Decomposition of Douglas-fir and red alder wood in clear-cuttings

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Decomposition rates of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and red alder (*Alnus rubra* Bong.) wood (simulating logging residues) were determined in clear-cuttings at the Charles Lathrop Pack Experimental Forest of the University of Washington, which is located approximately 120 km south of Seattle, WA. The influence of diameter (1–2, 4–6, and 8–12 cm), vertical location (buried, on the soil surface, and elevated), season of logging (summer and winter), aspect (north and south), and wood temperature, moisture, and chemistry on wood decomposition rates were determined. Red alder wood decomposed faster (k = 0.035–0.517 year^{-1}) than Douglas-fir wood (k = 0.006–0.205 year^{-1}). In general, buried wood decomposed faster than surface wood, which decomposed faster than elevated wood. Small diameter wood generally decomposed faster than larger diameter wood. Aspect and season of logging had little influence on decomposition rates. Moisture and temperature were the dominant factors related to Douglas-fir wood decomposition, with initial chemistry playing a minor role. Initial wood chemistry, particularly soda solubility, was the dominant factor related to red alder wood decomposition.

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Les taux de décomposition du bois (simulant des résidus de coupe) de sapin de Douglas (*Pseudostuga menziesii* (Mirb.) Franco) et d'aulne roux (*Alnus rubra* Bong.) furent déterminés dans des éclaircies de la forêt expérimentale Charles Lathrop Pack de l'Université de Washington, à quelque 120 km au sud de Seattle, WA. On a mesuré l'influence du diamètre (1–2, 4–6 et 8–12 cm), la localisation verticale (enfoui, à la surface du sol et surélevé), la saison d'exploitation (été et hiver), l'exposition (nord et sud), de même que la température, l'humidité et la composition chimique du bois sur le taux de décomposition. Le bois de l'aulne roux s'est décomposé plus rapidement (k = 0,035–0,517 an^{-1}) que celui du sapin de Douglas (k = 0,006–0,205 an^{-1}). En général, le bois enfoui s'est décomposé plus rapidement que le bois à la surface du sol, lequel s'est décomposé plus rapidement que le bois surélevé. Le bois de petit diamètre s'est généralement décomposé plus rapidement que le bois de plus grand diamètre. L'exposition et la saison d'exploitation ont eu peu d'influence sur les taux de décomposition. Chez le bois de sapin de Douglas, la vitesse de décomposition était fortement influencée par l'humidité et la température du bois alors que la composition chimique initiale du bois n'avait qu'une influence limitée. Par contre, la composition initiale du bois, en particulier la solubilité à la soude, était le facteur le plus important dans la vitesse de décomposition du bois d'aulne roux.

[Traduit par la revue]

Logging residues in the Pacific Northwest may be burned, removed, or left on the forest floor to decompose. Burning may have detrimental effects by removing the litter layer and nutrients (Harvey et al. 1976) and creating air pollution (Cramer 1974). Leaving residues on the site may have significant benefits. Decaying wood in the soil appears to be an important factor in maintaining long-term forest productivity (Aho 1974; Larsen et al. 1978; Larsen et al. 1980; Swift 1977; Jurgensen et al. 1979). However, until residues decay, they may be a fire hazard and can inhibit regeneration activities. Thus, there is an interest in examining the decomposition rates of woody logging residues.

Woody litter decomposition typically has been studied under intact forest canopies (Yoneda 1975; Swift et al. 1976; Christensen 1977; Grier 1978; Lambert et al. 1980; Foster and Lang 1982; Graham and Cromack 1982; Sollins 1982; Harmon et al. 1986). Harvesting modifies the decomposition environment on the forest floor. Furthermore, new locations for decomposition are created since some woody residues are buried and (or) left elevated after logging as well as being on the soil surface. Although decomposition of woody residues has been studied in the eastern (Spaulding 1929; Spaulding and Hansbrough 1944; Abbott and Crossley 1982; Barber and van Lear 1984) and the western United States (Childs 1939; Wagener and Offord 1972; Larsen et al. 1980; Yavitt and Fahey 1982; Erickson et al. 1985), decomposition rates of buried, surface, and elevated residues have not been determined at the same time.

This study was initiated to determine (*i*) the natural decay rates of different diameter Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and red alder (*Alnus rubra* Bong.) wood above the surface, on the soil surface, and buried in clear-cuttings in western Washington, and (*ii*) the influence of season of logging (summer and winter), aspect (north and south), and wood chemistry, temperature, and moisture on decomposition.

Materials and methods

Study site

The study was conducted at the Charles Lathrop Pack Experimental Forest of the University of Washington, which is located approximately 120 km south of Seattle, near Eatonville, WA. Rainfall averages 102 cm year^{-1} and mean annual temperature is 9.7°C (U.S. Weather

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Bureau Station, La Grande). Any snowfall normally melts within a few days. Soils are of the Baumgard series (a fine loamy, mixed, mesic, Typic Xerumbrept) formed from andesitic parent material.

Two plots were located in clear-cuttings. One plot was on a south-facing slope (aspect, 150°; slope, 27%; elevation, 442 m), while the other was on a north-facing slope (aspect, 325°; slope, 32%; elevation, 457 m). Douglas-fir dominated both slopes before clear-cutting, which took place in 1976 on the south slope and in 1978 on the north slope.

Wood decomposition

Douglas-fir and red alder trees (40–50 years old) were felled in summer 1978 and winter 1979 in areas adjacent to the clear-cuttings 2–4 weeks before placement in the field. Wood in three diameter classes (1–2, 4–6, and 8–12 cm) was cut to length on a band saw: 48 cm long for the two smaller diameter classes and 30 cm for the 8–12 cm diameter class. The samples, with bark intact, were placed in both plots on 19 August 1978 and 21 February 1979. Strictly speaking, this wood was not logging residue, but was an analog and, thus, will be referred to as wood rather than residue. Samples were placed at three different heights: above the soil (+20 cm, suspended on chicken wire frames), on the soil surface (0 cm), and buried 10 cm below the soil surface (−10 cm). Three replicates were used for each treatment analyzed and were removed from the field after 6, 12, 18, 24, and 60 months (summer logging) and 6, 12, 24, 36, and 54 months (winter logging).

Decomposition rates were determined by calculating dry weight loss at each sampling time. Buried wood was washed with water and brushed to remove mineral soil. Surface and elevated wood samples were also brushed. Specimens were dried at 75°C until weight was constant. Decomposition constants or fractional loss rates (k, year^{-1}) were determined after 2 years for both summer- and winter-logged wood, after 3 years for winter-logged wood, and after 4.5 and 5 years for winter- and summer-logged wood, respectively. The "best-fit" regression model of Schlesinger and Hasey (1981) and the exponential model of Olson (1963) were used to calculate k values.

Chemical composition of wood

Subsamples of wood and bark of both species from each diameter class and season were taken for initial chemical analyses. Carbon was determined using a Leco carbon analyzer and N was determined using a wet oxidation digestion (Parkinson and Allen 1975) and a Technicon autoanalyzer II. Soda solubility (an indicator of readily available substrates: simple sugars and hemicellulose) was determined using the TAPPI) (Technical Association of the Pulp and Paper Industry) (Anonymous 1976) method and Klason lignin and alcohol–toluene extractives were determined using the TAPPI (Anonymous 1974) method.

Temperature and moisture

Temperatures in the center of Douglas-fir wood in each diameter class and at each vertical location on both slopes as well as air temperatures at 1 m were continuously monitored using Yellow Springs Intrument Co. thermistors. One thermistor was placed in each wood section. Alder temperatures were not taken. Millivolt signals from the 20 thermistors were recorded on 12 channel Leeds and Northrup strip chart recorders (model H on the north-facing slope and model 165 on the south-facing slope) and converted to temperature (degrees Celsius).

Moisture contents of buried, surface, and elevated wood of both species were determined gravimetrically every 6 months for the first 24 months using the decomposition samples. Subsamples from each wood section were taken to determine initial moisture contents. Percent moisture was expressed on a dry-weight basis after oven-drying at 75°C until weight was constant.

Statistical analyses

One-way analysis of variance was used to test main effects of species, diameter, vertical location, aspect, and season of logging on weight loss. Regression analysis was used to determine relationships among weight loss after 2 years and wood moisture, temperature, and chemical variables.

Results and discussion

Wood decomposition rates

Differences between species

Although many studies of woody litter decomposition have been conducted, few have been carried out in clear-cuttings. In this case, we examined decomposition of both Douglas-fir and red alder wood in clear-cuttings in western Washington. Overall, red alder wood decomposed significantly faster ($p < 0.05$) than Douglas-fir wood, based on weight-loss data. However, there were a few instances where no significant differences occurred, as discussed below.

Weight losses after 24 and 60 months for summer-logged Douglas-fir and red alder wood are shown in Table 1. Tables 2 and 3 show similar data for winter-logged wood after 24, 36, and 54 months decomposition; 6-, 12-, and 18-month weight-loss data are not presented since only small weight losses were recorded at these times and 12-month data were previously discussed by Edmonds et al. (1980). These data, however, were included in the calculation of decomposition constants using the "best-fit" regression method.

For summer-logged wood, maximum weight loss after 24 months in the 1–2 cm diameter class was 25.5% for Douglas-fir (in buried wood) and 60.6% for red alder (in surface wood) (Table 1). In the 4–6 cm class, there was no significant difference between species in maximum weight loss (Douglas-fir, 25.3%; red alder, 24.2%). However, in the 8–12 cm class, red alder decomposed much faster than Douglas-fir (maximum weight losses were 29.2 and 13.3%, respectively, in buried wood). After 60 months, in the 8–12 cm class, maximum weight loss was 79.7% in red alder and 59.0% in Douglas-fir, also in buried wood (Table 1).

Winter-logged red alder wood also decomposed faster than that of Douglas-fir at 24, 36, and 54 months (Tables 2 and 3). Maximum weight losses occurred in buried wood. After 36 months, losses for Douglas-fir were 35.9% (1–2 cm), 38.1% (4–6 cm), and 27.0% (8–12 cm) (Table 2), while those for red alder were 54.7% (1–2 cm), 58.1% (4–6 cm), and 48.5% (8–12 cm) (Table 3).

Comparison of decomposition constants (k values) also shows that red alder wood decomposed much faster than Douglas-fir. Decomposition constants were calculated in two different ways: the "best-fit" regression method of Schlesinger and Hasey (1981) and Olson's (1963) exponential model. Ranges of "best-fit" and Olson's k values for Douglas-fir wood were 0.006–0.205 and 0.013–0.178 year^{-1}, respectively, from Tables 4 and 5 (1–2 and 4–6 cm diameter) and Table 6 (8–12 cm diameter; these k values were determined over the longest time period). For red alder, the corresponding ranges were 0.035–0.517 and 0.058–0.466 year^{-1}. There was generally good agreement between the two methods, especially as the decomposition period increased (Tables 5 and 6).

Erickson et al. (1985) also examined Douglas-fir residue decomposition in clear-cuttings and found k values ranging from 0.004 to 0.037 year^{-1} for similar diameter wood. They, however, only examined surface and elevated residues. For surface and elevated wood in our study, the ranges of "best-fit" and Olson's k values were 0.006–0.062 and 0.012–0.090 year^{-1}, respectively, slightly higher than the range of Erickson et al. (1985).

Edmonds (1984) suggested that the "best-fit" regression model gave a better estimate of k than Olson's method for slowly decomposing needles. Examination of Tables 4, 5, and 6 reveals that k values for both methods tend to increase with time, especially with large diameter wood. This is opposite to

TABLE 1. Percent weight loss (mean (SD)) after 24 and 60 months of three diameters of summer-logged* Douglas-fir and red alder wood placed 20 cm above the soil surface (+20 cm), on the soil surface (0 cm), and buried (−10 cm) on south- and north-facing slopes

Vertical location (cm)	Diameter class (cm)	Douglas-fir				Red alder†			
		South aspect‡		North aspect		South aspect§		North aspect	
		24 months	60 months	24 months	60 months	24 months	60 months	24 months	60 months
−10	1–2	25.5(5.1)*1a*	—	16.4(3.0)*1a*	—	21.7(0.3)*1a*	—	39.4(20.1)*1a*	—
	4–6	25.3(2.7)*1a*	—	13.5(7.7)*1a*	—	24.2(21.9)*1a*	—	22.2(11.5)*1a*	—
	8–12	11.6(1.5)*2a*	56.6(6.4)*a*	13.3(1.6)*1a*	59.0(7.3)*a*	29.2(15.5)*1a*	79.7	17.2(15.5)*1a*	77.5(4.0)*a*
0	1–2	11.3(2.9)*1b*	—	10.8(1.4)*1a*	—	43.4(20.8)*1a*	—	60.6(10.0)*1a*	—
	4–6	9.0(1.1)*1b*	—	12.3(4.8)*1a*	—	22.5(4.4)*1a*	—	13.21(1.8)*2a*	—
	8–12	3.8(0.8)*2b*	19.4(1.0)*b*	5.2(0.4)*1b*	12.7(1.6)*b*	23.6(6.0)*1a*	75.9(6.4)*a*	12.9(4.4)*2ab*	47.4(10.7)*b*
+20	1–2	9.1(2.3)*1b*	—	7.5(5.9)*1a*	—	26.0(0.4)*1a*	—	33.7(1.9)*1a*	—
	4–6	7.7(1.4)*1b*	—	9.5(2.4)*1a*	—	15.1(1.7)*1a*	—	15.0(2.3)*2a*	—
	8–12	3.4(0.9)*2b*	10.5(1.1)*c*	4.0(0.9)*1b*	8.2(3.9)*b*	15.7(10.3)*1a*	42.6(16.1)*a*	7.0(2.1)*3b*	45.9(10.6)*b*

NOTE: Weight loss values followed by a different number among diameter classes in the same vertical location are significantly different ($p < 0.05$). Weight loss values followed by a different letter among vertical locations in the same diameter class are significantly different ($p < 0.05$).

*There was no significant difference between summer and winter (see Tables 2 and 3), except 24-month Douglas-fir, 8–12 cm, +20 cm, south (summer > winter) and 24-month red alder, 1–2 cm, 0 cm, north (summer > winter).

†Red alder weight loss was significantly greater than that of Douglas-fir, except 1–2, 4–6, and 8–12 cm, −10 cm (buried), north (not significantly different; $p < 0.05$).

‡24 months, no significant difference between aspects; 60 months, no significant difference between aspects, except 0 cm (surface; south > north).

§24 months, no significant difference between aspects, except 4–6 cm, 0 cm (surface; south > north) and 1–2 cm, +20 cm (above soil; north > south); 60 months, no significant difference between aspects, except 0 cm (surface; south > north).

TABLE 2. Percent weight loss (mean (SD)) after 24, 36, and 54 months of three diameters of winter-logged Douglas-fir wood placed 20 cm above the soil surface (+20 cm), on the soil surface (0 cm), and buried (−10 cm) on south- and north-facing slopes

Vertical location (cm)	Diameter class (cm)	South aspect*			North aspect		
		24 months	36 months	54 months	24 months	36 months	54 months
−10	1–2	30.2(1.9)*1a*	31.9(20.7)*1a*	—	12.3(2.5)*1a*	35.9(1.7)*1a*	—
	4–6	16.1(2.8)*1a*	31.3(10.5)*1a*	—	16.5(4.9)*1a*	38.1(20.0)*1a*	—
	8–12	23.4(10.6)*1a*	15.2(9.9)*1a*	36.1	14.1(10.1)*1a*	27.0(3.9)*1a*	11.3(4.9)*a*
0	1–2	6.5(2.8)*1b*	10.2(3.6)*1a*	—	7.9(1.4)*1a*	10.8(2.9)*1b*	—
	4–6	4.0(2.3)*1b*	7.7(2.1)*1,2b*	—	6.7(4.4)*1a*	3.9(2.2)*1b*	—
	8–12	4.9(2.2)*1b*	3.8(0.4)*2a*	14.7(2.3)*a*	2.2(0.8)*1a*	5.4(3.6)*1b*	5.7(0.7)*a*
+20	1–2	5.7(3.4)*1b*	9.3(5.8)*1a*	—	5.2(4.2)*1a*	8.2(3.5)*1b*	—
	4–6	5.2(2.3)*1b*	6.3(1.3)*1b*	—	7.5(4.9)*1a*	4.6(1.5)*1b*	—
	8–12	1.1(0.7)*1b*	2.0(1.1)*1a*	10.1(0.9)*a*	3.4(0.4)*1a*	3.41(1.3)*1b*	5.1(2.2)*a*

NOTE: Weight loss values followed by a different number among diameter classes in the same vertical location are significantly different ($p < 0.05$). Weight loss values followed by a different letter among vertical locations in the same diameter class are significantly different ($p < 0.05$).

*24 months, no significant difference between aspects, except 1–2 and 8–12 cm, −10 cm (buried; south > north); 36 months, no significant difference between aspects; 54 months, no significant difference between aspects, except 0 cm (surface; south > north).

the trend observed for needles (Edmonds 1984) and no doubt reflects the initial slow decomposition of wood involving a lag period, especially in larger sizes. This is further illustrated in Fig. 1, particularly for 8–12 cm diameter Douglas-fir wood. There is small initial leaching loss in contrast to needles and leaves. This probably explains why k values calculated by the two methods are reasonably close. Which method gives the best estimate of k is debatable, but we think that the "best-fit" regression model provides values that are more indicative of decomposition rates on our sites. Furthermore, the k values of Erickson et al. (1985) are closer to our "best-fit" k values. Thus, these k values are used in the following discussion.

Effect of vertical location

From the above data it is apparent that vertical location, particularly burying, had a strong influence on decomposition rates. Weight loss of Douglas-fir generally followed the sequence buried > surface > elevated (Tables 1 and 2). Buried wood weight loss was generally significantly greater ($p < .05$) than surface wood weight loss, but elevated and surface wood weight losses were generally not significantly different. The effect of burying was particularly noticeable in summer-logged, large diameter wood after 60 months (Table 1). For example, weight losses on the north slope were 59.0, 12.7, and 8.2% in buried, surface, and elevated wood, respectively. A similar trend is shown for red alder, but losses were much larger: 77.5, 47.4, and 45.9 in buried, surface, and elevated wood, respectively.

Buried Douglas-fir wood decomposed 1.1 to 6.4 times faster than surface wood (Tables 1 and 2). The burying effect was less pronounced for red alder (Tables 1 and 3) and this is clearly illustrated in Fig. 1 for 8–12 cm diameter wood. Burying did

TABLE 3. Percent weight loss (mean (SD)) after 24, 36, and 54 months of three diameters of winter-logged red alder* wood placed 20 cm above the soil surface (+20 cm), on the soil surface (0 cm), and buried (−10 cm) on south- and north-facing slopes

Vertical location (cm)	Diameter class (cm)	South aspect†			North aspect		
		24 months	36 months	54 months	24 months	36 months	54 months
−10	1–2	36.7(23.3)*1a*	54.7(14.2)*1a*	—	33.5(5.5)*1a*	43.2(12.3)*1a*	—
	4–6	14.4(6.9)*1a*	58.1(18.7)*1a*	—	27.2(9.2)*1a*	41.7(9.2)*1a*	—
	8–12	21.3(3.2)*1a*	48.5(16.1)*1a*	53.0(12.5)*a*	13.6(3.6)*2a*	19.8(4.5)*1a*	46.4(16.4)*a*
0	1–2	33.7(4.1)*1a*	49.9(9.6)*1a*	—	25.9(5.4)*1a*	29.1(2.4)*1a*	—
	4–6	16.9(4.1)*2a*	32.9(6.2)*1b*	—	14.5(3.1)*2a*	27.8(3.4)*1b*	—
	8–12	10.7(0.7)*2b*	23.3(9.0)*1a*	43.2(2.8)*a*	9.6(13.8)*2ab*	11.2(0.5)*2b*	35.6(3.6)*a*
+20	1–2	31.0(9.7)*1a*	35.0(6.4)*1a*	—	28.7(4.4)*1a*	35.3(6.0)*1a*	—
	4–6	11.0(7.9)*2a*	22.7(4.1)*2b*	—	17.8(2.0)*2a*	24.4(4.2)*2b*	—
	8–12	5.6(1.6)*2c*	30.1(2.4)*1,2a*	42.7(11.5)*a*	7.1(0.7)*3b*	9.9(3.1)*3b*	41.1(11.7)*a*

NOTE: Weight loss values followed by a different number among diameter classes in the same vertical location are significantly different ($p < 0.05$). Weight loss values followed by a different letter among vertical locations in the same diameter class are significantly different ($p < 0.05$).

*Red alder weight loss was significantly greater than that of Douglas-fir (see Table 2), except 1–2, 4–6, and 8–12 cm, −10 cm (buried), south and north, at 24 months, and 1–2, 4–6, and 8–12 cm, −10 cm (buried), north, at 36 months.

†24 months, no significant difference between aspects; 36 months, no significant difference between aspects, except 8–12 cm, +20 cm (above surface; south > north); 60 months, no significant difference between aspects, except at 0 cm (surface; south > north).

not always result in increased decomposition, however. For example, in 1–2 cm diameter, summer-logged red alder wood, burying actually resulted in less decomposition on both slopes (Table 1), probably because of high moisture conditions, as will be discussed later. This trend was not noted in winter-logged red alder wood, however (Table 3).

Others have noted that burying wood increases the rate of decomposition. Ward and McLean (1976) found that buried conifer residues less than 1.3 cm diameter in Oregon were completely decayed after 3 years. In our study, decay wasn't as rapid, since weight loss for 1–2 cm diameter Douglas-fir ranged from 31.9 to 35.9% after 3 years (Table 2). Even red alder had not completely decayed after 3 years.

Many studies on decay resistance of wood of different species have involved the effects of burying or soil contact. Most of these have been conducted under laboratory conditions. Weight loss under these circumstances is generally faster than that in the field. Käärik (1973) reported that weight loss of *Pinus sylvestris* sapwood blocks was 65% after 4 months when buried in the soil, compared with 18% on the soil surface. Buried blocks decomposed 3.6 times faster than surface blocks like the Douglas-fir wood in our study. The rate of decay, however, not only depends on the wood species, but also depends on the species of decay fungi used in these tests (Käärik 1973).

Only a few determinations of weight loss or decomposition constants of belowground wood in forests have been made, although there is extensive documentation that soil contact reduces the life of forest products such as fence posts and stakes (Gjovich and Davidson 1975, 1979). Untreated southern pine sapwood stakes had an average life of 1.8–3.6 years in the southeastern United States, but 6 years in Wisconsin (Gjovich and Davidson 1979). It is difficult to calculate k values from these studies, but Yavitt and Fahey (1982) found k values for lodgepole pine root wood in Wyoming to average 0.041 year^{-1} for 1–2.5 cm diameter roots and 0.027 year^{-1} for 2.6–5 cm diameter roots. These are much slower rates than we calculated for Douglas-fir wood after 3 years of decomposition, which ranged from 0.095 to 0.138 year^{-1} for 1–2 cm diameter wood and from 0.110 to 0.179 year^{-1} for the 4–6 cm diameter wood (Table 5). This probably reflects the warmer wetter climate in Washington. Red alder k values for buried wood ranged from 0.190 to 0.240 year^{-1} for the 1–2 cm diameter and from to 0.187–0.297 year^{-1} for the 4–6 cm diameter. A k value of 0.297 year^{-1} represents a time for 95% decay of about 10 years, which is similar to the Wisconsin value of a 6-year life for pine sapwood stakes (Gjovich and Davidson 1979).

Termites and other insects may be involved with increasing decomposition rates of wood in contact with soil (Käärik 1973; Gjovich and Davidson 1979). We, however, found an insignificant number of wood-boring insects in buried and surface wood, although many small soil animal, e.g., collembola, millipedes, etc., were visible between bark and wood. Fine roots and rhizomorphs were also present in this zone.

Erickson et al. (1985) found that surface Douglas-fir residues decomposed significantly faster than elevated ones: (e.g., for the 1–2 cm diameter class, k = 0.011 and 0.004 year^{-1} for surface and elevated residues, respectively). In the 8–12 cm diameter class, Erickson et al. (1985) found k = 0.037 and 0.016 year^{-1} for surface and elevated residues, respectively. Similarly, Barber and van Lear (1984) found that residues in contact with the ground decomposed 50% faster than elevated residues. Our data showed a similar trend. For Douglas-fir, k values averaged 0.035 and 0.029 year^{-1} for 1–2 cm diameter surface and elevated wood (Table 5) and 0.020 and 0.011 year^{-1} for 8–12 cm surface and elevated wood, respectively (Table 6).

Effect of diameter

From the above discussion it appears that diameter had a strong influence on wood decomposition rate. In general, there was a trend for weight loss to follow the sequence 1–2 cm diameter > 4–6 cm diameter > 8–12 cm diameter for both Douglas-fir and red alder (Tables 1–3). Differences, however, were not always significant, particularly in buried wood. Significant differences among diameter classes were most commonly observed in elevated wood. Similar trends are observed using k values (Tables 3–5). Abbott and Crossley (1982) also found that small diameter (1–3 cm) oak branches decomposed faster (k = 0.173 year^{-1}) than 3–5 cm diameter branches (k = 0.091 year^{-1}) in North Carolina. Furthermore,

TABLE 4. Decomposition constants (k, years^{-1}) calculated after 2 years for 1–2, 4–6, and 8–12 cm diameter, summer- and the surface (0 cm), and elevated (+20 cm)) on north and south aspects using the "best-fit"

Season of logging	k method	South aspect: Buried 1–2 cm	Buried 4–6 cm	Buried 8–12 cm	Surface 1–2 cm	Surface 4–6 cm	Surface 8–12 cm	Elevated 1–2 cm	Elevated 4–6 cm	Elevated 8–12 cm
										Douglas-fir
Summer	R	0.122	0.171	0.083	0.035	0.062	—*	0.015	0.010	—*
	O	0.147	0.146	0.062	0.060	0.047	0.019	0.048	0.040	0.017
Winter	R	0.164	0.071	0.144	0.027	0.015	0.006	0.025	0.020	—*
	O	0.180	0.088	0.133	0.034	0.020	0.025	0.029	0.027	0.006
										Red alder
Summer	R	0.187	0.173	0.181	0.330	0.164	0.194	0.158	0.052	0.090
	O	0.122	0.139	0.173	0.285	0.127	0.135	0.151	0.082	0.085
Winter	R	0.172	0.045	0.122	0.222	0.097	0.046	0.229	0.051	0.019
	O	0.229	0.078	0.120	0.205	0.093	0.057	0.186	0.058	0.029

*The k value could not be calculated.

TABLE 5. Decomposition constants (k, years^{-1}) calculated after 3 years for 1–2, 4–6, and 8–12 cm diameter, surface (0 cm), and elevated (+20 cm)) on north and south aspects using the

k method	South aspect: Buried 1–2 cm	Buried 4–6 cm	Buried 8–12 cm	Surface 1–2 cm	Surface 4–6 cm	Surface 8–12 cm	Elevated 1–2 cm	Elevated 4–6 cm	Elevated 8–12 cm
									Douglas-fir
R	0.095	0.110	0.046	0.034	0.024	0.0017	0.031	0.011	0.010
O	0.128	0.125	0.055	0.036	0.027	0.013	0.033	0.022	0.007
									Red alder
R	0.240	0.297	0.238	0.239	0.138	0.085	0.167	0.086	0.122
O	0.264	0.290	0.241	0.230	0.133	0.088	0.146	0.086	0.119

Yavitt and Fahey (1982) found that smaller diameter roots decomposed faster than larger diameter roots.

Erickson et al. (1985) and Barber and van Lear (1984), on the other hand, found that larger diameter residues decomposed significantly faster than smaller diameter ones in the same vertical location.

How are these conflicting data with respect to residue diameter to be resolved? Barber and van Lear (1984) suggest that decay retardation in small branches is attributed to case hardening, which is the early and complete drying out or seasoning of the outer sapwood (Spaulding and Hansbrough 1944). Earlier studies certainly indicate that small branches may remain virtually intact several years after logging (Spaulding 1929; Spaulding and Hansbrough 1944; Wagener and Offord 1972).

Barber and van Lear (1984) explained the discrepancy by indicating that Abbott and Crossley (1982) only studied decomposition for a 1-year period; if a longer period had been used they felt that small diameter residues would decompose slower than larger pieces. Small branches may be more quickly colonized by microbes and, thus, may have greater initial decay. Subsequent case hardening, however, will retard decay. Our data involving residues of different diameters were collected over 2- to 5-year periods, while those of Erickson et al. (1985) and Barber and van Lear (1984) involved longer time periods (up to 15 years). Unfortunately, the longest decomposition period used for small diameter wood in our study was 3 years and this may not have been long enough to observe the case-hardening effect. The latter studies also used specific gravity and not weight loss as an indicator of decomposition. Relationships between specific gravity and weight loss have not been fully explored in wood decomposition and it is possible that differences in the techniques are responsible for the discrepancy.

Effect of aspect

There was no significant difference between decomposition rates on north and south slopes based on weight loss, with only a few exceptions (Tables 1–3). In these cases, weight loss was greater on the south slope in buried and surface wood. Moisture conditions on the south slope were probably responsible since, in the early summer, soil on the south slope was moister than that on the north slope.

Season of logging

Season of logging also had little influence on Douglas-fir and red alder wood decomposition rates. However, weight loss was winter-logged Douglas-fir and red alder wood in different vertical locations (buried (−10 cm), on regression analysis (R) and Olson's (1963) method (O)

North aspect								
Buried			Surface			Elevated		
1–2 cm	4–6 cm	8–12 cm	1–2 cm	4–6 cm	8–12 cm	1–2 cm	4–6 cm	8–12 cm
0.049	0.041	0.069	0.014	0.051	0.003	0.016	0.038	0.0002
0.090	0.073	0.071	0.057	0.066	0.027	0.039	0.050	0.020
0.030	0.102	0.074	0.043	0.022	0.006	0.022	0.053	0.017
0.066	0.090	0.076	0.041	0.035	0.011	0.027	0.039	0.017
0.241	0.084	0.099	0.517	0.035	0.005	0.203	0.065	0.009
0.250	0.126	0.094	0.466	0.071	0.069	0.205	0.081	0.036
0.208	0.162	0.083	0.143	0.085	0.035	0.178	0.120	0.007
0.204	0.159	0.073	0.150	0.078	0.050	0.169	0.098	0.037

winter-logged Douglas-fir and red alder wood in different vertical locations (buried (−10 cm), on the "best-fit" regression analysis (R) and Olson's (1963) method (O)

North aspect								
Buried			Surface			Elevated		
1–2 cm	4–6 cm	8–12 cm	1–2 cm	4–6 cm	8–12 cm	1–2 cm	4–6 cm	8–12 cm
0.138	0.179	0.108	0.036	0.006	0.016	0.026	0.027	0.010
0.148	0.160	0.105	0.038	0.013	0.019	0.029	0.016	0.012
0.190	0.187	0.084	0.104	0.116	0.061	0.150	0.105	0.015
0.189	0.180	0.074	0.115	0.109	0.040	0.145	0.093	0.035

significantly greater ($p < 0.05$) in the elevated, 8–12 cm diameter, Douglas-fir, summer-logged wood on the south slope and in the surface, 1–2 cm diameter red alder wood on the north slope (Table 1).

Initial residue chemistry

Summer-logged red alder wood had higher initial N concentrations (0.18–0.33%) and lower C/N ratios (150–274) than Douglas-fir (0.05–0.10% and 515–1012, respectively) (Table 7). Red alder wood also had higher soda solubilities (22.5–25.9%) and extractives (3.6–5.3%) than Douglas-fir (18.5–20.0% and 2.4–3.5%, respectively). On the other hand, red alder wood had lower lignin and lignin/N ratios than Douglas-fir. Nitrogen concentrations in bark were considerably higher than those in wood, with red alder having higher concentrations than Douglas-fir. Overall, N concentrations, extractives, and soda solubility decreased and C/N and lignin/N ratios increased with increasing wood diameter. Lignin concentrations and diameter were not strongly related, but there was a trend for smaller diameter wood to have higher lignin concentrations.

The chemistry of wood and bark changed from summer to winter. Nitrogen concentrations in winter-logged wood and bark were higher than those in the summer in both species, resulting in lower C/N and lignin/N ratios (Table 7). However, extractives, soda solubility, and lignin concentrations changed little from summer to winter.

Initial substrate lignin concentration has been shown to have a strong influence on litter decomposition (Fogel and Cromack 1977). In this study, soda solubility was better related to wood decomposition. Soda solubility is an index of readily available substrate, so it is not surprising that it had a strong relationship to decomposition rate in the first 2 years. When combined Douglas-fir and red alder weight-loss data were regressed against initial chemical variables, the following correlation coefficients resulted: r = 0.71, 0.62, −0.53, −0.39, and −0.05 for soda solubility, extractives, C/N ratio, lignin, and lignin/N ratio, respectively (Table 8). This sequence changed little when each species was considered separately. However, it should be noted that initial wood chemistry had a greater influence on red alder than on Douglas-fir; 45% of the variance in weight loss in red alder was explained by soda solubility ($r^2 =$ 0.45), but only 5% of the variance in Douglas-fir weight loss was explained by this variable ($r^2 = 0.05$).

Erickson et al. (1985) also found that initial lignin was not well related to residue decomposition rates. Needle decomposi-

TABLE 6. Decomposition constants (k, years^{-1}) calculated after 5 years (summer logged) and 4.5 years (winter logged) for 8–12 cm diameter Douglas-fir and red alder wood in different vertical locations (buried (−10 cm), on the surface (0 cm), and elevated (+20 cm)) on north and south aspects using the "best-fit" regression analysis (R) and Olson's (1963) method (O)

Season of logging	k method	South aspect			North aspect		
		Buried	Surface	Elevated	Buried	Surface	Elevated
				Douglas-fir			
Summer	R	0.190	0.038	0.014	0.205	0.023	0.012
	O	0.114	0.043	0.022	0.178	0.027	0.017
Winter	R	0.080	0.027	0.012	0.108	0.013	0.009
	O	0.010	0.035	0.024	0.026	0.013	0.012
				Red alder			
Summer	R	0.355	0.320	0.123	0.345	0.127	0.122
	O	0.319	0.285	0.111	0.298	0.128	0.122
Winter	R	0.195	0.129	0.140	0.145	0.091	0.106
	O	0.168	0.126	0.124	0.139	0.098	0.118

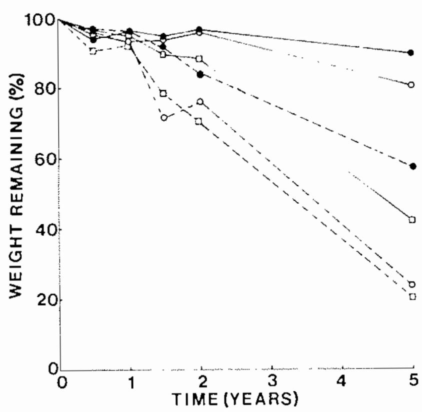

FIG. 1. Weight remaining in relation to time of decomposing 8–12 cm diameter, summer-logged Douglas-fir and red alder wood sections on the south slope. —, Douglas-fir; - - -, red alder; ●, elevated (+20 cm); ○, on the soil surface; □, buried (−10 cm).

tion studies (Berg et al. 1982; Edmonds 1984) have indicated that lignin concentration may not relate well to weight loss until after about 45% of initial weight is lost. This will occur more rapidly with needles than wood; only one of our treatments had lost more than 45% of initial weight in the first 2 years. Also, smaller diameter wood tended to have higher lignin concentrations than larger diameter wood, particularly Douglas-fir (Table 7). Thus, it was not surprising that initial lignin concentration was not well related to decomposition.

Residue temperature and moisture

Maximum air temperature on the south slope (34.5°C) was higher than that on the north slope (29.1°C) (Table 9), but there was little difference in minimum temperatures on north and south slopes. In general, maximum wood temperatures on the south slope were higher than those on the north slope, reflecting differences in air temperature. Table 9 shows that the maximum temperature in Douglas-fir wood (46.0°C) occurred in the smallest diameter wood on the soil surface of the south slope. On the north slope, the highest maximum temperatures occurred in elevated wood (42.4 to 42.8°C). Lowest maximum temperatures on the south and north slopes occurred in buried wood.

Two-year Douglas-fir weight losses were related to both minimum and maximum wood temperatures (r = 0.78 and −0.54, respectively; Table 8). This reflects the fact that slowest decomposition rates generally occurred in elevated wood, which had higher maximum and lower minimum temperatures (Table 9).

Douglas-fir and red alder wood moisture contents for the summer loggings are shown as functions of time in Figs. 2 and 3, respectively. Winter-logged wood moisture contents are not shown since season of logging had little influence on decomposition rates. Douglas-fir moisture contents ranged from 46 to 125, 15 to 84, and 15 to 81% in buried, surface, and elevated wood, respectively (Fig. 2). Red alder moisture contents were higher and ranged from 65 to 191, 15 to 161, and 15 to 79% in buried, surface and elevated locations, respectively (Fig. 3).

In summer-logged Douglas-fir wood, initial moisture contents were highest in the smallest diameter classes (Fig. 2); the reverse situation occurred in red alder (Fig. 3). Buried wood maintained the highest moisture contents over time in both species (Figs. 2A and 3A) and moisture contents were high even during the summer. Red alder maintained higher moisture contents than Douglas-fir. Wood moisture contents of both species when buried never fell below initial levels and, in red alder, they actually increased with time. In buried, 1–2 cm diameter red alder wood, moisture contents as high as 191% occurred (Fig. 3A). This could have inhibited decomposition (Griffin 1977) and explain why summer-logged, surface red alder wood decomposed faster than buried wood in this diameter class.

Surface and elevated Douglas-fir wood had similar drying patterns over time (Fig. 2B and 2C). Surface (Fig. 3B) and elevated (Fig. 3C) red alder wood sections had different moisture content patterns than Douglas-fir. They did not dry out as rapidly, particularly the elevated residues (Fig. 3C), and surface residues became very moist during the second winter (Fig. 3B). However, the moisture contents of all three diameter classes of both species converged after 24 months to about 15%. During the 1st year, smaller diameter wood of both species tended to be moister than larger wood and this possibly explains

TABLE 7. Initial chemical analyses (mean (SD)) for summer- and winter-logged Douglas fir and red alder wood

Species	C (%)* Wood	C (%)* Bark	N (%) Wood	N (%) Bark	C/N Wood	C/N Bark	Wood soda solubility (%)	Wood klason lignin (%)	Wood extractives (%)	Lignin/N (wood)
Summer-logged										
Douglas-fir										
1–2 cm	51.5(0.4)	52.0(1.7)	0.10(0.02)	0.42(0.01)	515	124	20.0(2.4)	33.5(1.4)	3.5(0.6)	335
4–6 cm	50.3(0.6)	53.7(3.2)	0.07(0.02)	0.34(0.01)	719	158	19.1(2.7)	26.1(4.0)	2.4(0.6)	373
8–12 cm	50.6(0.7)	54.2(2.7)	0.05(0.01)	0.23(0.03)	1012	194	18.5(1.8)	27.3(0.9)	2.7(0.3)	546
Alder										
1–2 cm	49.6(0.6)	52.7(1.1)	0.33(0.03)	1.22(0.01)	150	43	25.9(3.6)	22.9(1.7)	5.3(1.3)	69
4–6 cm	50.7(0.8)	51.8(2.5)	0.23(0.03)	0.88(0.03)	220	59	22.6(0.4)	21.3(2.2)	4.1(0.3)	93
8–12 cm	49.3(1.4)	51.9(1.1)	0.18(0.01)	0.75(0.03)	274	69	22.5(0.4)	23.7(0.6)	3.6(0.1)	132
Winter-logged										
Douglas-fir										
1–2 cm	51.5	52.0	0.14(0.01)	0.38(0.17)	368	137	18.9(1.2)	31.2(2.3)	3.1(0.5)	223
4–6 cm	50.3	52.0	0.09(0.01)	0.47(0.10)	564	114	15.9(0.8)	28.2(1.6)	2.5(0.5)	313
8–12 cm	50.6	54.2	0.08(0.01)	0.39(0.04)	633	139	15.9(0.8)	28.4(0.9)	2.4(0.7)	355
Alder										
1–2 cm	49.7	52.7	0.40(0.07)	1.16(0.04)	124	45	29.2(3.3)	23.1(2.3)	7.7(1.3)	58
4–6 cm	50.7	51.8	0.43(0.17)	0.93(0.20)	118	56	21.6(2.2)	19.4(2.7)	4.4(1.4)	45
8–12 cm	49.3	51.9	0.28(0.06)	0.75(0.07)	175	69	22.6(2.0)	22.9(2.0)	5.2(1.2)	82

*Winter-logged C values are assumed to be the same as summer-logged values.

TABLE 8. Correlation coefficients of Douglas-fir and red alder wood weight loss after 2 years and temperature, moisture, and initial wood chemistry variables

Variable	All‡ data ($n = 72$)	Douglas-fir ($n = 36$)	Red alder ($n = 36$)
Minimum moisture	0.35*	0.72*	0.06
Maximum moisture	0.48*	0.61*	0.27
Minimum temperature	—	0.78*	—†
Maximum temperature	—	−0.54*	—†
Lignin	−0.39*	−0.16	−0.22
C/N	−0.53*	−0.20	−0.31
Lignin/N	−0.05	−0.19	−0.26
Soda solubility	0.71*	0.22	0.67*
Extractives	0.62*	0.17	0.44*

*Significant at $p < 0.05$.
†Temperature in red alder wood was not determined.

TABLE 9. Maximum and minimum temperatures (°C) in the air and in various sized Douglas-fir wood on north and south aspects

Vertical location	Diameter class (cm)	Maximum, 8/10/1979* S	Maximum, 8/10/1979* N	Minimum, 11/25/1979* S	Minimum, 11/25/1979* N
−10 cm	1–2	31.3	23.7	3.5	3.5
	4–6	32.9	27.5	2.7	2.7
	8–12	31.9	30.2	3.0	1.3
0 cm	1–2	46.0	36.1	0.2	−0.03
	4–6	41.1	26.1	1.2	−0.3
	8–12	38.1	34.0	0.8	−0.3
+20 cm	1–2	42.4	42.8	−0.6	−0.03
	4–6	42.8	42.4	0.2	−0.03
	8–12	41.5	42.4	−2.2	0.2
Air (1 m)		34.5	29.1	−0.3	−0.3

*Month/day/year.

why smaller diameters decomposed at the fastest rate. These differences in moisture were not apparent in the 2nd year.

Moisture is an important variable controlling residue decomposition rates both in the eastern (Abbott and Crossley 1982) and western United States (Erickson et al. 1985). Regression analysis of our Douglas-fir data also supports this premise. Weight losses were strongly related to both maximum and minimum wood moisture contents (r = 0.61 and 0.72, respectively; Table 8). In fact, 52% of the variance in weight loss in Douglas-fir was explained by minimum moisture (r^2 = 0.52). Faster decomposing buried wood had the highest weight losses and highest moisture contents (Fig. 2A). Surface wood decomposed at an intermediate rates with intermediate moisture values (Fig. 2B), while elevated wood had the lowest decomposition rates and lowest moisture contents (Fig. 2C).

On the other hand, decomposition rates of red alder wood were not well related to moisture content (Table 8). Differences in decomposition rate with vertical location in red alder were not as dramatic as they were in Douglas-fir and there were few signficant differences between buried and surface wood. Moisture contents of red alder were much higher than those for Douglas-fir and there was little difference in moisture between buried (Fig. 3A) and surface wood (Fig. 3B).

Relationships between decomposition and wood moisture temperature and chemistry

Both temperature and moisture influenced Douglas-fir wood decomposition in this study. Typically, these factors interact (Boddy 1983) and it is difficult to determine their separate influences. Slowly decomposing elevated residues tended to

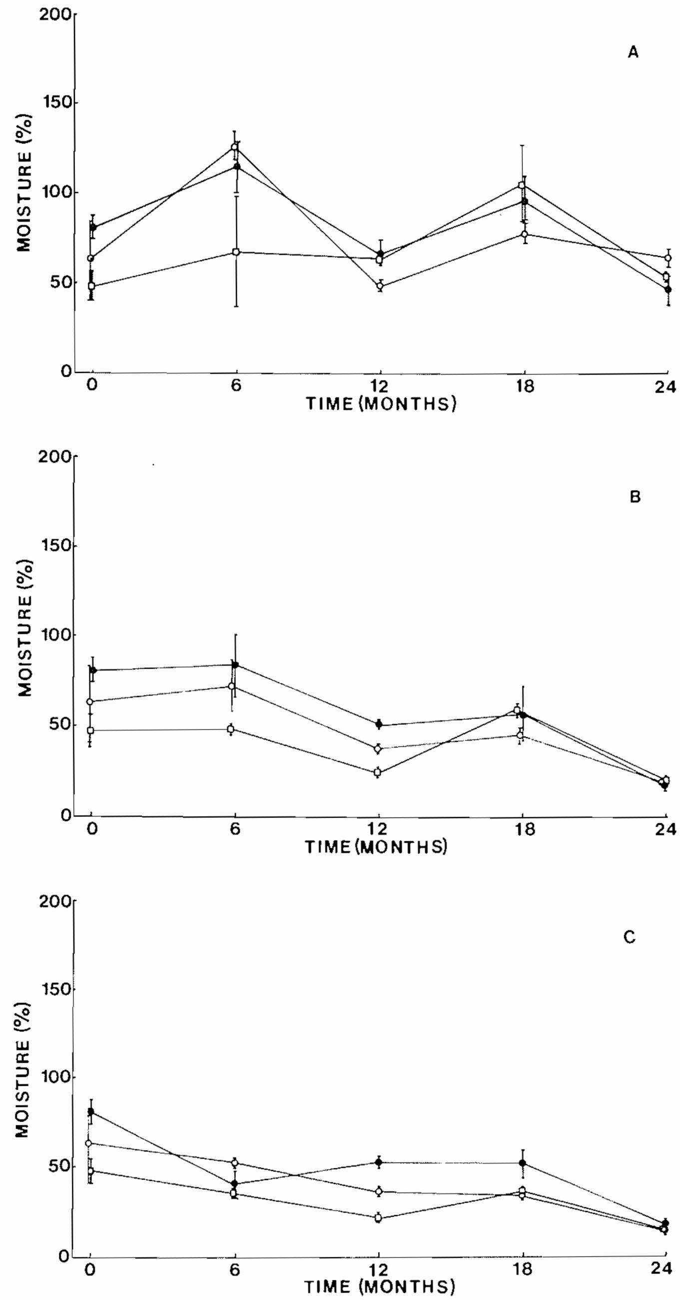

FIG. 2. Moisture contents (dry weight, mean ± SD) of different diameter (●, 1–2 cm; ○, 4–6 cm; □, 8–12 cm) Douglas-fir wood sections on the south slope in relation to time since logging in summer (August) 1978: A, buried (−10 cm); B, soil surface; C, elevated (+20 cm).

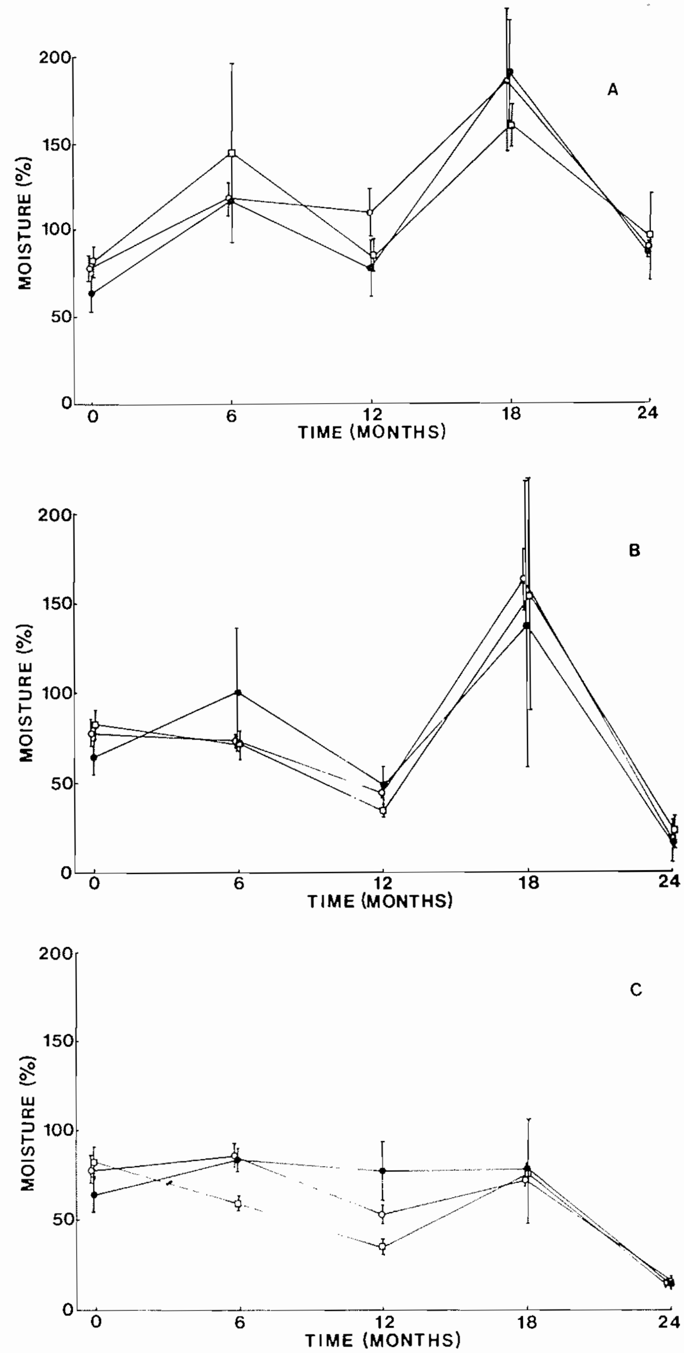

FIG. 3. Moisture contents (dry weight, mean ± SD) of different diameter (●, 1–2 cm; ○, 4–6 cm; □ 8–12 cm) red alder wood sections on the south slope in relation to time since logging in summer (August) 1978; A, buried (−10 cm); B, soil surface; C, elevated (+20 cm).

have lower moisture contents and a greater range of temperatures than faster decomposing surface and buried residues. Douglas-fir wood chemistry had little influence on decomposition in the first 2 years, despite the rather dramatic difference in chemistry between summer and winter logged wood. Erickson et al. (1985) also concluded that Douglas-fir initial wood chemistry had little influence on decomposition, with moisture having the dominant influence.

Initial wood chemistry, particularly soda solubility, however, had a strong influence on red alder wood decomposition with moisture playing a secondary role. Wood moisture contents were higher and closer to optimum levels for decomposition.

Conclusions

Red alder wood decomposed significantly faster than Douglas-fir wood regardless of vertical location and diameter. Vertical location strongly influenced decomposition rates with weight loss generally following the sequence buried > surface > elevated. This trend was more strongly developed in Douglas-fir than in red alder. In fact, there were few significant differences in decomposition rates between surface and buried red alder wood. Smaller diameter wood of both species generally decomposed faster than larger diameter wood.

Aspect and season of logging did not influence decomposition rates. Douglas-fir wood decomposition rates were strongly related to wood moisture and temperature, with chemistry playing a secondary role. Initial wood chemistry, particularly soda solubility, played a more important role than moisture relative to red alder wood decomposition.

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