Fuel succession in a western hemlock/Douglas-fir forest

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Fuel succession was quantified for a 515-year chronosequence in a *Tsuga heterophylla*/*Pseudotsuga menziesii* forest. Postfire stand ages selected were 1, 3, 19, 110, 181, and 515. After initial reductions due to mortality from fire in the first 3 years, live aboveground biomass in the tree component increased over time to over 1100 t/ha. Shrub and herb layer biomass was highest in year 19 and year 515. Dead aboveground biomass had different trends for different fuel size classes; normalized fuel loadings of five dead and down fuel categories peaked at four different stand ages: 1-h and 10-h timelag (TL) fuels, age 1; 100-h TL fuels, age 19; 1000-h TL fuels, age 110; >1000-h TL fuels, age 515. Surface fire behavior was highest early in the sere and lowest at ages 110–181. Old-growth forest patches appear to be best buffered against forest fire by mature forest patches rather than old growth or recently burned natural stands.

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La succession des combustibles a éte quantifiée pour une chronoséquence de 515 ans dans une forêt de *Tsuga heterophylla*/*Pseudotsuga menziesii*. Les âges après feu des peuplements choisis étaient de 1, 3, 19, 110, 181 et 515 ans. Après des réductions initiales provoquées par la mortalité due au feu pendant les trois premières années, la biomasse vivante au-dessus du sol dans les constituants de l'arbre a augmenté avec le temps jusqu'à 1100 t/ha. La biomasse de la strate abrustive et herbacée a été à son maximum à l'année 19 et l'année 515. La biomasse morte au-dessus du sol se comportait différemment selon la classe de grosseur des combustibles; les charges normalisées de combustibles morts de catégories 5 et moins ont culminé à quatre âges différents de peuplement: les combustibles avec un délai de 1 h et de 10 h à l'âge 1, ceux d'un délai de 100 h à l'âge 19, ceux d'un délai de 1000 h à l'âge de 110 et ceux d'un délai supérieur à 1000 h à l'âge 515. Le comportement du feu en surface fut maximal tôt dans la serre et minimal aux âges de 110 et 181. Les ilôts de vieille forêt semblent être mieux préservés du feu par d'autres ilôts de vieille forêt que par de vieux peuplements ou des peuplements récemment brûlés.

[Traduit par la revue]

Introduction

Fire has been an important disturbance factor in the forests of the Pacific Northwest for millenia. In national parks and wilderness areas, maintenance of natural disturbance patterns is an important element of landscape management. Such disturbance may occur infrequently, but its effects on forest species composition, structure, and function may be apparent for centuries with the very long-lived tree species found in the Pacific Northwest. Fire may play a crucial role in the dynamics of woody debris. Such debris has crucial ecological functions: as habitat for organisms, in nutrient cycling, by influencing geomorphic processes (Harmon *et al.* 1986) and as fuel for the next fire. This study evaluates effects of naturally occurring forest fires on live and dead fuel patterns and potential fire behavior in a moist temperate coniferous forest.

The typical fire regime for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)/Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) forests is one of infrequent fires (fire return intervals >100 years) and intensities sufficiently high to kill most of the trees in the stand (Agee 1981; Fahnestock and Agee 1983; Agee and Flewelling 1983). After ignition, fires may remain small for several days or weeks and spread when severe burning conditions, associated with dry east winds, affect the region (Huff and Agee 1980). Once fires begin to spread, they may move rapidly through the understory; the primary cause of tree mortality is through root death and crown scorch. Surviving trees are usually found in ravines, debris chutes, seeps, and riparian areas.

Regeneration after fire is often prompt but may extend in some instances over decades. Franklin and Hemstrom (1981) suggest that long postfire tree recruitment periods may reflect reburning of forests soon after a stand replacement fire. Harris (1984) has proposed that mature forests are less flammable than very young forests and are desirable to provide wildfire buffers for old-growth wildlife habitat "islands" in this forest type. Within this context, our study hypothesis was that while site biomass would increase over time since disturbance, fireline intensity and fire rate of spread would decrease. An age sequence of forests over a 500-year timeframe was the setting used to test this hypothesis.

Methods

The stands were selected within the western hemlock/sword fern (*Polystichum munitum* (Kaulf.) Presl.) habitat type of Olympic National Park (Franklin and Dyrness 1973; Fig. 1). This plant association is one of the wettest within the *Tsuga heterophylla* series. Five study sites receiving 250–400 cm of precipitation annually were chosen to represent postfire stand development stages (Oliver 1981): stand initiation (Hoh Fire replication in years 1–3, and Queets Fire year 19), stem exclusion (North Fork Fire year 110), understory reinitiation (Mineral Creek Fire year 181), and old growth (Olympus Guard Fire year 515). Study sites were selected to have a similar geographical characteristics: habitat type, aspect, elevation, and slope (Table 1). These sites represent a general successional trend but do not represent the same stand at different developmental stages. All but the oldest fires are known to have burned forests 300 years of age or older with extensive overstory mortality. This was determined on recent fires by the age structure of trees burned by the fires; on older fires (>100 years) ages of residual trees were used to establish stand age at the time of the fire. No information on stand age at time of burn was available for the 515-year site. At the Hoh (1- to 3-year) and Queets (19-year) sites, fires scorched crowns and killed the trees but generally did not consume the crowns; similar information at the older fire sites was not available.

Two randomly located 50 × 50 m plots were established in each study area between 100 and 400 m inside the fire boundary. Species, height, and diameter at breast height (dbh) of live and dead trees

TABLE 1. Site characteristics of stands in the chronosequence

Study area	Age (years)	Elevation (m)	Aspect (deg.)	Slope (%)	Tree density[a] (no./ha)	Basal area (m^2/ha)
Hoh	1	400–530	150	50	6	28.7 (100)[b]
Hoh	3	400–530	150	50	0	0 —
Queets	19	520–640	120	45	228	9.6 (54)
North Fork	110	500–600	260	40	698	81.7 (61)
Mineral Creek	181	430–550	180	65	560	83.5 (44)
Olympus Guard	515	460–610	160	60	444	84.7 (40)

[a] Trees >5.5 cm dbh only.
[b] Numbers in parentheses refer to percent of total basal area in *Pseudotsuga menziesii*.

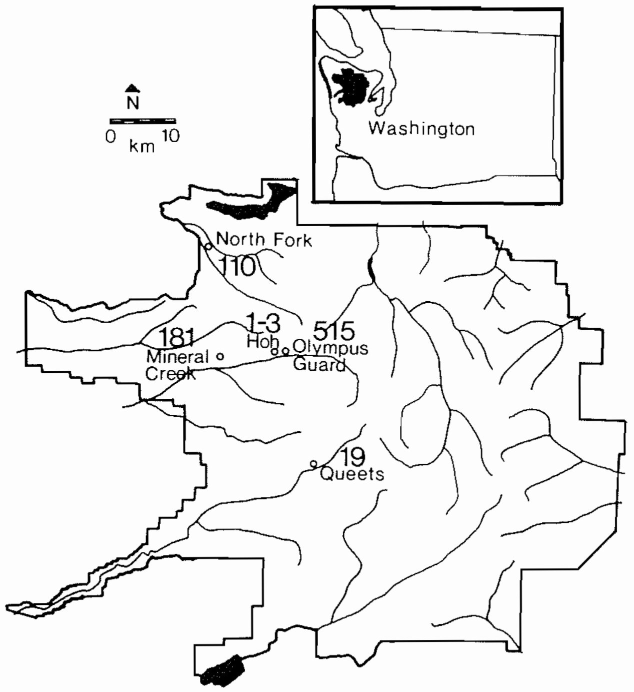

FIG. 1. Location of study areas on Olympic Peninsula, Washington. All sites are within Olympic National Park.

>5.5 cm dbh were measured; density of smaller trees was measured on four 12.5-m^2 circular subplots. Decay class of snags (cf. Cline *et al.* 1980) was recorded. Herb and shrub frequency was recorded on a total of 96 0.1-m^2 subplots. Dead and down woody fuels were measured by the planar intersect method (Brown 1974). Along a continuous line 5 m inside the edge of each plot and along two lines bisecting each plot center, fuel transects totalling 15 m for 1-h timelag fuels (0–0.62 cm diameter), 30 m for 10-h (0.63–2.54 cm diameter) and 100-h (2.55–7.62 cm diameter) timelag fuels, and 240 m for >100-h timelag (>7.62 cm diameter) fuels were established. Diameter and decay class of individual 1000-h (7.63–20.32 cm diameter) and >1000-h (>20.32 cm diameter) timelag fuels were measured. A total of 25 litter-duff depth samples was measured on each plot.

Biomass of live fuels was estimated by applying allometric equations contained in Gholz *et al.* (1979) for most species on all plots. Foliar biomass of Douglas-fir larger than 50 cm dbh was adjusted downward using equations in Dale and Hemstrom (1984). The diameter of tree regeneration (<5.5 cm dbh) was usually below the limits of the Gholz *et al.* equations, so equations from Brown (1978) were applied. Although these data were from the western Rocky Mountains, geographic location may be less important than whether the trees were open grown or understory grown (Agee 1983). Weights of shrub and herb layer fuels were estimated by visually determining depth of each layer averaged over the macroplot and a bulk density class similar to those of Burgan and Rothermel (1984) but adapted with equations for western Washington shrub types (Agee *et al.* 1985); loads were reduced proportional to percent cover for each plant layer.

TABLE 2. Dead and down fuel densities by decay class

Species	Decay classes I	II	III	IV	V
Douglas-fir	0.411	0.313	0.285	0.204	0.146
Western hemlock	0.412	0.290	0.241	0.150	0.130[a]

[a] Estimated; others from references in text.

The mass of dead and down fuels was calculated by size class. Values were adjusted by known densities for different decay classes (USDA Forest Service 1974; Graham and Cromack 1982; Sollins 1982) and weighted by species. Weights were apportioned by species according to relative snag and tree species density of each study area, as species of down wood was often difficult to determine. Quadratic mean diameters (Bevins 1978) were assigned to fine woody fuels (≤100-h timelag) and density was assumed to be the average of decay categories II and III (Table 2).

Litter biomass was calculated using depth–weight regressions developed for the northern Cascade Range (Agee *et al.* 1985). Duff biomass was estimated from depth–weight regressions for the Cascades (Williams and Dyrness 1967). Biomass of standing dead stems was estimated by computing volumes from large end diameter and height, with taper estimated from the international log rule (Avery and Burkhart 1983) and multiplied by appropriate density based on decay class (Sollins 1982). Dead stems were assumed to have no branches except for the 1- and 3-year-old sites where branch biomass was calculated from the live branch equations in Gholz *et al.* (1979), and on the 19-year site where 50% of branch biomass.was asssumed to have fallen.

Fire behavior estimates were made with the BEHAVE system, a series of interactive computer programs for estimating wildland fire behavior in various fuels, weather, and topography situations (Burgan and Rothermel 1984). Available biomass for fire was defined to include live regeneration, shrub and herb biomass, litter, and 1-, 10-, and 100-h timelag fuels on each site and were derived from the total biomass at each stand age. Topography was held constant at 50% slope, which is quite common in the area. A late summer condition was assumed, with 50% of herbaceous fuels cured and a 70% live fuel moisture for the live understory. Fire behavior was calculated for many combinations of fuel moisture and wind; results are reported for midflame windspeeds of 268 m/min (10 mph) and dead fuel moistures of 6, 7, and 8% for 1-, 10-, and 100-h timelag fuels. In the older stands (110–515 years), microclimatic amelioration was assumed and additional results are presented for midflame windspeeds of 134 m/min (5 mph) and dead fuel moistures of 10, 11, and 12% for 1-, 10-, and 100-h timelag fuels.

TABLE 3. Biomass (t/ha) in western hemlock/sword fern forest by stand age

	Stand age (years)					
Biomass category	1	3	19	110	181	515
Live biomass						
Live overstory trees (>5.5 cm dbh)						
Foliage	0.6	0	0.3	21.7	20.9	21.1
Branch	4.6	0	0.3	66.3	65.6	154.1
Stem	188.6	0	2.3	472.2	436.1	829.4
Bark	22.5	0	0.3	62.0	56.0	103.3
Live regeneration	0	0.1	4.1	0.3	0.2	2.2
Shrub and herb layers	0.9	4.5	7.4	0.4	2.7	4.0
Total live biomass	217	5	15	623	581	1114
Dead biomass						
Standing stem	775.6	1066.3	279.2	35.3	33.4	84.5
Standing branch	184.1	188.7	22.3	9.9	7.4	9.0
Litter layer	5.6	6.2	27.2	9.0	5.6	10.5
Duff layer (F+H)	26.4	12.0	20.4	22.8	26.4	87.8
1-h TL fuels	9.4	6.9	0.5	3.1	2.2	2.9
10-h TL fuels	1.5	0.7	1.1	1.1	1.2	1.1
100-h TL fuels	2.6	1.6	3.7	1.0	0.9	2.1
1000-h TL fuels	24.9	19.7	19.8	31.2	13.9	11.4
>1000-h TL fuels	281.9	229.5	438.4	118.4	112.7	441.5
Total dead biomass	1312	1532	813	232	435	651
Total biomass	1529	1536	827	855	785	1765

NOTE: Totals are rounded to nearest t/ha.

The fire behavior results are theoretical in that no confirming experiments were conducted to test the validity of the output; in addition, the BEHAVE program is limited to predicting surface fire behavior.

Results

Live aboveground biomass

Live biomass (Table 3) followed a sequence in which seral tree regeneration occurred for several decades. In year 1, a considerable amount of live biomass remained from residual Douglas-fir, all of which died by year 3. Regeneration was evident by year 3, but the shrub and herb component was dominant at this time, comprising sprouts from most of the prefire shrubs, herbs, and ferns, plus disturbance-oriented herbs such as fireweed (*Epilobium angustifolium* L.), woodland groundsel (*Senecio sylvaticus* L.), and wall lettuce (*Lactuca muralis* (L.) Fresen.). By year 19, tree biomass (4.5 t/ha) was still less than shrub and herb biomass, which at 7.4 t/ha was at its peak for the chronosequence. Bracken fern (*Pteridium aquilinum* (L.) Kuhn), a dominant rhizomatous herb layer species, created a deep, fluffy litter layer.

At year 110, the overstory canopy had been closed for at least 40 to 50 years (Huff 1984). Most biomass was in the canopy layer, predominantly in stems and branches. The tree regeneration and shrub and herb layers had only 7 and 5% of the biomass of the respective layers in the 19-year-old stand. By year 181, the understory reinitiation phase was underway; the shrub and herb layer responded more significantly than the tree regeneration layer, however. By the old growth stage, the regeneration and shrub and herb layers were approaching levels not attained since early in the sere. This multilayered stand is a classic feature of old-growth Douglas-fir forest (Franklin *et al.* 1981).

Foliar biomass leveled off after crown closure. There were no available stands to measure near the age where crown closure occurs, but all the stands past the age of crown closure had foliar biomass near 21 t/ha. Tree biomass increases occurred largely as wood and bark of stems and branches. The apparent decrease in live biomass between year 110 and year 181 is probably due to minor site variation or sampling error. Although density of Douglas-fir (220/ha at year 110 to 20/ha at year 515) and proportional basal area (Table 1) declined with time, the proportion of total biomass accounted for by Douglas-fir remained at about 67% over this time period.

Dead aboveground biomass

Coarse woody debris (snags and down logs) dominated aboveground dead biomass. Snag biomass was highest in year 3, given complete overstory mortality at this site, and declined over time as snags fell and decomposed. Most of the snags at the 110- to 181-year sites were smaller stems that died in the stem exclusion phase of succession. A few large trees that died in the old-growth stand and remained standing for several decades caused a late successional increase in the snag biomass category.

Litter layers were replenished rapidly after the fire through additions of foliage from scorched and dying trees and herbaceous production at ground level. Bracken fern in particular caused a large litter increase in year 19. Depth measurements of the duff layer revealed that patches of duff were not completely consumed by the fire, but appeared to be rapidly decomposing (e.g., Turner and Long 1975) in the open postfire environment. This apparent loss may also reflect redistribution of fuel from the transects by slope wash and trampling by ungulates. As the stand sequence became older, duff depth and weight increased steadily.

Small dead and down fuels exhibited several patterns by size class across the sere (Fig. 2). The 1-h timelag category reached a maximum of 9.4 t/ha in year 1, as fine branch fuels fell from dead overstory trees. Larger 10-h timelag fuels, while maximum in year 1, did not show large changes over the entire sere. The

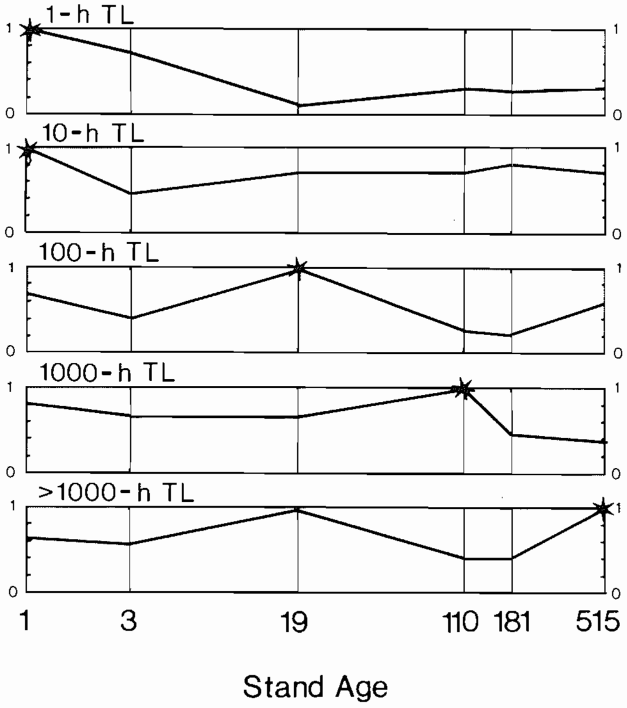

FIG. 2. Normalized fuel loadings by size class for dead and down fuels by stand age. Maximum fuel loading within a size class is scaled to 1.0. Loadings of that size class at other stand ages are shown as proportions of the maximum level.

100-h timelag fuels peaked at 3.7 t/ha in the 19-year-old stand, after many of the larger fire-killed trees and associated branches had fallen to the ground. The 1000-h timelag fuels peaked in the 110-year-old stand (31.2 t/ha), as a result of natural thinning of many overstory trees within this size class. Maximum loading in each of the five dead and down fuel categories occurred at four different stand ages.

The largest downed fuels (>1000-h timelag) showed a predictable trend across the chronosequence. A considerable mass of prefire downed material remained on the forest floor during replicate measurements of years 1 and 3 after the Hoh Fire (Fig. 3); additional material immediately accrued after the fire as snags and even small live trees fell to the ground since roots or root support were consumed. The well-decayed logs were easily fragmented by falling debris and increased ungulate activity. Most fire-killed trees, now snags, had not yet begun to fall in large numbers; however, the immediate decline in large log biomass by year 3 represents a single exponential decay rate (k = 0.48) for fragmentation and mineralization much higher than any reported to date for these species (Harmon *et al.* 1986). The difference probably is the result of fire exposing rotten logs (decay class 5) at the ground surface, making them visible for measurement. By year 3, moss and litter had totally obscured some of these logs and ungulate activity had fragmented others; the apparent biomass loss was primarily in the rotten log category (Huff 1984). By year 19, the log biomass was higher, primarily from fallen snags. However, the combined biomass of logs plus snags at year 19 was 600 t/ha below levels in year 3. Such a large difference was not expected within a 16-year period. The difference of 600 t/ha is part real, part accounting technique, and part site selection and lack of replication for the chronosequence. As trees fall and become logs, there are volume losses due to fragmentation and density changes due to decay. These may have resulted in biomass decreases of 12–20% (cf. Grier 1978; Graham and Cromack 1982) by year 19, particularly if tree diameter decreases due to bark sloughing are recognized. The accounting technique used for all live biomass and recently killed trees on the Hoh Fire (years 1 and 3) assumed all live tree wood was sound; once trees fall, internal rot becomes evident, and rot in 19-year-old snags was more obvious because of broken tops and excavations by birds. At the Olympus Guard (515 year) site, 60% of the dominant western hemlock and 30% of the dominant Douglas-fir had decay. If 25% of the volume at years 1 and 3, for example, is hollow, the decay rate constant to year 19 is reduced to k = 0.018, within the range for those species (Harmon *et al.* 1986). Site differences in prefire vegetation characteristics may also be responsible for some of the biomass difference. Lower parts of both plots on the year 19 site are steep, allowing material to roll off the plot (e.g., lower one-third of year 19 plot, Fig. 3); upper sections are gentle so that little material rolled into the plots from upslope. This situation is not as evident at other stand ages studied. By years 110 and 181, decades of decay combined with a lack of continuous input of large diameter logs resulted in decreased large log biomass. The calculated decay rate constant from year 19 (dead standing stem plus >1000-h timelag fuel) to year 110 (>1000-h timelag fuel) represents k = 0.02; given that some input of >1000-h timelag fuel at the 110 year site is from the new stand, the actual decay rate constant is somewhat below 0.02. As the average dominant tree size increased in older stands, large fuels again became available through the occasional death of overstory dominants.

Total aboveground biomass reached a maximum in the old-growth stage. Fire consumed only a small proportion of total biomass, so aboveground biomass remained high immediately after disturbance. Minimum aboveground biomass levels probably occurred between the stand initiation stage and the stem exclusion stage (years 20–110).

Surface fire behavior

Patterns of aboveground biomass accumulation are not always useful in determining differences in surface fire behavior between stands. Some of the fuel is too large to contribute to the spread of fire, although it may contribute significantly to total energy release levels. Other fuel is too moist or may be spatially removed from the usual combustion zone in very tall tree canopies. Surface fire behavior potential is evaluated using those fuels affecting surface fire intensity and spread: live fuels near the ground, litter, and smaller dead fuels (<1000-h timelag). The fire behavior evaluation does not consider crown fire behavior, although crown fire behavior is often linked to intense surface fire behavior (Van Wagner 1977).

Rate of spread and flame length (an index to fireline intensity) followed similar patterns (Fig. 4). Values were highest in the immediate postfire stands due to fine fuel inputs from the canopy and fine herbaceous fuel production, then declined over time and reached a minimum in the stem exclusion phase of stand development. Increases in rate of spread and fireline intensity occurred on older study sites as understories grew taller and slightly thicker litter layers developed. The values in Fig. 4 for stands older than year 19 also reflect microclimate amelioration (lower wind speed and higher fuel moisture) compared with the open, early successional stages (Morris 1937; Albini and Baughman 1979). The unconnected points in Fig. 4 are flame lengths and rates of spread on the older sites assuming the microclimate on all sites is constant. In this scenario, relative

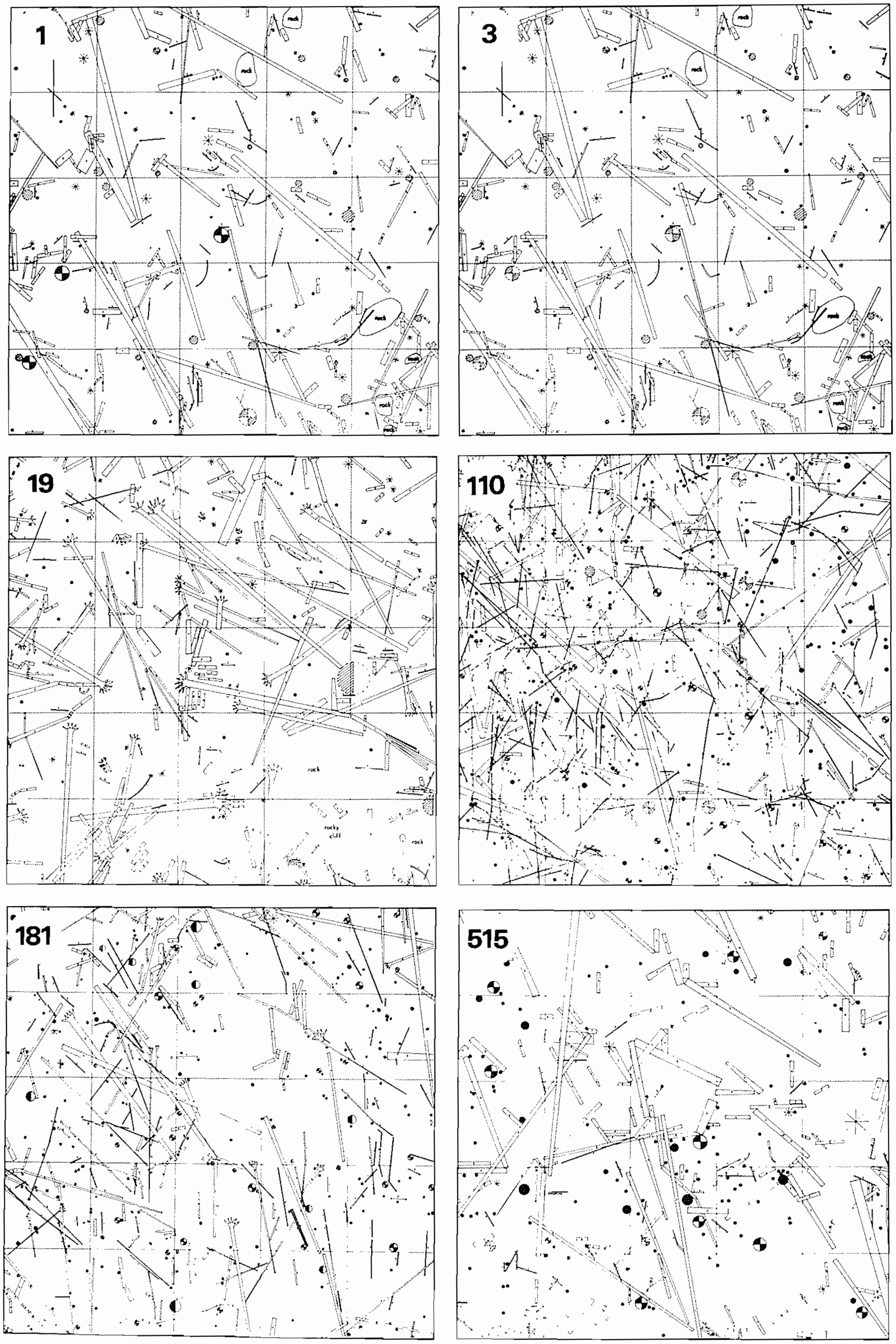

FIG. 3. Stem maps of large down log accumulations by stand age. Each plot is 50 × 50 m, and all pieces >8 cm diameter and >3 m long are mapped. Live trees are in black: black circles are western hemlock, target patterns are Douglas-fir, and half-black circles are western red cedar. Dead trees are shown with the same patterns but with stripes. The log distribution for years 1 and 3 appears identical. Logs were not remapped in year 3; this figure is included to show tree mortality.

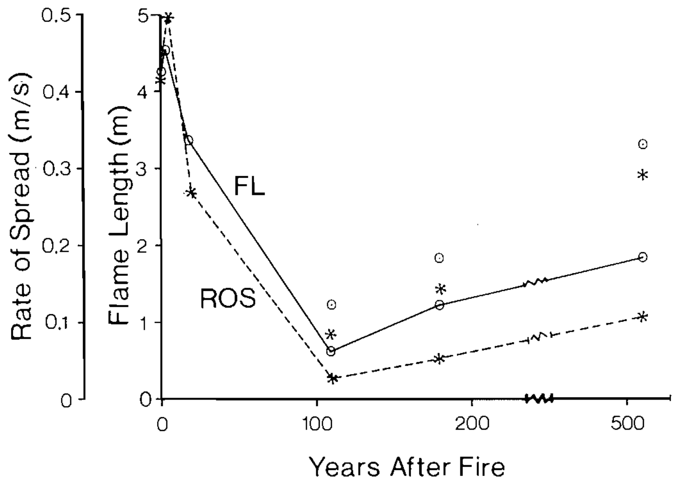

FIG. 4. Rate of spread and flame length by stand age. Wind speed is 268 m/min, and dead fuel moisture contents are 6, 7, and 8% for 1-h, 10-h, and 100-h timelag fuels at stand ages 1, 3, and 19. Connected points represent microclimate buffering at stand ages 110, 181, and 515: wind speed is reduced to 134 m/min and fuel moisture increases to 10, 11, and 12%. Unconnected points at these ages represent constant microclimate across all sites.

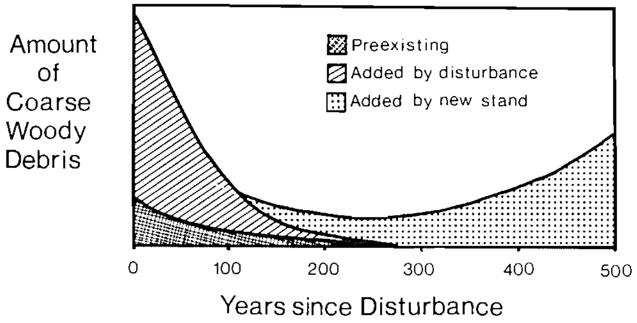

FIG. 5. Coarse woody debris patterns are a result of interactions between preexisting debris, that caused by disturbance, and that created by the post-disturbance stand.

flammability of the 110-year and 181-year stands remained low, while the old-growth stand flammability began to approach that of the 19-year stand.

Discussion

Patterns of fuel succession after fire have been based primarily on empirical studies. For lodgepole pine forests, Lotan *et al.* (1985) documented three different patterns of succession for large fuels and concluded that predicting fuel quantity from stand age was unreliable; age of the stand at the time of burning was a critical variable, since the burning of young stands would contribute only small stems to postfire large log biomass. For forest types that burn with stand replacement fires, fuel loadings that are high in the juvenile period, low in the early mature period, and high again in the late mature to overmature period are a common pattern, although considerable variation occurs (Fahnestock 1976, Brown and See 1981). The western hemlock/Douglas-fir forest type fits this pattern. There are few consistent patterns by size class of fuel, however.

Coarse woody debris mass following disturbance (Fig. 5) in moist western hemlock/Douglas-fir forests follows one of four hypothetical debris accumulation patterns identified by Harmon *et al.* (1986, Fig. 10, pattern B). Initial mass is composed of that present before the disturbance and that created by the disturbance (additional mortality between years 1 and 3 is considered instantaneous in the time frame being considered). A U-shaped trough occurs at the mature stage as pre- and post-disturbance fuels are largely decayed but the new stand has not created much new coarse woody debris. Eventually the woody debris levels increase again.

A confounding factor in the succession patterns for fine fuels is fire intensity; crown fires consume leaf and fine branch fuels and leave fewer of these fuels in the postfire sere than fires that only scorch the tree crowns. For the *Tsuga heterophylla/Polystichum munitum* association, the ratio of high intensity crown fires to lower intensity crown scorch fires, both of which can result in total stand mortality, has not been established for various burning conditions in this fire regime. For the Hoh fire, only 8% of the burned area in the *Tsuga heterophylla* series was a crowning fire (Agee and Huff 1980); aerial photographs taken the year after the Queets fire suggest a similar percent of crowning activity. More crown fire activity would be likely if fire weather were more severe or on drier associations in the *Tsuga heterophylla* series, and fuel succession trends would be different. Amounts of fine fuels would decrease in early succession and result in lower surface fireline intensity and rate of spread.

Maximum levels of total aboveground biomass were reached in the oldest stand; these levels are high but are not the highest in the region or for this forest type (Waring and Franklin 1979). While at 500 years Douglas-fir remains a dominant live biomass component, simulation modeling of older stands and observations in limited examples of such stands suggest that Douglas-fir density continues to decline and without catastrophic disturbance disappears from the stand by age 750–1000 (Dale *et al.* 1986): foliar biomass then increases because of the dominance of shade-tolerant species, but total live aboveground biomass remains stable. Dead aboveground biomass was not simulated, but once Douglas-fir logs decay a lower standing crop of logs is likely (Spies *et al.* 1985) because western hemlock produces smaller stems, which generally decay faster (Graham 1982).

Surface fire behavior is not a simple function of stand age. Over the sere studied, it was highest in the early successional stages, lowest in midsuccessional stages, and then gradually increased in the old-growth stage. Patterns beyond 500 years are speculative: continuing the trend towards a multilayered, all-sized stand structure could link surface fuels to crown fuels and increase crowning potential. A clearly evident lower surface fire behavior occurred after crown closure, when surface fuels may be separated from crown fuels by a vertical gap of 20 m or more.

High surface fire potential during early successional stages in western hemlock/Douglas-fir forest is well known (Isaac 1940). Fire encourages bracken fern, which is conducive to reburning because of its highly flammable cured fronds; this "vicious cycle" can significantly delay forest development. The best example of reburning in this forest type is the Tillamook fire, which burned first in 1933, with reburns of portions of the original fire in 1939, 1945, and 1951 (Pyne 1982). The potential for early reburns has prompted speculation that reburns may be a cause of wide periods for early seral species recruitment commonly noted in this forest type (Franklin and Hemstrom 1981). Given sufficient sources for reignition, this hypothesis is likely to be valid in certain areas, particularly with higher lightning fire probability towards the southern Cascades (Komarek 1968). However, factors such as absence of seed source and post-fire climate have also affected seral species recruitment after fires (Hemstrom and Franklin 1982).

A key element in the design of old-growth forest "islands" as wildlife habitat is protection from catastrophic fire. Harris (1984) has suggested that old-growth patches be surrounded by mature forest, which he assumed was less flammable than early successional stages. From a fire protection standpoint, mature forest appears to be a better buffer than either very young or very old natural stands. However, where young stands are created by timber harvesting rather than by fire, lowered fuel conditions created by yarding unmerchantable material or careful slash burning might reduce some of the early sere fire behavior potential.

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AGEE, J. K. 1981. Fire effects on Pacific Northwest forests: flora, fuels, and fauna. *In* Northwest Fire Council Proceedings, Northwest Fire Council, Portland, OR. pp. 54–66.

——— 1983. Fuel weights of understory-grown conifers in southern Oregon. Can. J. For. Res. **13**: 648–656.

AGEE, J. K., and FLEWELLING, R. 1983. A fire cycle model based on climate for the Olympic Mountains, Washington. *In* Seventh Conference on Fire and Forest Meteorology. American Meteorological Society, Boston. pp. 32–37.

AGEE, J. K., and HUFF, M. H. 1980. First year ecological effects of the Hoh Fire, Olympic Mountains, Washington. *In* Sixth Conference on Fire and Forest Meteorology. Society of American Foresters, Washington, DC. pp. 175–181.

AGEE, J. K., PICKFORD, S. G., KERTIS, J., FINNEY, M., DE GOUVENAIN, R., QUINSEY, S., NYQUIST, M., ROOT, R., STITT, S., WAGGONER, G., and TITLOW, B. 1985. Vegetation and fuel mapping of North Cascades National Park Service Complex. Final Contract Report, National Park Service, Seattle.

ALBINI, F. A., and BAUGHMAN, R. G. 1979. Estimating windspeeds for predicting wildland fire behavior. U.S. For. Serv. Res. Pap. INT-221.

AVERY, T. E., and BURKHART, H. E. 1983. Forest measurements. McGraw-Hill Book Co., New York.

BEVINS, C. D. 1978. Fuel particle diameters of western hemlock slash. U.S. For. Serv. Res. Note INT-243.

BROWN, J. K. 1974. Handbook for inventorying downed woody material. U.S. For. Serv. Gen. Tech. Rep. INT-16.

——— 1978. Weight and density of crowns of Rocky Mountain conifers. U.S. For. Serv. Gen. Tech. Rep. INT-97.

BROWN, J. K., and SEE, T. E. 1981. Downed dead woody fuel and biomass in the northern Rocky Mountains. U.S. For. Serv. Gen. Tech. Rep. INT-117.

BURGAN, R. E., and ROTHERMEL, R. C. 1984. BEHAVE: fire behavior prediction and fuel modeling system – FUEL subsystem. U.S. For. Serv. Gen. Tech. Rep. INT-167.

CLINE, S. P., BERG, A. B., and WIGHT, H. M. 1980. Snag characteristics and dynamics in Douglas-fir forests, western Oregon. J. Wildl. Manage. **44**: 773–786.

DALE, V. H., and HEMSTROM, M. 1984. CLIMACS: a computer model of forest stand development for western Oregon and Washington. U.S. For. Serv. Res. Pap. PNW-327.

DALE, V. H., HEMSTROM, M., and FRANKLIN, J. 1986. Modeling the long-term effects of disturbances on forest succession, Olympic Peninsula, Washington. Can. J. For. Res. **16**: 56–67.

FAHNESTOCK, G. R. 1976. Fires, fuels, and flora as factors in wilderness management: the Pasayten case. Proc. Tall Timbers Fire Ecol. Conf. **15**: 33–70.

FAHNESTOCK, G. R., and AGEE, J. K. 1983. Biomass consumption and smoke production by prehistoric and modern forest fires in western Washington. J. For. **81**: 653–657.

FRANKLIN, J. F., and DYRNESS, C. T. 1973. Natural vegetation of Oregon and Washington. U.S. For. Serv. Gen. Tech. Rep. PNW-8.

FRANKLIN, J. F., and HEMSTROM, M. A. 1981. Aspects of succession in the coniferous forests of the Pacific Northwest. *In* Forest succession: concepts and application. Chap. 14. *Edited by* D. C. West, H. H. Shugart, and D. B. Botkin. Springer-Verlag, New York.

FRANKLIN, J. F., CROMACK, K., JR., DENISON, W., MCKEE, A., MASER, C., SEDELL, J., SWANSON, F., and JUDAY, G. 1981. Ecological characteristics of old growth Douglas-fir forests. U.S. For. Serv. Gen. Tech. Rep. PNW-118.

GHOLZ, H. L., GRIER, C. C., CAMPBELL, A. G., and BROWN, A. T. 1979. Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Oreg. State Univ. For. Res. Lab. Res. Pap. No. 41.

GRAHAM, R. L. 1982. Biomass dynamics of dead Douglas-fir and western hemlock boles in mid-elevation forests of the Cascade Range. Ph.D. thesis, Oregon State University, Corvallis, OR.

GRAHAM, R. L., and CROMACK, K., JR. 1982. Mass, nutrient content, and decay rate of dead boles in rain forests of Olympic National Park. Can. J. For. Res. **12**: 511–521.

GRIER, C. C. 1978. A *Tsuga heterophylla – Picea sitchensis* ecosystem of coastal Oregon: decomposition and nutrient balances of fallen logs. Can. J. For. Res. **8**: 198–206.

HARMON, M. E., FRANKLIN, J. F., SWANSON, F. J., SOLLINS, P., LATTIN, J. D., ANDERSON, N. H., GREGORY, S. V., CLINE, S. P., AUMEN, N. S., SEDELL, J. R., CROMACK, K., JR., and CUMMINS, K. W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. **15**: 133–302.

HARRIS, L. D. 1984. The fragmented forest. University of Chicago Press, Chicago.

HEMSTROM, M. A., and FRANKLIN, J. F. 1982. Fire and other disturbances of the forests in Mount Rainier National Park. Quat. Res. **18**: 32–51.

HUFF, M. H. 1984. Post-fire succession in the Olympic Mountains, Washington: forest vegetation, fuels, and avifauna. Ph.D. dissertation, University of Washington, Seattle.

HUFF, M. H., and AGEE, J. K. 1980. Characteristics of large lightning fires in the Olympic Mountains, Washington. *In* Sixth Conference on Fire and Forest Meteorology. American Meteorological Society, Boston. pp. 117–123.

ISAAC, L. A. 1940. Vegetation succession following logging in the Douglas-fir region with special reference to fire. J. For. **38**: 716–721.

KOMAREK, E. V., SR. 1968. The nature of lightning fires. Proc. Tall Timbers Fire Ecol. Conf. **7**: 5–42.

LOTAN, J. E., BROWN, J. K., and NEUENSCHWANDER, L. F. 1985. Role of fire in lodgepole pine forests. *In* Lodgepole pine: the species and its management. Washington State University, Seattle. pp. 133–152.

MORRIS, W. G. 1937. Diurnal changes in fuel moisture in the Douglas-fir forest as affected by cover conditions. U.S. For. Serv. Pac. Northwest For. Range Exp. Stn. Res. Notes 23.

OLIVER, C. D. 1981. Forest development in North America following major disturbances. For. Ecol. Manage. **3**: 153–168.

PYNE, S. J. 1982. Fire in America: a cultural history of wildland and rural fire. Princeton University Press, Princeton, NJ.

SOLLINS, P. 1982. Input and decay of coarse woody debris in coniferous stands in western Oregon and Washington. Can. J. For. Res. **12**: 18–28.

SPIES, T. A., FRANKLIN, J. F., THOMAS, T. B., SPYCHER, G., and AHRENS, G. 1985. Patterns of coarse woody debris in a chronosequence of Douglas-fir stands in the western Cascades of Oregon and Washington. Bull. Ecol. Soc. Am. **66**: 276.

TURNER, J., and LONG, J. N. 1975. Accumulation of organic matter in a series of Douglas-fir stands. Can. J. For. Res. **5**: 681–690.

USDA FOREST SERVICE. 1974. Wood handbook: wood as an engineering material. U.S. Forest Products Laboratory, Agric. Handb. No. 72.

VAN WAGNER, C. E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. **7**: 23–34.

WARING, R. H., and FRANKLIN, J. F. 1979. Evergreen coniferous forests of the Pacific Northwest. Science (Washington, D.C.), **204**: 1380–1386.

WILLIAMS, C. B., and DYRNESS, C. T. 1967. Some characteristics of forest floors and soils under true fir-hemlock stands in the Cascade Range. U.S. For. Serv. Res. Pap. PNW-37.