Decomposition of logging residues in Douglas-fir, western hemlock, Pacific silver fir, and ponderosa pine ecosystems

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Logging residue decomposition rates were determined in four conifer forest ecosystems in the State of Washington, U.S.A. (coastal western hemlock, Puget lowland Douglas-fir, high-elevation Pacific silver fir, and eastern Cascade ponderosa pine), by examining wood density changes in a series of south-facing harvest areas with residues of different ages. Decomposition rates were determined for two diameter classes (1−2 and 8−12 cm) and two vertical locations (on and >20 cm above the soil surface). Pacific silver fir and ponderosa pine ecosystems had the lowest k values (0.005 and 0.010 year^{-1}, respectively) followed by Douglas-fir (range, 0.004−0.037 year^{-1}) and western hemlock (range, 0.010−0.030 year^{-1}). Small-diameter residues decomposed at rates significantly slower than large-diameter residues in Douglas-fir and western hemlock ecosystems; this relationship was also implied in the other ecosystems. In all four ecosystems, dry season moisture contents were lower in smaller-diameter residues. Moisture levels associated with small-diameter residues were too low for significant decomposition to occur during the dry summer period and probably contributed to the slow annual decay rates. Residues located above the soil surface decomposed significantly slower than residues on the soil surface only in the Douglas-fir ecosystem. Dry season residue moisture, rather than initial lignin concentration, appeared to be the dominant factor determining residue decomposition rates on exposed harvested areas.

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Les auteurs ont mesuré le taux de décomposition des résidus de coupe dans quatre écosystèmes forestiers de conifères dans l'État de Washington, U.S.A., par l'examen des changements de la densité du bois dans une série de parterres de coupe d'exposion sud et d'âges différents. Les quatre types d'écosystèmes forestiers sont une forêt côtière de pruche de l'ouest, une forêt de douglas des basses-terres Puget, une forêt de sapin argenté du Pacifique de haute altitude et une forêt de pin ponderosa de l'est des Cascades. Les taux de décomposition furent déterminés pour deux classes de diamètre (1−2 et 8−12 cm) et deux positions verticales (à la surface du sol et à >20 cm au-dessus de la surface). C'est dans les écosystèmes de sapin argenté du Pacifique et de pin ponderosa que les valeurs k étaient les plus faibles (0,005 et 0,010 an^{-1}, respectivement) suivies par celles du douglas (0,004−0,037 an^{-1}) et de la pruche de l'ouest (0,010−0,030 an^{-1}). La décomposition des résidus de petit diamètre fut significativement plus lente que celles des résidus de fort diamètre dans les écosystèmes de douglas et de pruche de l'ouest; on assume le même comportement dans les autres écosystèmes. Dans les quatre écosystèmes, les niveaux d'humidité des résidus de petit diamètre étaient trop faibles pour qu'une décomposition significative se produise au cours de la période sèche estivale et ceci a probablement contribué aux faibles taux annuels de décomposition. C'est seulement dans l'écosystème de douglas que les résidus situés au-dessus de la surface du sol se sont décomposés plus lentement que les résidus en contact avec le sol. Il semble que l'humidité des résidus en saison sèche, plutôt que la concentration initiale en lignine, soit le facteur dominant qui détermine le taux de décomposition des résidus dans les parterres de coupe.

[Traduit par le journal]

Introduction

Clear-cutting in the Pacific Northwest results in an average woody residue volume of 280 m^3 ha^{-1} (Howard 1981), representing about a 40% increase over preharvest dead and cull materials on a site. Decomposition (decay) of woody debris on harvested sites may assist in area recovery and productivity maintenance (Covington 1981; Harvey et al. 1976; Kimmins and Feller 1976). Little is known, however, about wood decomposition processes or turnover rates under postharvest microclimatic conditions. Studies of residue turnover rates indicate wide variabilities both between and within species as well as between and within sites (Abbott and Crossley 1982; Barber and Van Lear 1984; Edmonds et al. 1980). It is known that site microclimate may be altered by overstory removal, causing high temperatures that can exceed tolerance limits of decay organisms (Loman 1965; Seastedt and Crossley 1981; Whitford et al. 1981) and reduced moisture contents in litter and upper soil layers (Harvey et al. 1976; Seastedt and Crossley 1981). Additional knowledge regarding woody residue decom-

position rates is necessary to determine the influence of residues on site productivity and to assess their potential as fuel for forest fires.

This study was designed to quantify logging residue decomposition rates in four coniferous ecosystems in the State of Washington and to examine the influence of microclimate, residue diameter, residue chemistry, and contact with the soil surface on these rates.

Materials and methods

Study areas

Study areas were established in four coniferous ecosystems in Washington, U.S.A.: coastal western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Puget lowland Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western Cascade mountain Pacific silver fir (*Abies amabilis* (Dougl.) Forbes), and eastern Cascade ponderosa pine (*Pinus ponderosa* Dougl. ex D. Don) (Fig. 1). These ecosystems represent the dominant vegetation communities along an approximate southwest−northeast transect through the maritime Pacific Northwest province.

Climate in all areas is predominantly temperate−marine, resulting from moist air masses originating over the Pacific Ocean. Prevailing

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TABLE 1. Location, climatic data, age structure, and proximity of harvest units in the western hemlock, Douglas-fir, Pacific silver fir, and ponderosa pine ecosystems

Ecosystem	Mean elevation (m)	Mean annual temperature* (°C)	Mean maximum July temperature* (°C)	Mean annual precipitation* (cm)	Harvest year	Residue age (years)	Maximum distance between harvest units (km)
Western hemlock: Olympic peninsula (13 km east of Pacific Ocean)	60	10.0	19.4	250	1982,1979,1976,1974	0†,3,6,8	13.8
Douglas fir: University of Washington's Pack Forest (95 km south of Seattle, WA)	430	9.2	24.4	104	1981,1978,1976,1973	0†,3,5,8	3.2
Pacific silver fir: Cedar River Watershed (15 km southwest of Snoqualmie Pass)	1130	4.7	17.1	230	1981,1979,1976,1973	0†,2,5,8	4.8
Ponderosa pine: Wenatchee National Forest (58 km east of Steven's Pass)	750	8.3	27.3	60	1982,1975,1971,1967	0,7,11,15	4.3

*Obtained from nearest permanent weather station.
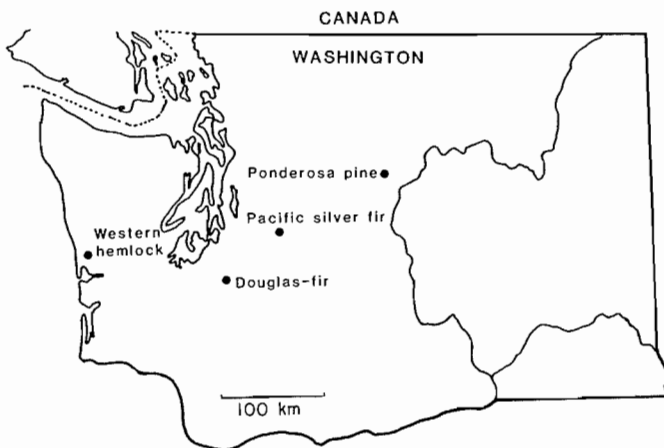†Clear-cuttings less than 1 year old.

FIG. 1. Location of the study sites in Washington.

winds are from the southwest in fall and winter, gradually shifting to the northwest in late spring and summer. There is a well-defined dry season in summer; generally less than 10% of the annual precipitation falls in the 3-month period from June to August. The ponderosa pine ecosystem is occasionally influenced by arctic air masses from Canada, which generally are prevented from affecting the western Washington ecosystems by the shielding effect of the Cascade mountain range. Likewise, during the rainy season, the ponderosa pine site is shielded by the Cascades from major precipitation. The western hemlock and Douglas-fir sites typically do not accumulate snow; the Pacific silver fir and ponderosa pine sites are often snow covered from November to June and from November to March, respectively. Climate specifics are given in Table 1.

Sampling residues for estimating decomposition rates

Specific gravity (density) was used to calculate decay rates as described by Foster and Lang (1982). Four different-aged harvest units were chosen within each ecosystem. Each had similar aspect (south), slope, original stand composition, and soil. Within each ecosystem, the only residues sampled were of the same species as the name of that ecosystem, e.g., in the Douglas-fir ecosystem, only Douglas-fir residues were sampled. Old-growth stands had been harvested by clearcutting in the western hemlock, Douglas-fir, and Pacific silver fir ecosystems. The ponderosa pine stands had been precommercially

thinned at age 40–50 years. Age structures of the resulting harvest units are given in Table 1. Residues from units harvested during the same year that sampling occurred were used for time 0 sampling in the western hemlock, Douglas-fir, and silver fir ecosystems. Fresh material was cut from 22 live trees in the ponderosa pine ecosystem. Field sampling was conducted during the summer of 1981 in the Douglas-fir and Pacific silver fir ecosystems and during the summer of 1982 in the western hemlock and ponderosa pine ecosystems.

Residues were sampled from two diameter classes (1–2 and 8–12 cm diameter inside bark (DIB)) and two vertical locations (on and >20 cm above the soil surface). Within each harvest unit (except time 0) the number of samples taken for a diameter class – vertical location combination averaged 25 (Table 2). On the average, 350 residue samples were collected from each ecosystem. Four transects were established in each harvest unit; transect length was defined by the clear-cut boundary and spacing between sampling points depended on the quantity of slash. When a suitable residue was encountered, it was sampled as follows: 10–30 cm long sections were cut with a chain saw from 8–12 cm DIB residues (branches or stem tops) avoiding side branches and knots. The 1- to 2-cm residue (minimum length, 15 cm) was collected from the soil surface, a debris pile, or broken from a main stem or branch. Broken or extremely rotten pieces of either diameter class were placed in paper bags. To prevent microbial and insect activity during storage, samples were either air dried or ovendried depending on moisture content and amount of insect activity.

Dry season residue moisture contents

Residue moisture contents were estimated in all harvest units during August of 1981 or 1982. These moisture values were assumed to represent the annual low, occurring during the 3-month period from June to August when precipitation is lowest. A minimum of 3–4 days free of precipitation was required prior to sampling (often this moisture-free period extended for 2 weeks or more). To prevent moisture loss during transportation, cross sections of residues were broken up to fit into 500-mL polybottles. Samples were weighed, dried at 70°C for 48 h, and reweighed for calculation of percent moisture content on a dry-weight (DW) basis. Approximately 10 replications per treatment were collected. After an angular (arc sine) transformation of the data, a three-way analysis of variance (ANOVA) was used to determine the infuence of residue age, diameter, and vertical location on percent moisture within each ecosystem.

Microclimate influence on decomposition rates in different ecosystems

To determine the influence of microclimate on residue decom-

position in the four sites, red alder (*Alnus rubra* Bong) "reference substrates" 30 cm long and 1–2 cm diameter were cut from living trees at the University of Washington's Charles Lathrop Pack Forest. Green weights were obtained and moisture contents were subsampled for initial DW estimations. Within each ecosystem, 20 reference substrate samples were placed on the soil surface in either the 1975 or 1976 harvest unit (see Table 1) during the month of September 1981. Ten samples were removed after each of 1 and 2 years. Weight loss was calculated as the difference in estimated initial DW and measured final DW.

During May 1982, an underburn in the ponderosa pine ecosystem skimmed over the site, visibly damaging nearly one-half of the 20 alder standards and at least momentarily affecting the microclimate. Nine standards showing no damage were removed as scheduled in September 1982, leaving none available for the 2-year removal.

A one-way ANOVA was performed to determine ecosystem effects on red alder decomposition. Scheffe's multiple-comparison test was used to define homogeneous groups.

Laboratory analyses

Specific gravity of coniferous wood increases from the pith to the bark (Panshin and de Zeeuw 1970). Additionally, branch and top wood often contain large amounts of compression wood, marked by eccentric growth rings, which contain an abnormally large proportion of latewood and thicker cell walls. Specific gravity in compression wood is increased by about one-third over that shown in normal wood (Panshin and de Zeeuw 1970). Therefore, to account for both radial and vertical variation in specific gravity, entire cross sections were sampled.

Using a band saw, an approximately 1.5 cm thick disk was cut from the large-diameter slash and a 2.5 cm thick disk was cut from the small-diameter slash. Branch stubs or knot sections were not used. Any loose bark was removed. Species verifications were determined by light microscopy, based on anatomical characteristics (Core et al. 1976).

Because wood volume is a function of moisture content and will increase until the fiber saturation point is reached (approximately 30% on a DW basis; Anonymous 1974), moisture contents at the time of mass and volume determination must be known and standardized for all samples. This is particularly important when expressing densities of logging debris and other woody substances that are sampled at low moisture content levels. Specific gravity was expressed on an ovendry weight per "green" (saturated) volume basis (Anonymous 1974). Samples were saturated overnight in distilled water under a vacuum. This soaking also facilitated removal of any remaining bark. Volume determinations were made by a water-displacement technique (Anonymous 1952). Dry weights were obtained after drying at 105°C for 24 h.

Several modifications were necessary to process rotten wood samples which tended to disintegrate upon bark removal, saturation, or handling. Samples were enclosed in nylon mesh bags for saturation. Individual pieces were then transferred after being shaken to remove excess water into an immersed wire screen basket on a top-loading balance. The volume of the entire sample was estimated collectively.

Concentrations of lignin, cellulose, and noncell wall (extractives, hemicelluloses, etc.) constituents in initial (time 0) wood samples were determined using the Van Soest (1963) technique.

Estimating residue decomposition rates

Residue decomposition rates were estimated using an exponential decay model (multiplicative error assumed) which has found wide use in studies of this nature (Barber and Van Lear 1984; Foster and Lang 1982; Graham and Cromack 1982):

[1] $\quad Y_t = Y_0 e^{-kt}$

where Y_t represents specific gravity at time t, Y_0 is the specific gravity at time 0, t is the years since harvesting, e is the base of natural logarithms, and k is the coefficient of residue decay.

By taking the logarithm ($\log_e$) of both sides, the above model was converted into the form used in making actual calculations:

[2] $\quad \log_e Y_t = \log_e Y_0 - kt$

TABLE 2. Mean (±SD) specific gravity values (number of replicates in parentheses) for western hemlock, Douglas-fir, Pacific silver fir, and ponderosa pine logging debris from harvest units of varying ages (years)

	Douglas fir						Western hemlock						Silver fir						Ponderosa pine					
	SM		LG		Age (years)		SM		LS		Age (years)		SM		LG		Age (years)		SM		LG		Age (years)
Age (years)	A	O	A	O			A	O	A	O			A	O	A	O			A	O	A	O	
0	0.520± 0.042 (27)	0.520± 0.042 (27)	0.466± 0.058 (24)	0.466± 0.058 (24)	0		0.576± 0.046 (24)	0.576± 0.046 (24)	0.450± 0.046 (25)	0.450± 0.046 (25)	0		0.542± 0.049 (37)	0.542± 0.049 (37)	0.423± 0.084 (25)	0.423± 0.084 (25)	0		0.467± 0.032 (22)	0.467± 0.032 (22)	0.411± 0.044 (22)	0.411± 0.044 (22)	0
3	0.523± 0.032 (16)	ND	0.420± 0.029 (7)	0.387± 0.057 (7)	3		0.579± 0.051 (26)	0.569± 0.036 (21)	0.427± 0.058 (26)	0.453± 0.076 (25)	2		0.549± 0.041 (28)	0.525± 0.063 (25)	0.423± 0.057 (26)	0.466± 0.064 (22)	2		0.458± 0.055 (26)	0.415± 0.062 (27)	0.332± 0.063 (26)	0.325± 0.101 (25)	7
5	0.522± 0.034 (20)	0.499± 0.047 (25)	0.425± 0.032 (25)	0.403± 0.063 (24)	5		0.525± 0.055 (28)	0.549± 0.055 (25)	0.380± 0.052 (23)	0.345± 0.054 (25)	5		0.550± 0.047 (20)	0.539± 0.045 (36)	0.428± 0.068 (23)	0.466± 0.081 (24)	5		0.424± 0.039 (27)	0.438± 0.067 (27)	0.352± 0.067 (23)	0.341± 0.081 (24)	11
8	0.503± 0.044 (34)	0.477± 0.051 (42)	0.407± 0.044 (20)	0.345± 0.068 (21)	8		0.550± 0.050 (25)	0.539± 0.091 (24)	0.383± 0.064 (25)	0.360± 0.055 (27)	8		0.533± 0.051 (25)	0.520± 0.042 (25)	0.392± 0.085 (25)	0.401± 0.065 (26)	8		0.446± 0.061 (26)	0.404± 0.084 (26)	0.336± 0.051 (24)	0.345± 0.087 (26)	15

NOTE: SM, 1–2 cm diameter; LG, 8–12 cm diameter; O, residue location on the forest floor or soil surface; A, residue location >20 cm above soil surface; ND, no data available.

TABLE 3. Values of k obtained as slopes of regression equations from analysis of covariance using the linear transformation of the negative exponential model (ln specific gravity (final) = ln specific gravity (initial) $-kt$, where k is the decay coefficient and t is the number of years since death)

	k values* for significant treatment(s)			k-values for individual treatments	
Ecosystem	Treatment†	k	n	Treatment†	k‡
Western hemlock	8–12 cm, A+O	0.030	176	8–12 cm, A	0.024a
				8–12 cm, O	0.036a
	1–2 cm, A+O	0.010	173	1–2 cm, A	0.010b
				1–2 cm, O	0.010b
Douglas-fir	8–12 cm, A	0.016	76	8–12 cm, A	0.016a
	8–12 cm, O	0.037	76	8–12 cm, O	0.037b
	1–2 cm, A	0.004	97	1–2 cm, A	0.004c
	1–2 cm, O	0.011	94	1–2 cm, O	0.011d
Pacific silver fir	1–2, 8–12 cm, A+O	0.005	367	8–12 cm, A	0.009a
				8–12 cm, O	0.009a
				1–2 cm, A	0.002a
				1–2 cm, O	0.003a
Ponderosa pine	1–2, 8–12 cm, A+O	0.010	351	8–12 cm, A	0.013a
				8–12 cm, O	0.012a
				1–2 cm, A	0.005a
				1–2 cm, O	0.009a

*All k values listed for significant treatments (column 2) have overall regression significance of $p < 0.01$, except Douglas-fir 1–2 cm, A, where $p = 0.07$.
†A, above ground; O, on ground.
‡Values (slopes) within the same ecosystem followed by the same letter are not significantly ($p = 0.05$) different.

It should be pointed out that k, the decay coefficient or annual fractional loss rate (Olson 1963), is the only parameter of interest in the above expression. If our objective was also to predict specific gravity (parameter Y), then bias as a result of the transformation would have to be considered for an estimate of Y. The logarithmic transformation does not, however, bias the resulting estimate of k.

To determine whether the rate of decomposition was affected by ecosystem, diameter class (1–2 and 8–12 cm), and vertical location (on or above the ground), Eq. 2 was expanded to include these factors. The expanded model was then tested for heterogeneity of slopes using an analysis of covariance (Klienbaum and Kupper 1978; Nie *et al.* 1975) where the different regression slopes represent differing coefficients of decomposition (i.e., k values).

Results

Differences in decomposition rates among ecosystems

Initial specific gravity values for debarked, undecomposed residues of the 1–2 cm DIB classes (range, 0.467–0.576) were higher than the initial values for the 8–12 cm DIB classes (range, 0.411–0.466) in all ecosystems (Table 2). Initial coefficients of variation averaged 11%. A coefficient of variation of about 10% is typical in describing density variability in most domestic species (Anonymous 1974). Specific gravity generally decreased with increasing residue age (Table 2).

Analysis of covariance detected an overall significant ecosystem effect on decomposition rates ($p < 0.01$). A separate regression model was then used for each ecosystem to examine the effects of diameter and vertical location. The decay coefficients (slopes) obtained from these regressions are shown in Table 3. The highest of these k values were from the Douglas-fir and western hemlock ecosystems.

Reference red alder decomposition showed significant differences in weight loss among ecosystems after 1 and 2 years (Table 4). Alder decomposed significantly faster in the Douglas-fir and western hemlock ecosystems than in the Pacific silver fir ecosystem. After 1 year, reference red alder

TABLE 4. Alder standard decomposition data: percent weight ($\pm$SE) remaining after 1 or 2 years decomposition (number of replicates in parentheses)

Site of alder standard location	% weight remaining*	
	After 1 year	After 2 years
Western hemlock	86.2±1.4(10)a	69.4±3.2(10)a
Douglas-fir	87.5±1.3(10)a	67.3±3.8(8)a
Ponderosa pine	90.4±1.1(9)a,b	
Pacific silver fir	93.3±1.0(10)b	84.9±0.9(10)b

*Values within a sample time followed by the same letter(s) are statistically similar at $p = 0.05$ (Sheffé multiple-range test).

removed from the ponderosa pine ecosystem showed no significant difference in weight loss relative to the other ecosystems.

Differences in decomposition rates within ecosystems

In the Pacific silver fir and ponderosa pine ecosystems, neither residue diameter nor vertical location had any significant effect on decay rates. Therefore, one decay coefficient is sufficient to describe decay rates for these sites. Treatment coefficients are shown for comparative purposes (Table 3). Both ecosystems exhibited a similar trend; the 8- to 12-cm classes decomposed faster (indicated by higher k values) than the 1- to 2-cm classes.

Western hemlock decomposition rates were significantly influenced by residue diameter ($p < 0.01$), but not by vertical location; therefore, two coefficients are necessary to describe residue decay rates in that ecosystem (Table 3). The k value for the large-diameter residue class is greater than the k value for the small-diameter class.

In the Douglas-fir ecosystem, the effects of both diameter and vertical location on decay rates were significant (Table 3). Of the four separate coefficients (k values) ascribed to residue
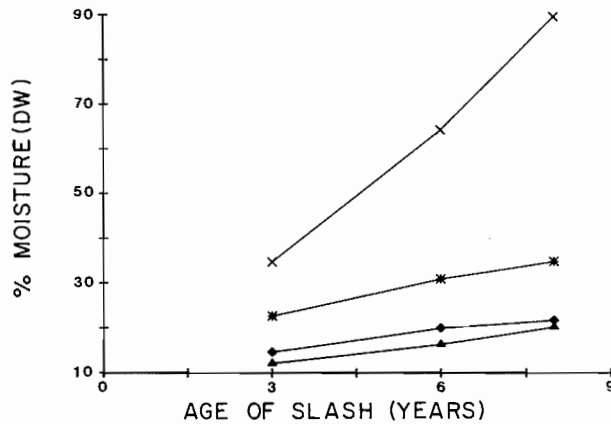
FIG. 2. Dry season moisture content of western hemlock residues in relation to residue age and diameter. For explanation of treatment codes, refer to Table 2: $*$, LG, A; $\times$, LG, O; $\blacktriangle$, SM, A; $\blacklozenge$, SM, O.
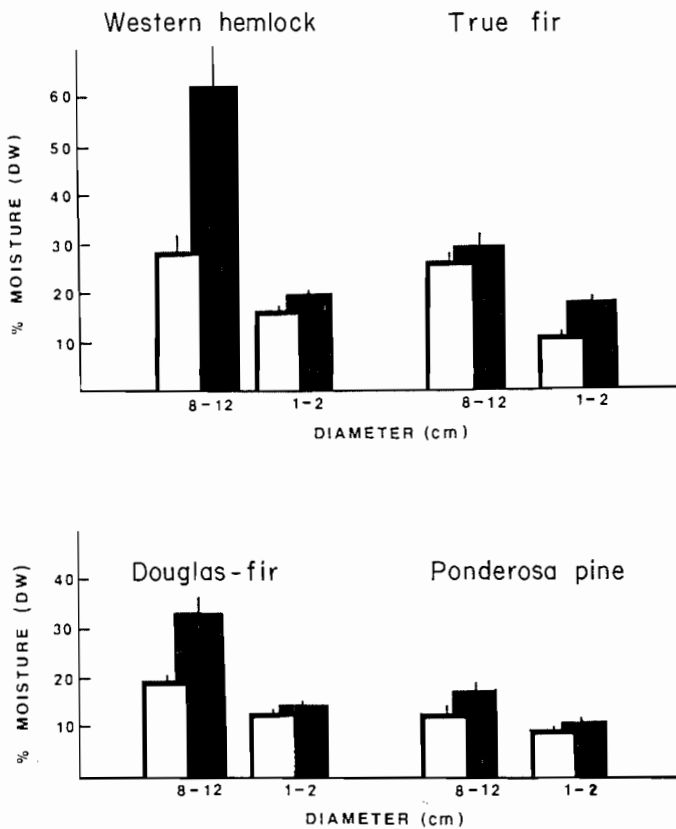

FIG. 3. Mean dry season residue moisture contents averaged over residue age in relation to diameter and vertical location ($\square$, above surface; $\blacksquare$, on surface) in western hemlock, Pacific silver fir, Douglas-fir, and ponderosa pine ecosystems.

FIG. 4. Relationship between residue decay constant (k value) and mean dry season residue moisture content for all treatments. $+$, 8−12 cm diameter; $\blacklozenge$, 1−2 cm diameter; WH, western hemlock; DF, Douglas-fir; TF, Pacific silver fir; PP, ponderosa pine; A, >20 cm above soil; O, on the soil surface.

TABLE 5. Initial lignin, cellulose and noncell wall percentages ($\pm$SD) in two diameters of Douglas-fir, western hemlock, Pacific silver fir and ponderosa pine logging residues ($n = 3$, except for Douglas-fir 8−12 cm, where $n = 4$)

Species	Diam. (cm)	Lignin	Cellulose	Noncell wall
Western hemlock	1−2	25.4±2.1	42.9±1.2	31.3±2.6
	8−12	25.2±0.5	51.4±2.8	22.7±3.4
Douglas-fir	1−2	24.6±3.6	41.0±3.7	34.4±0.3
	8−12	26.9±6.3	44.5±4.9	28.6±1.9
Pacific silver fir	1−2	28.4±2.2	41.0±0.8	30.5±1.7
	8−12	26.8±1.7	43.8±0.8	29.4±2.3
Ponderosa pine	1−2	17.8±3.8	53.2±3.5	29.0±0.9
	8−12	25.7±0.4	34.8±1.5	39.5±1.7

ture content changed significantly ($p < 0.01$) with time since harvesting only at the western hemlock site, where residue moisture increased with time, particularly for the 8- to 12-cm treatment located on the soil surface (Fig. 2). Although the Douglas-fir residues did not collectively exhibit increases in moisture content, the 8- to 12-cm residues did show significant increases in moisture ($p < 0.05$). Moisture data from fresh material (i.e., time 0) was omitted from this analysis.

Figure 3 shows dry season residue moisture contents pooled over residue age for all study areas. The effect of diameter on moisture was significant in all ecosystems (ANOVA, $p < 0.05$), 1- to 2-cm residues being drier than the larger 8- to 12-cm residues. Analysis of variance also showed a significant ($p < 0.05$) vertical location effect on moisture content in three ecosystems (western hemlock, Douglas-fir, and silver fir); elevated residues had lower moisture contents during the dry season.

The effect of diameter is also evident in Table 3 where the k values for 8−12 cm are greater than those for 1−2 cm. As stated previously, this general trend was present in all ecosystems, albeit not statistically significant for Pacific silver fir and ponderosa pine. The relationship between decay coefficient and dry season moisture content is depicted in Fig. 4, showing a cluster of 1- to 2-cm data in the low range on each axis. Both pine and silver fir lie within or near the cluster, whereas moisture contents and k values for Douglas-fir and hemlock are more variable with residue size and location.

decomposition in that ecosystem, only the coefficient for 1−2 cm diameter above surface was not significant ($p < 0.05$). Decomposition rates for both diameter classes were slower for residues above the ground. The effect of diameter on decay rates of Douglas-fir was the same as that for western hemlock (and similar to trends exhibited by Pacific silver fir and ponderosa pine); smaller-diameter residues decomposed slower than larger-diameter residues.

Decomposition rates and residue moisture

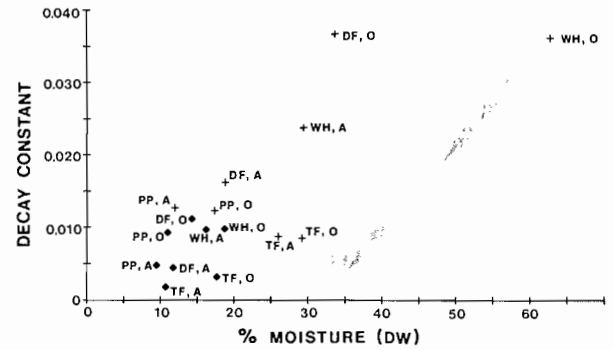Analysis of variance showed that dry season residue mois-

Decomposition rates and initial lignin concentration

Initial lignin percentages in the two diameter classes of res-

idues in the four ecosystems are shown in Table 5 along with cellulose and noncell wall percentages. There was little difference in lignin concentration among species and diameter classes (ANOVA, $p > 0.05$). Lowest lignin concentrations occurred in the 1- to 2-cm ponderosa pine (17.8%) with the highest in the 1- to 2-cm Pacific silver fir (28.4%). Cellulose concentrations ranged from 34.8 to 53.2%. Noncell wall concentrations ranged from 39.5% in $8-12$ cm diameter ponderosa pine residues, which were very resinous, to 22.7% in $8-12$ cm western hemlock.

Discussion

Slash decomposition rates and effects of local microclimate

Decay rate differences among ecosystems are due to the local microclimate, the effects of resident decomposer organisms, and the quality of the wood as a resource for the decomposers (Swift 1977). Ecosystems with the lowest overall k values (ponderosa pine and Pacific silver fir) exhibited climatic extremes characterized by winter minimum air temperatures typically below 0°C and accumulations of snow. The highest decay coefficients were in the western hemlock and Douglas-fir sites where winter temperatures were warmest. "Reference" alder wood decay rates indicated that nonnative residues also decompose slowest in those ecosystems with low natural k values, suggesting that the microclimate is a major factor controlling decomposition in these ecosystems. Low precipitation at the ponderosa pine site and low mean annual temperatures at the Pacific silver fir site contributed to microclimates resulting in lower decomposition rates. Within the time frame of this study, differences in decay rates among diameter classes and vertical heights within the two ecosystems characterized by low k values were not observed. A longer time may be necessary to observe decay rate differences among woody substrates in ecosystems with slow decomposition rates.

Residue moisture and decomposition

For woody material there is a widely accepted correlation between the fiber saturation point (FSP) and the minimal moisture necessary for aerobic fungal decomposition to occur, approximately 30% on a DW basis (Griffin 1977). Abbott and Crossley (1982) implied that reduced soil moisture could result in low decay coefficients for xeric clear-cut sites. Although we did not measure soil moisture, our research indicates that low annual decay rates may have been a result of low dry season (summer) residue moisture content (Fig. 4). Furthermore, dry season residue moisture contents were influenced by residue diameter and to some extent by vertical location. For example, the only treatments with greater than 30% moisture content during the dry summer months were 8- to 12-cm western hemlock and Douglas-fir residues located on the soil surface (Fig. 3); these were the two treatments with the highest k values (Fig. 4). In addition, these treatments were among the treatments to show significant increases in dry season moisture content with increasing residue age, as shown for western hemlock in Fig. 2. Decomposing wood gains moisture with time (Ausmus 1977; Lambert et al. 1980; McFee and Stone 1966; Meredith 1960; Yoneda 1975) as a result of the fungal liberation of metabolic water (Griffin 1977) and by the replacement of decomposed cell wall material with water contacting the wood surface. For the two treatments with the greatest decay rates, decomposition had proceeded to the point where moisture limitation, even during the dry season, was less likely.

Contrary to the current hypothesis that increased surface area to volume ratios (in smaller diameter material) result in greater surface colonization and therefore higher decay rates (Foster and Lang 1982; Graham and Cromack 1982; Sollins 1982), this study suggests that surface area on exposed sites may be functioning more as a vehicle of moisture loss than as a colonization foothold. Barber and Van Lear (1984), showing a direct relationship between decay coefficient and residue diameter, demonstrated that small-diameter (<2.5 cm) loblolly slash decomposed slower than medium- (2.5−7.5 cm) or large-diameter (>7.5 cm) slash. Although moisture content information was not presented, they attributed the differences to "case hardening" (surface hardening; MacLean 1960), a condition of early seasoned wood dried below the FSP.

Observations of decay phenomena reported in the older literature describe "case-hardened" pieces of wood (generally <3 cm diameter and occurring in exposed locations) that are resistant to decay (Kimmey and Furniss 1943; Spaulding 1929; Spaulding and Hansbrough 1944). Solar radiation heats and hardens the outer wood layers. Once wood is heated and dried to below the FSP, a hysteresis effect is known to occur (Browning 1967). This would further maintain wood in conditions inhospitable to decay organisms. Low moisture content levels for small (and some large) diameter residues in this study suggest surface hardening is an important process limiting decay rates.

Low decay rates for woody residues are probably not static, but can be thought of as describing a lag phase in decomposition (Ausmus 1977), prolonged by the exposed conditions on the clear-cuttings. Childs (1939) observed that residues on dry sites decayed slowly until vegetation returned the temperature−moisture environment to one more conducive to decay. Fogel and Cromack (1977) reported k values ranging from 0.059 to 0.084 for Douglas-fir branches 1.0−1.5 cm in diameter decomposing under a canopy. For 1−2 cm diameter Douglas-fir in this study, k values were 0.004 and 0.011. We expect that incoming vegetation and the accompanying microclimatic changes occurring in the south-facing clear-cuttings would eventually result in decay coefficients closer to these reported in the literature for similar woody substrates.

Relationships between residue decomposition and other factors

Moisture limiting conditions for decomposer organisms may not be the only factor infuencing the low decay rates reported in this study. *Gloeophyllum sepiarium* (Fr.) Karst., a slash rotting fungus common in all four of the ecosystems, causes isolated decay pockets in small-diameter branches (0.64−6.4 cm) resulting in breakage at these points (Spaulding 1929). These decayed branch ends may have been undersampled by the techniques used in this study. The presence of compression wood in logging residues results in slower decay rates. Certain characteristics of compression wood probably contribute to a decay recalcitrance: more latewood, thicker cell walls, and a 9% increase in lignin over normal growth increments. Spaulding (1929) may have been referring to compression wood when he observed that "branches with red heartwood" resisted decay for a maximum length of time. The *Wood handbook* (Anonymous 1974) published the following specific gravity values for bole wood: western hemlock, 0.42; Douglas-fir, 0.45; Pacific silver fir, 0.40; ponderosa pine, 0.38. All of these values are substantially lower than the initial values for any of our diameter classes (Table 2). Although the amount of compression wood in residues was not quantified in this study,

visual documentation as well as the higher density values over normal bole wood suggest that compression wood is prevalent and may contribute to slower decay rates in small coniferous residues. Compaction of woody materials as a result of cell wall breakdown has been cited as a cause for inflated density values (Grier 1978). Wilcox (1968) found that cell wall collapse in pine blocks did not occur until 30−40% weight loss as a result of brown rot decay and not until 50% weight loss in white rotted wood. The treatment with the fastest decay rate (large-diameter Douglas-fir on the soil surface) had an average of 75% residual weight after 8 years of decay in the oldest harvest unit; compaction, therefore, was not a significant consideration in this study. Another potential reason for low k values is the possibility of not accounting for fragmentation (Lambert et al. 1980; Sollins 1982). However, other than bark sloughing, no evidence of fragmentation was noted. Fogel and Cromack (1977) indicated that litter decomposition was strongly related to initial lignin concentration and habitat type (moisture). In this study, initial lignin concentrations were essentially similar for all residue species and diameters and would not account for the observed differences in decomposition rates.

Conclusions

Low residue moisture levels during the dry season, rather than residue chemistry (i.e., lignin concentration), appeared to be the dominant factor controlling decomposition rates in harvested areas of four different coniferous ecosystems. This was supported by the weight loss differences among the "reference" red alder wood placed in the four ecosystems, which coincided with the trend of native residue decay rates (western hemlock > Douglas-fir > ponderosa pine > Pacific silver fir).

Small-diameter residues decomposed slower than large-diameter residues, especially in Douglas-fir and western hemlock ecosystems. Moisture limitations to decomposer organisms in small-diameter residues on exposed sites are the presumed causes. Residues located above the soil surface decayed significantly slower than those located on the surface only in the Douglas-fir ecosystem.

Decay coefficients (k values) for logging debris are lower than values reported for similar substrates decomposing under forest canopies. This may be due, in part, to the presence of compression wood in branches as well as to the inhospitably dry microclimate in clear-cuttings. It is expected that as clear-cuttings are revegetated, conditions will become more conducive to decay and decomposition rates would therefore increase.

Acknowledgments

ABBOTT, D. T., and D. A. CROSSLEY, JR. 1982. Woody litter decomposition following clearcutting. Ecology, **63**: 35−42.

ANONYMOUS. 1952. Methods for determining the specific gravity of wood. U.S. For. Prod. Lab. Tech. Notes, No. B-14.

ANONYMOUS. 1974. Wood handbook: Wood as an engineering material. Agric. Handb. (U.S. Dep. Agric., Sci. Educ. Adm.), No. 72.

AUSMUS, B. S. 1977. Regulation of wood decomposition rates by arthropod and annelid populations. *In* Soil organisms as components of ecosystems. *Edited by* U. Lohm and T. Persson. Ecol. Bull. No. 25. pp. 180−192.

BARBER, B. L., and D. H. VAN LEAR. 1984. Weight loss and nutrient dynamics in decomposing woody loblolly pine logging slash. Soil Sci. Soc. Am. J. **48**: 906−910.

BROWNING, B. L. 1967. Methods of wood chemistry. John Wiley & Sons, New York.

CHILDS, T. W. 1939. Decay of slash on clearcut areas in the Douglas-fir region. J. For. **37**: 955−959.

CORE, H. A., W. A. CÔTÉ, and A. C. DAY. 1976. Wood structure and identification. Syracuse University Press, Syracuse, NY.

COVINGTON, W. W. 1981. Changes in forest floor organic matter and nutrient content following clearcutting in northern hardwoods. Ecology, **62**: 41−48.

EDMONDS, R. L., D. J. VOGT, and C. H. DRIVER. 1980. Decomposition of Douglas-fir and red alder logging residues in western Washington. *In* Proceedings of the 6th Forest Fire and Meterology Conference, Seattle, WA, April 22−24, 1980. Society of American Foresters, Washington, DC. pp. 102−107.

FOGEL, R., and K. CROMACK, JR. 1977. Effect of habitat and substrate quality on Douglas-fir litter decomposition in western Oregon. Can. J. Bot. **55**: 1632−1640.

FOSTER, J. R., and G. E. LANG. 1982. Decomposition of red spruce and balsam fir boles in the White Mountains of New Hampshire. Can. J. For. Res. **12**: 617−626.

GRAHAM, R. L., and K. CROMACK, 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.

GRIFFIN, D. M. 1977. Water potential and wood-decay fungi. Annu. Rev. Phytopathol. **15**: 319−329.

HARVEY, A. E., M. F. JURGENSEN, and M. J. LARSEN. 1976. Intensive fiber utilization and prescribed fire: effects on the microbial ecology of forests. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. INT-28.

HOWARD, J. O. 1981. Ratios for estimating logging residue in the Northwest. U.S. For. Serv. Res. Pap. PNW-288.

KIMMEY, J. W., and R. L. FURNISS. 1943. Deterioration of fire-killed Douglas-fir. Tech. Bull. U.S. Dep. Agric. No. 851.

KIMMINS, J. P., and M. C. FELLER. 1976. Effect of clearcutting and broadcast slashburning on nutrient budgets, stream-water chemistry and productivity in western Canada. XVI IUFRO World Congress, Proceedings of Division 1, Norway. 1976. Norwegian IUFRO Congress Committee, c/o Norwegian Forest Research Institute, Ås-NLH, Norway. pp. 186−197.

KLEINBAUM, D. G., and L. L. KUPPER. 1978. Applied regression analysis and other multivariable methods. Duxbury Press, North Scituate, MA.

LAMBERT, R. L., G. E. LANG, and W. A. REINERS. 1980. Loss of mass and chemical change in decaying boles of a subalpine balsam forest. Ecology, **61**: 1460−1473.

LOMAN, A. A. 1965. The lethal effects of periodic high temperature on certain lodgepole pine slash decaying basidiomycetes. Can. J. Bot. **43**: 334−338.

MacLean, J. D. 1960. Preservative treatment of wood by pressure methods. Agric. Handb. (U.S. Dep. Agric., Sci. Educ. Adm.), No. 40.

McFee, W. W., and E. L. Stone. 1966. The persistence of decaying wood in the humus layers of northern forests. Soil. Sci. Soc. Am. Proc. 30: 512–516.

Meredith, D. S. 1960. Further observations on fungi inhabiting pine stumps. Ann. Bot. (London), 24: 63–78.

Nie, N. H., C. H. Hull, J. G. Jenkins, K. Steinbreener, and D. H. Bent. 1975. SPSS: statistical package for the social sciences. 2nd ed. McGraw-Hill, Inc., New York.

Olson, J. S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology, 44: 322–331.

Panshin, A. J., and C. de Zeeuw. 1970. Textbook of wood technology. Vol. I. 3rd ed. McGraw-Hill, Inc., New York.

Seastedt, T. C., and D. A. Crossley, Jr. 1981. Microarthropod response following cable logging and clearcutting in the Southern Appalachians. Ecology, 62: 126–135.

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.

Spaulding, P. 1929. Decay of slash of northern white pine in southern New England. Tech. Bull. U.S. Dep. Agric. No. 132.

Spaulding, P., and J. R. Hansbrough. 1944. Decay of logging slash in the Northeast. Tech. Bull. U.S. Dep. Agric. No. 876.

Swift, M. J. 1977. The ecology of wood decomposition. Sci. Prog. (Oxford), 64: 179–203.

Van Soest, P. J. 1963. Use of detergents in the analysis of fibrous feeds. II. A rapid method for the determination of fiber and lignin. J. Assoc. Off. Anal. Chem. 46: 829–835.

Whitford, W. G., V. Meentemeyer, T. R. Seastedt, K. Cromack, Jr., D. A. Crossley, Jr., P. Santos, R. L. Todd, and J. B. Waide. 1981. Exceptions to the AET model: deserts and clearcut forest. Ecology, 62: 275–277.

Wilcox, W. W. 1968. Changes in wood microstructure through progressive stages of decay. Res. Pap. FPL-70 For. Prod. Lab. (U.S.).

Yoneda, T. 1975. Studies on the rate of decay of wood litter on the forest floor. I. Some physical properties of decaying wood. Jpn. J. Ecol. 25: 40–46.