coastal Western Hemlock Zone Forests in Southwestern British Columbia

Michael C. Feller[1] and Stefanie L. Pollock[2]

Abstract*—Surface and crown fuels were measured in 186 stands ranging in age from 0 years after clearcutting to old-growth forests > 300 years old in Douglas-fir (*Pseudotsuga menziesii*) – western hemlock (*Tsuga heterophylla*) – western redcedar (*Thuja plicata*) – dominated forests in southwestern British Columbia. Indexes of surface fire hazard based on woody debris loads, and of crown fire hazard based on 5 factors (canopy foliar bulk density, height to live crown, woody debris loads, ladder fuels, and snag quantities), were developed. Using the indexes developed, surface fire hazard followed a U-shaped trend with stand age, being highest for the first few years after clearcutting, declining to a minimum 20 to 40 years after harvesting before increasing. Crown fire hazard was lowest for the first few years after clearcutting, rose to a maximum 20 to 90 years after harvesting and then declined to low values in 100 to 150 year old forest, before rising to higher values in old-growth. In the absence of fuel reduction treatments, some post-harvesting age classes of forests will have higher surface or crown fire hazards than old-growth forests.*

Introduction

Fuel management in forests of southern coastal British Columbia, dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*), in the recent past has been characterized by a dichotomy. On the one hand, in active forest harvesting areas, strips of old-growth forest were left between clearcut blocks partly because it was believed that the old-growth strips could serve as fuel breaks as they presented a lower fire hazard than the clearcuts (Grant 1984). On the other hand, in the water supply watersheds for the city of Vancouver, management involved clearcutting old-growth forests to produce younger plantations with a perceived lower fire hazard state (Economic and Engineering Services 1991). This raised the question of how fire hazard varied with forest age.

Forest fire hazard (a fuel complex defined by volume, type, condition, arrangement, and location, that determines the degree both of ease of ignition and of fire suppression difficulty (Forest Resources Development Branch 1986)) can be broken into two components – surface fire hazard and crown fire hazard – which are not necessarily correlated. Assuming surface fire hazard is directly related to surface fuel quantity, different trends with stand age in surface fire hazard have been reported. Brown and See (1981) described three different trends for lodgepole pine (*Pinus contorta*) as well as for subalpine fir (*Abies lasiocarpa*) forests in the U.S. Rocky Mountains – i) a general increase with age, peaking in old-growth, ii) an inverse U-shaped curve with a peak occurring in mature (110 – 160-year old) forests, and iii) a U-shaped curve

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[1] Associate Professor, Department of Forest Sciences, University of B.C., Vancouver, BC, Canada. feller@interchange.ubc.ca

[2] Graduate student, Département de biologie and Centre d'études nordiques, Université Laval, Québec, QC, Canada.

with maximum values occurring in the youngest as well as the oldest forests. Most studies have found U-shaped curves (Feller 2003), particularly in B.C. and the adjacent U.S. Pacific Northwest (Agee and Huff 1987; Fahnestock 1976; Spies and others 1988; Wells and Trofymow 1997).

In areas subjected to forest harvesting, surface fire hazard for the first few years after harvesting can be greater than at any other time in the life of a forest due to inputs of logging slash (Feller 2003; Wells and Trofymow 1997). Feller (2003) considered that a U-shaped curve could be the normal trend in surface fire hazard with forest age after harvesting, with deviations from this occurring for different reasons. For example, initial hazard may not be particularly high if initial post-disturbance inputs are low as a result of a severe fire, slow collapse of snags, or low pre-disturbance vegetation or surface fuel biomass. An inverse U-shaped curve may occur if thinning occurs or if tree mortality is particularly high during the mid-life period of a forest as a result of high tree densities, insects, disease or blowdown.

Surface fire hazard is likely to depend not only on the total surface fuel load, but also on the distribution of size classes and decay states of surface fuels (Baker 2003; Van Wagner 1983). Baker (2003) considered that large sound fuels are relatively unimportant to fire behaviour since they are usually not consumed, while large well-decayed fuels and fine fuels were considered important. Fine fuels may increase slowly after a fire for 150-200 years, and then decline, while large sound fuels, legacies of the pre-disturbance forest, generally decrease with time for long periods until they are replenished again (Baker 2003; Harmon and others 1986; Romme 1982). Van Wagner (1983) proposed that surface fire hazard in northern coniferous forests peaked before canopy closure and again in old-growth forests, primarily due to fluctuations in the quantity of fine fuels present.

Crown fire hazard depends on the ease of initiation and of propagation of crown fires. Van Wagner (1977) developed conceptual models of both initiation and propagation, and most subsequent work on crown fire hazard has used these models (for example, Cruz and others 2003; Scott and Reinhardt 2001). According to Van Wagner (1977), ease of initiation depends on the intensity of the surface fire, the height above the ground of the base of the live canopy, and foliar moisture content. Ladder fuels can be considered to either increase the surface fire intensity or increase flame length (Alexander 1988), or decrease canopy height (Van Wagner 1993), facilitating crown fire initiation. Once in the crowns, ease of propagation depends on the bulk density of available fuel in the canopy as well as rate of spread of the fire which in turn, depends on wind speed. Scott and Reinhardt (2001), using Van Wagner's (1977) conceptual models, developed a quantitative Torching Index and Crowning Index, but did not sample surface and crown fuels across all forest ages. The Canadian Fire Behavior Prediction System indicates that crown fire intensity and spread rate are greater in immature than in mature lodgepole pine forests for a given set of fuel moisture conditions (Forestry Canada Fire Danger Group 1992). No study, however, appears to have determined an index of crown fire hazard for an entire range of age classes of a forest, although Van Wagner (1983) has proposed that crown fire hazard was greatest in young stands with closed canopies, then decreased before increasing again in old-growth stands. Fahnestock (1976), using fire hazard keys, reported a similar trend in subalpine fir – false box (*Pachistima myrsinities*) forests in north central Washington, but Hawkes (1979), using Fahnestock's keys, found little difference in crowning potential between young and old-growth stands in Canada's southern Rocky Mountains in Alberta.

Due to the contrasting beliefs about the fire hazard in old-growth versus managed forests and the lack of quantitative data on successional changes in forest fire hazard in southwestern British Columbia, this study was begun in 1994 with the objective of determining the relative surface and crown fire hazards of old-growth forests, and those arising from a forest harvesting regime.

Study Area

The study occurred in the Coastal Western Hemlock biogeoclimatic zone of southwestern British Columbia, within 50 km from the city of Vancouver, specifically in the dry maritime (CWHdm) and very wet maritime (CWHvm) biogeoclimatic subzones (Meidinger and Pojar 1991).

A total of 186 study plots, each approximately 0.5 to 1 ha in size, were located in old-growth forests and adjacent areas that had been clearcut up to 80 years previously, or burned from 80 to 150 years previously. No stands aged 151 to 250 years old were sampled due to their unavailability. All stands older than 250 years, regardless of their actual age, were classed as old-growth. Clearcuts up to 60 years old had not been subjected to any slash disposal treatment and had mostly been planted with Douglas-fir. All forests were dominated by western hemlock, western redcedar, and Douglas-fir and, at higher elevations, Pacific silver fir (*Abies amabilis*) as well. All study plots were located on sites intermediate in moisture and nutrient status to avoid the confounding factor of site variability.

The CWHdm and CWHvm subzones have wet mild climates, with mean annual precipitation of 1800 to 2800 mm, most of which is rain, and mean annual temperatures of 8 to 10° C. All months have mean temperatures > 0° C. Due to the high forest productivity resulting from this climate, relatively long intervals between fires, and the presence of slowly decaying western redcedar, old-growth CWH forests generally contain the greatest surface fuel loads of all B.C. old-growth forests (Feller 2003).

Methods

Field Measurements

Within each study plot, 3 surface fuel plots and 3 crown fuel plots were randomly located. Each surface fuel plot consisted of an equilateral triangle with 20 m or 30 m sides, depending on fuel load and spatial orientation of the study plot. The mass of all surface woody fuels > 1 cm diameter was determined using the line intersect technique (Van Wagner 1968) measuring along the sides of the triangles. Each piece measured had its species or decay state recorded. Volumes calculated from the line intersects were converted to masses using relative densities determined for each size class (1.l-3.0, 3.1-5.0, 5.1-7.0, 7.1-12.0, and > 12 cm) for each species and decay class present. Nine to 32 samples per size class for each species or decay class were cut from randomly chosen woody materials and taken to the laboratory for density analysis. Fine fuels (≤ 1 cm diameter) were collected from nine 1 m^2 plots, each located 2 m away from each triangle apex along a line projected outwards from the centre of the triangle.

Each crown fuel plot consisted of a 20 x 20 m or 20 x 10 m plot, depending on spatial orientation of the study plot. Within each crown fuel plot, the species and d.b.h. of every tree present was measured. The dominance class and state of decay of each snag present were also recorded. Canopy volume was estimated by multiplying surface area by crown length, which was measured as the difference between the height to the base of the live crown and the height to the top of the tree canopy, with 1 to 3 measurements per crown fuel plot. Relative ladder fuel amount was estimated visually using a 6 category system. Ladder fuel was considered to be any dead woody material or small conifers occurring between the surface fuel bed (up to 1.5 m above the ground) and the live canopy.

Stand age was determined from forest cover maps where known, or from counting rings in cores extracted from 2 to 3 of the largest trees in each crown fuel plot.

Laboratory Procedures

Surface fuel materials—Relative densities of all woody materials were measured using a water displacement technique and an average value calculated per size class and species or decay class. Fine fuel samples were dried at 100 °C for 24 to 48 hours, then weighed. An average fine fuel mass was calculated from each of the nine samples collected per study plot.

Crown fuel data—For each study plot, an average canopy foliar bulk density, height to the base of the live crown, and relative ladder fuel quantity were calculated from the 3 crown fuel plot values. Canopy foliar bulk density was calculated by dividing the total foliage mass in a plot by the measured crown volume. Foliage mass was estimated by applying foliar biomass equations to the d.b.h. values of all trees measured in a plot. These equations had either been developed by M. Feller or were obtained from Gholz and others (1979).

Development of a surface fire hazard index (SFHI)—Surface fire hazard was considered to depend on the quantity of surface fuels present, particularly on fine fuels (≤ 1 cm diameter). It was assumed that a surface fire was unlikely to start if no fine fuels were present. The surface fire hazard index (SFHI) chosen was

$$\text{SFHI} = \text{FF}\ (1 + \text{CWD})$$

where FF is the quantity (kg/m^2) of fine fuels present, and CWD is the quantity (kg/m^2) of coarse woody debris (materials > 1 cm diameter). The study plots were placed into different age classes then the average SFHI was calculated for each age class. To test the sensitivity of the changes in SFHI with age to different age class groupings and different relative weighting of FF and CWD, the average SFHI was calculated for combinations of six different age class groupings (table 1) and nine different FF/CWD weightings. Thus, for SFHI = FF [1 + a(CWD)], "a" varied from 10 to 0.01.

Development of a crown fire hazard index (CFHI)—Crown fire hazard indexes which combined both initiation and propagation were developed. It was considered that a crown fire would not occur if it could not be initiated or if it could not propagate. Thus -

Crown Fire Hazard Index (CFHI) = (ease of propagation) x (ease of initiation).

Ease of initiation was considered to depend on surface fire intensity, ladder fuels, and height to the live crown, while ease of propagation was considered

Table 1—Different age class groupings used to calculate the Surface and Crown Fire Hazard Indexes and relative weightings of FF and CWD used to calculate the Surface Fire Hazard Index.

Groupings	A	B	C	D	E	F
Age class (years)	0-3	0-2	0-3	0-3	0-2	0-4
	4-9	3-5	4-10	4-9	3-6	5-10
	10-15	6-10	11-18	10-16	7-12	11-20
	16-29	11-20	19-30	17-25	13-20	21-30
	30-40	21-39	31-45	26-35	21-35	31-50
	41-61	40-60	46-65	36-55	36-50	51-70
	62-81	61-80	66-85	56-75	51-70	71-90
	82-105	81-100	86-105	76-100	71-90	91-110
	106-150	101-150	106-150	101-150	91-150	111-150
	>150*	>150	>150	>150	>150	>150

* All forests > 150-years-old were actually > 250 years old and could be considered old-growth.

to depend on canopy foliar bulk density. It was assumed that foliar moisture content would not vary with stand age and could be ignored. Surface fire intensity would depend on surface fire rate of spread and fuel consumption. It was then assumed that rate of spread would be similar beneath forests of different ages and that fuel consumption would depend on surface fuel load. The presence of tall snags (codominant to dominant in canopy height status) with rough surfaces, implying a high probability of blowing embers, was also considered as a factor which might enhance the likelihood of a crown fire.

Therefore, CFHI α [f(FD)] [f(SFL, LF, HC, SD)]

where FD is the canopy foliar density (kg/m^3), SFL is the surface fuel load (kg/m^2), LF is the relative ladder fuel quantity (dimensionless, with scale = 0-5), HC is the height to the live canopy (m), and SD is the density of tall, rough snags (no. snags/ha).

In its simplest form, this equation is CFHI = (FD) (SFL + LF – HC + SD).

The study plots were placed into different age classes then the average CFHI was calculated for each age class. Due to missing tree data, canopy foliar bulk densities could not be calculated for seven plots, so the analyses were conducted using 179 plots. To test the sensitivity of the changes in CFHI with age to different age class groupings and different relative weighting of SFL, LF, HC and SD, the average CFHI was calculated for combinations of six different age class groupings (the same as those used for SFHI (table 1)) and different SFL, LF, HC and SD relative weightings in the CFHI equation. The weighting given to each of these factors was increased or decreased by up to 6-10 times (table 2).

To determine which weighting factors might be most appropriate to use, the outputs from these equations were correlated with the Crowning Index (CI) of Scott and Reinhardt (2001), calculated for drought summer conditions using their figure D-1 for each of the study plots except those aged 0-3 years (table 2). This left 154 study plots for which the CI was calculated. The CI decreases as the ease of crowning increases, whereas the CFHI of the present study increases as the ease of crowning increases. Consequently, equations which produced CFHIs which were positively or weakly negatively ($r > -0.1$) correlated with CI values, were not considered to be appropriate.

Table 2—Pearson correlation coefficients (r) between the CFHI of the present study and the CI of Scott and Reinhardt (2001) for different weightings of SFL, LF, HC, and SD used in the equation CFHI = FD (SFL + LF – HC + SD).

Weighting	r			
	SFL	LF	HC	SD
10.00	--	–0.55	--	–0.18
6.00	–0.41	--	0.57	--
5.00	--	–0.61	--	--
4.00	–0.36	--	0.51	–0.16
3.00	–0.31	--	--	--
2.50	--	–0.36	--	--
2.00	–0.22	--	0.31	–0.13
1.67	--	–0.24	--	--
1.33	--	–0.17	--	--
1.00	–0.06	–0.06	–0.06	–0.06
0.67	--	0.07	--	--
0.50	0.03	0.14	–0.38	--
0.40	--	--	--	–0.06
0.33	0.07	0.22	--	--
0.25	0.08	--	–0.53	--
0.20	--	--	--	–0.05
0.17	0.10	0.30	–0.56	--
0.13	--	--	–0.58	--
0.10	--	--	–0.59	–0.05
0.07	--	0.33	--	–0.04

-- not calculated
The equation in which each of SFL, LF, HC, and SD has an equal weighting (1) is CFHI = FD (SFL + 6LF – HC + SD/20)

SFHIs and CFHIs, determined for the 6 different age class groupings were compared using a Kruskal Wallis test to identify significantly different ($P < 0.05$) values. All statistical analyses were conducted using SYSTAT 11 software (SYSTAT 2004).

Results and Discussion

Surface Fire Hazard

Average fine fuel and coarse fuel loads each varied approximately three fold from 0.1 to 0.3 and from 4.2 to 15.2 kg/m^2, respectively (table 3). The SFHI suggested that the surface fire hazard in old growth forests was less than in recently harvested areas, regardless of the relative weighting given to coarse fuels, which varied over 3 orders of magnitude (figure 1). Since the surface fire hazard in old-growth forests, relative to that in recently harvested areas, varied little with the magnitude of the coefficient "a" in SFHI = FF[(1 + a(CWD)], it was decided to use the simplest form of this equation, with a = 1, to express the relative surface fire hazard. When this equation was applied to different age groupings, the general trend in hazard with age was an initial very high hazard (up to five years post-harvest) which declined to

Table 3—Average values, with standard errors in parentheses, of each of the variables used in the SFHI and CFHI equations for each of the age classes assessed in age class grouping F.

Age class	Number of plots	FF	CWD	SFL	FD	LF	HC	SD
(years)		- - - - - - *(kg/m²)*	- - - - - -		*(kg/m³)*		*m*	*(no./ha)*
0 - 4	16	0.29	13.45	13.74	0.00	3.3	0.0	0
		(0.03)	(1.56)	(1.56)	(0.00)	(0.6)	(0.0)	(1)
5 - 10	17	0.10	15.15	15.25	0.03	3.9	0.2	4
		(0.03)	(1.73)	(1.74)	(0.01)	(0.4)	(0.1)	(3)
11 - 20	14	0.12	9.51	9.63	0.05	3.3	1.4	0
		(0.03)	(1.62)	(1.64)	(0.01)	(0.4)	(0.7)	(0)
21 - 30	24	0.12	4.81	4.93	0.13	3.4	7.4	16
		(0.01)	(0.52)	(0.52)	(0.02)	(0.2)	(0.8)	(14)
31 - 50	17	0.24	5.64	5.88	0.10	3.6	10.3	150
		(0.03)	(0.60)	(0.62)	(0.01)	(0.3)	(1.0)	(44)
51 - 70	19	0.29	6.54	6.83	0.13	2.5	15.9	54
		(0.05)	(0.74)	(0.77)	(0.01)	(0.3)	(1.1)	(22)
71 - 90	15	0.23	7.48	7.71	0.13	1.9	17.7	54
		(0.03)	(1.62)	(1.62)	(0.01)	(0.3)	(1.5)	(19)
91 - 110	7	0.26	6.93	7.19	0.09	1.4	14.9	69
		(0.03)	(0.60)	(0.60)	(0.01)	(0.2)	(2.0)	(12)
111 - 150	18	0.20	4.19	4.39	0.10	1.6	18.8	23
		(0.03)	(0.53)	(0.53)	(0.01)	(0.2)	(1.1)	(8)
> 150	32	0.21	10.00	10.21	0.12	2.4	18.9	23
		(0.02)	(0.94)	(0.94)	(0.01)	(0.1)	(1.0)	(4)

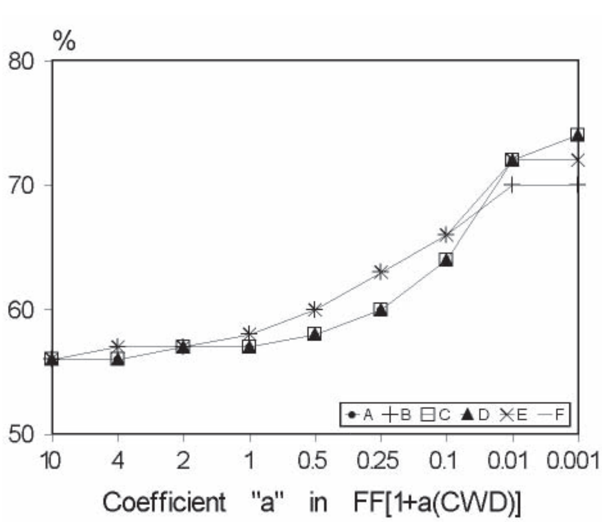

Figure 1—Surface Fire Hazard Index in old-growth forests as a percentage of that in the youngest post-harvesting forests for six different age class groupings (A-F).

a minimum around 20 to 40 years post harvest, followed by an increase to around 50 to 70 years post harvest, a decrease to around 100 to 150 years post harvest, then an increase again in old-growth (figure 2). Old-growth forests, however, generally had a lower surface fire hazard than forests 0 to 5 and 50 to 70 years old (figure 2), although the difference between the old-growth SFHI and the greatest SFHI was statistically significant for age class groupings A, C, D, and F, but not B and E (figure 2). The only age classes which had a statistically significant lower SFHI than that of old-growth were those in the range of 16 to 35 years (figure 2).

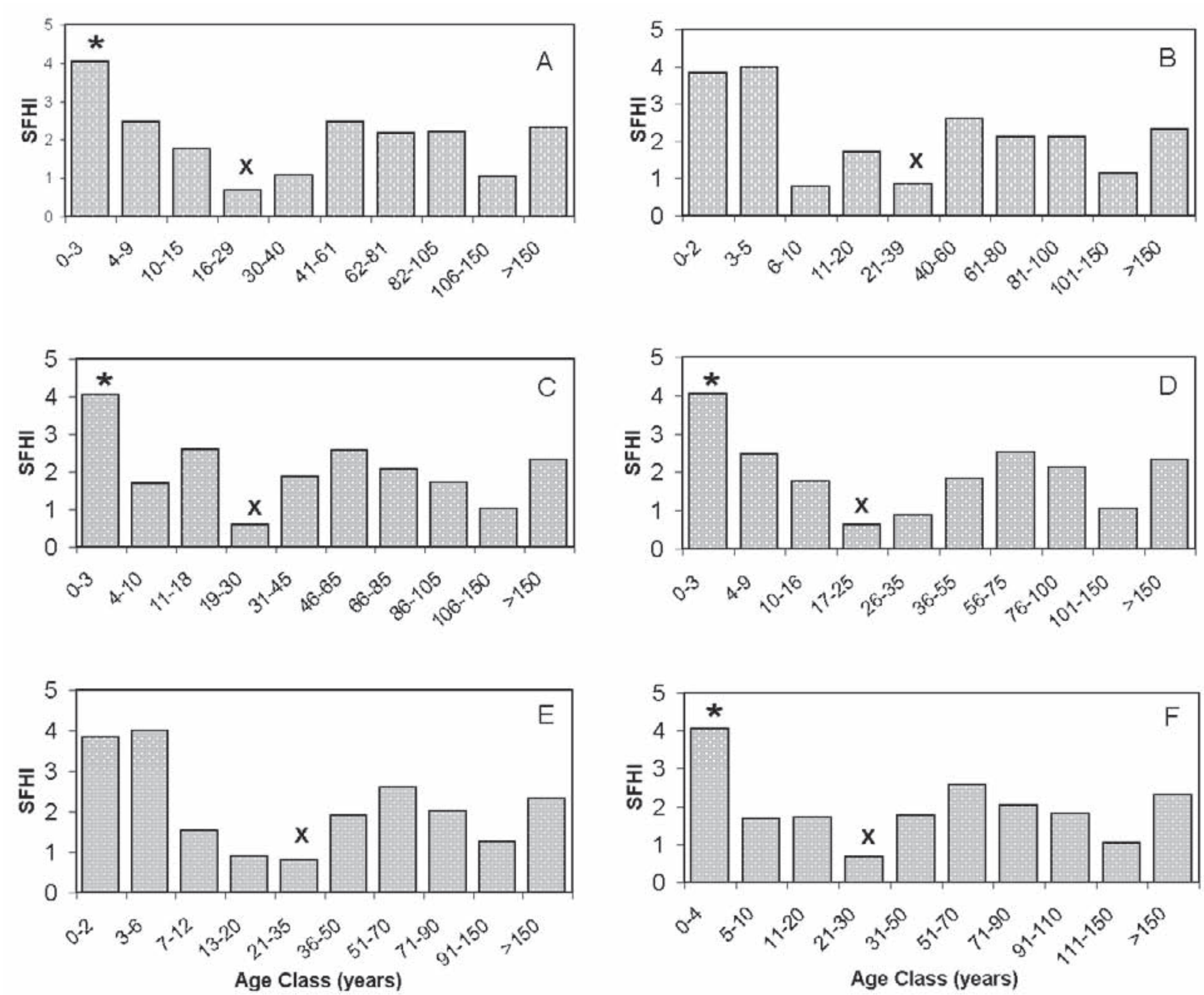

Figure 2—Average Surface Fire Hazard Indexes for different aged forests using six different age class groupings (A-F) and the equation SFHI = FF(1 + CWD).* designates a SFHI which is significantly higher ($P < 0.05$) than that of old-growth. x designates a SFHI which is significantly lower ($P < 0.05$) than that of old-growth.

The SFHI used total CWD and not just well decayed CWD, which has been considered more important in determining surface fire hazard (Baker 2003). Quantitative data to support this do not appear to be available, however. Furthermore, several studies in coastal western hemlock forests have found that well decayed materials constitute a greater proportion of total CWD mass in younger than in old-growth forests (Spies and others 1988; Wells and Trofymow 1997; Feller 2003). Consequently, if the SFHI had given greater weight to well decayed CWD than to less well decayed CWD, the differences in SFHI between old-growth and the youngest forests would likely have been greater. It was also assumed that wind speed was unaffected by forest age. This is unlikely to be correct as wind speed near the ground surface is usually greater in the open than beneath forests (Spittlehouse and others 2004), so fire forward rates of spread, and hence fire hazard would also be greater in the open. Tanskanen and others (2005) have also found that surface fire likelihood in Finnish conifer forests was greatest in recent clearcuts and declined with increasing age up to age 60 years, the oldest forest studied, due to increasing surface fuel moisture content. Consequently, microclimate differences even further emphasize the difference in surface fire hazard between old-growth and the youngest forests. Thus, it can be concluded that the surface fire hazard of the old-growth forests in the study area was less than that of recent clearcuts and was only greater than that of forests around 16 to 35 years old.

Crown Fire Hazard

Average surface fuel loads were greatest in 0 to 10 year old stands and least in 111 to 150 year old stands; average canopy foliar bulk densities increased with age up to 20 years, then remained relatively constant thereafter; ladder fuels were greatest in 0 to 70 year old stands; canopy heights tended to increase with stand age; and the density of dominant rough snags was least in the youngest stands and greatest in stands aged 31 to 110 years (table 3). Canopy foliar bulk densities may be overestimated in some old-growth stands as some of the tallest trees had dead tops and the foliar biomass regression equations used, which had been developed for trees up to 1.6 m d.b.h., were applied to trees up to twice this size.

Although the influence on the CFHI of variations in the weighting given to individual factors was assessed, the influence of variations in the weighting given simultaneously to 2 or more factors was not fully analyzed. Consequently, the appropriate CFHI equations chosen must be considered a first approximation. When the different crown fire initiation variables (whose range in values between individual plots were - SFL = 0.4 to 30.2 kg/m^2, LF = 0 to 5, HC = 0 to 32 m, and SD = 0 to 592 stems/ha) were given equal weight, the CFHI equation became CFHI = FD (SFL + 6LF – HC + SD/20). The weighting given to SFL had a major impact on the relative CFHI of old-growth versus younger forests. As the weighting increased, so did the CFHI of old-growth compared to that of younger forests (figure 3). Correlations between the CFHI and the CI of Scott and Reinhardt (2001) were > -0.1 for weightings of one or less (table 2). Consequently, an appropriate weighting factor would be > 1.

Regardless of the weighting given to LF, HC, or SD, the CFHI always remained lower in old-growth than in younger forests (figure 3). This applied even for weighting factors substantially greater or less than those given in figure 3. Based on correlations between the CI and CFHIs, appropriate weighting factors would be > 1 for LF and SD, and < 1 for HC (table 2).

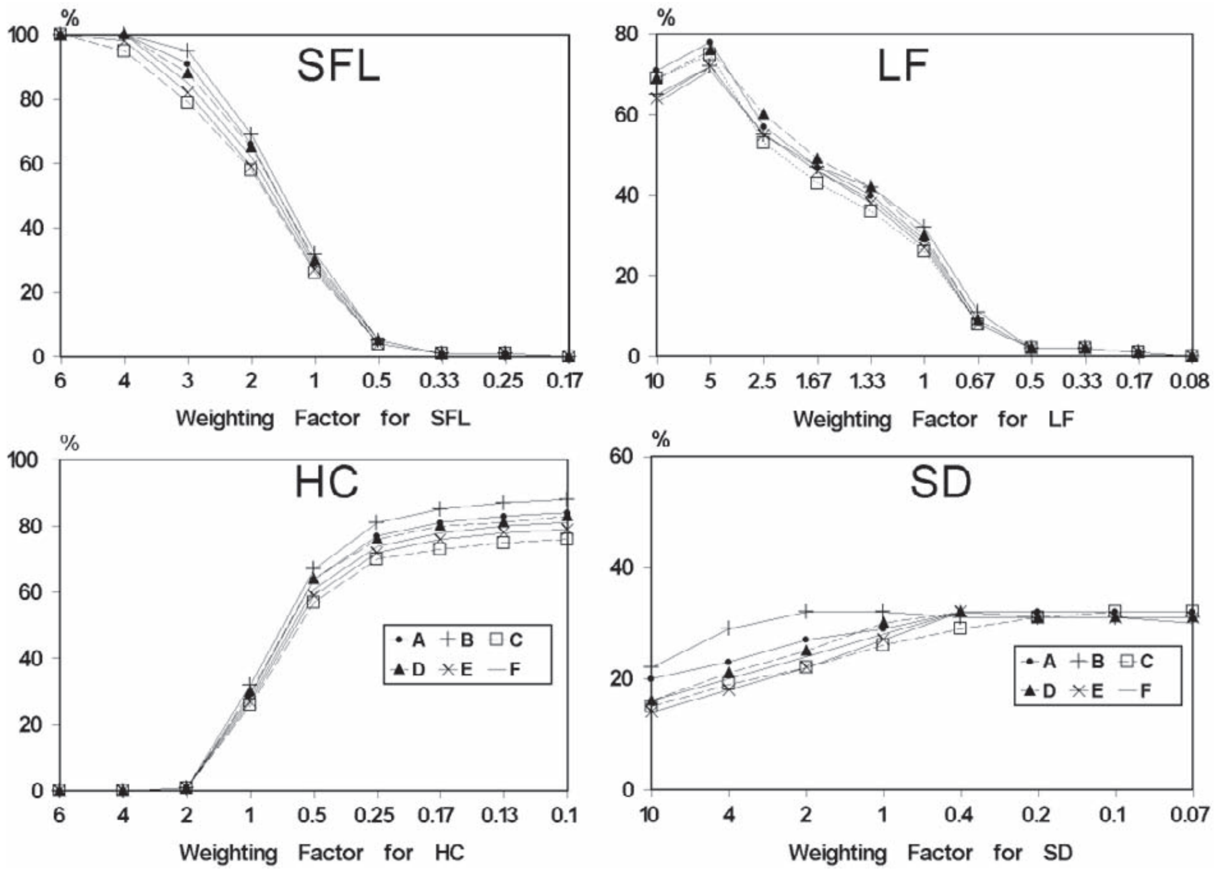

Figure 3—Crown Fire Hazard Index in old-growth forests as a percentage of the highest CFHI in all age classes of forests, using six different age class groupings (A-F) and different weightings for SFL, LF, HC, and SD.

Many possible equations could be chosen using different appropriate weighting factors. All equations with SFL preceded by a coefficient of 4 or less resulted in CFHIs being lower in old-growth than in some younger forests. For simplicity, several equations were chosen for use, using weighting factors that were not too extreme. Due to the lack of data or even theoretical models which link snag abundance to crown fire hazard, the weighting given to snag density was kept relatively low. It is currently unclear which equation best predicts crown fire hazard as none have been tested with real fires. CFHIs calculated from a sequence of equations with increasing weight being given to SFL from equation 1 through equation 4 are given in figure 4. The indexes calculated from the equations CFHI = FD(aSFL + bLF + cHC + dSD), with varying a-d, were multiplied by either 25, 10, or 8 to convert the index to a scale of 1 to 100. The CFHIs calculated from all 4 equations were significantly negatively correlated with the CI of Scott and Reinhardt (2001). These correlations progressively improved from r = –0.30 for equation 1 to r = –0.60 for equation 4, suggesting that as the relative weighting of SFL increases, the CFHI becomes a better predictor of crown fire propagation. This only occurs up to a weighting factor of 8, however, after which the closeness of the correlation declines.

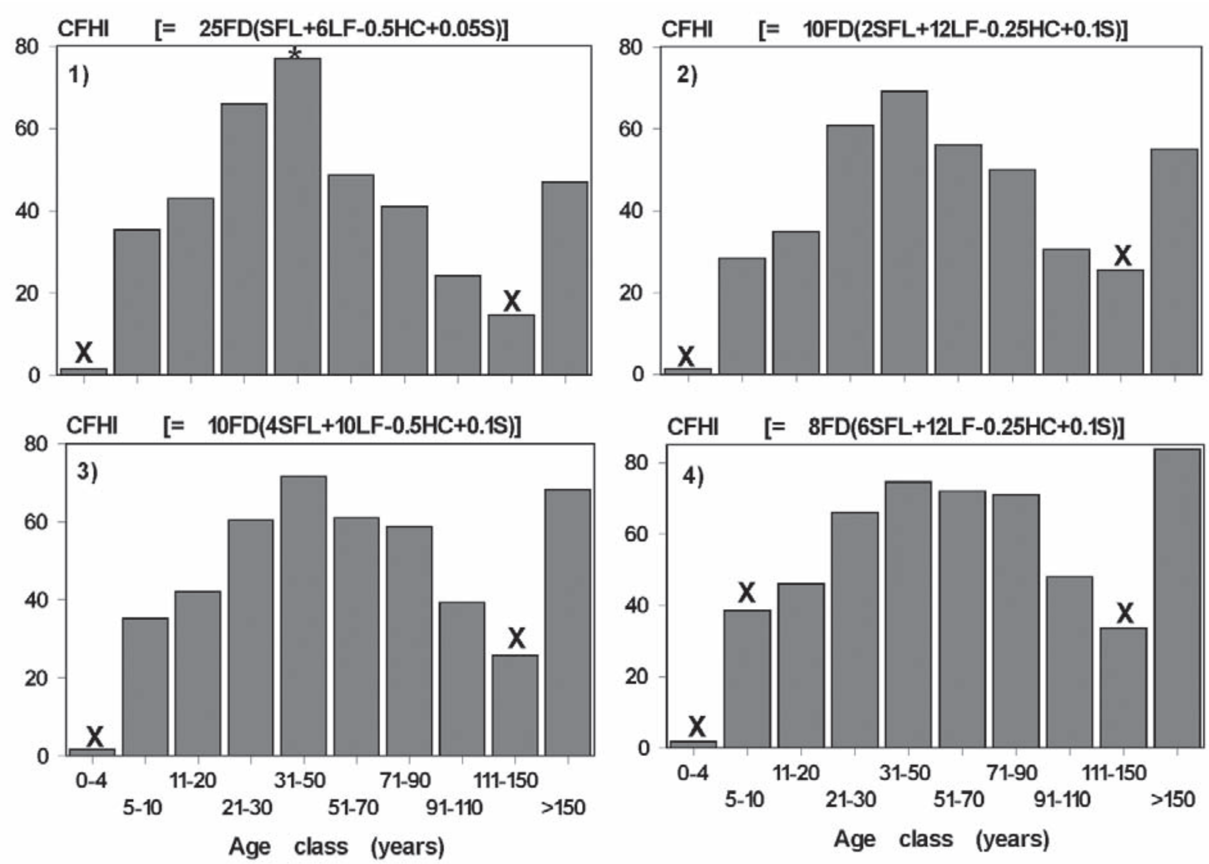

Figure 4—Average Crown Fire Hazard Indexes for different aged forests, calculated using four different CFHI equations and age class grouping F. * designates a CFHI which is significantly higher ($P < 0.05$) than that of old-growth. x designates a CFHI which is significantly lower ($P < 0.05$) than that of old-growth.

The CFHIs in figure 4 are shown only for one grouping of age classes as there were no substantial differences between the six different age groupings in the relative rankings of old-growth versus younger forests. The CFHI was always lowest for 0 to 5 year old age classes, then increased to peak values in 20 to 90 year old age classes, before declining in 100 to 150 year old age classes then rising again in old-growth. The CFHI for old-growth was lower than that of a younger age class forest for all equations in which SFL had a weighting factor < 5. However, it was statistically significantly lower (Kruskal Wallis tests, $P = 0.05$) only when the SFL weighting factor was < 2, as in equation 1 (figure 4). The CFHI for old-growth was also significantly higher than that for 0 to 4 and 111 to 150 year old stands (figure 4).

It can be concluded that whether or not younger forests have a higher crown fire hazard than old-growth in the study area depends primarily on the weighting given to surface fuel load. As the weighting given to this factor increases, the relative crown fire hazard of old-growth forests increases. However, as no reasonable equation could be found which resulted in old-growth forests having a statistically significantly higher crown fire hazard than all younger forests, it can also be concluded that simply clearcutting old-growth will not produce younger forests that always have a lower crown fire hazard than old-growth forests. Following clearcutting, fuel abatement treatments, such as slash reduction and thinning, would be necessary to significantly reduce crown fire hazards. Slash reduction would definitely be required to reduce post clearcutting surface fire hazard below that of old-growth forests. These conclusions are consistent with those of DellaSala and Frost (2001), who reported that old-growth forests in the western U.S. were less likely to burn catastrophically than younger forests.

Guidelines for fuel reduction treatments which lower fire hazards in forests are becoming available (for example, Keyes and O'Hara 2002; Peterson and others 2005). The present study suggests that both surface and crown fire hazard reduction would benefit from an emphasis on reducing surface fuels. However, the ecological benefits of surface fuels (Brown and others 2003; Feller 2003) as well as their influence on fire hazard must be considered.

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