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Surface Fuel Litterfall and Decomposition in the Northern Rocky Mountains, U.S.A.

Robert E. Keane

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Abstract

Surface fuel deposition and decomposition rates are important to fire management and research because they can define the longevity of fuel treatments in time and space and they can be used to design, build, test, and validate complex fire and ecosystem models useful in evaluating management alternatives. We determined rates of surface fuel litterfall and decomposition for a number of major forest types that span a wide range of biophysical conditions in the northern Rocky Mountains, USA. We measured fuel deposition for more than 10 years with semi-annual collections of fallen biomass sorted into six fuel components (fallen foliage, twigs, branches, large branches, logs, and all other canopy material). We gathered this material using a network of seven to nine, 1-m^2 litter traps installed at 28 plots that were established on seven sites with four plots per site. We measured decomposition for only fine fuels using litter bags installed on five of the seven sites and monitored for biomass loss from the bags each year for 3 years. Deposition and decomposition rates are summarized by plot, cover type, and habitat type series. We also present various temporal and spatial properties of litterfall and decomposition fluxes across the six fuel components.

Keywords: fuel dynamics, fuel accumulation, deposition, decay, downed dead woody, simulation modeling

The Author

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Introduction

Fire exclusion policies, coupled with a successful fire suppression program in many Western United States and Canadian landscapes over the last 70 years, have resulted in excessive accumulations of surface fuels that have, in turn, increased the potential for severe fires (Ferry and others 1995; Keane and others 2002c; Kolb and others 1998; Mutch 1994). Many government land management agencies are advocating extensive fuel treatments and ecosystem restoration activities to reduce the possibility of severe and intense wildfire that could damage ecosystems, destroy property, and take human life (GAO 2002, 2003; Laverty and Williams 2000). Knowledge of fuel deposition and decomposition rates before and after fuel treatments could help managers prioritize, design, and implement more effective fuel treatment programs. Unfortunately, these rates remain relatively unknown for many ecosystems. This is especially true for small down dead woody material because most studies measured only litter or large log fuel decay and accretion rates (Harmon and others 1986b).

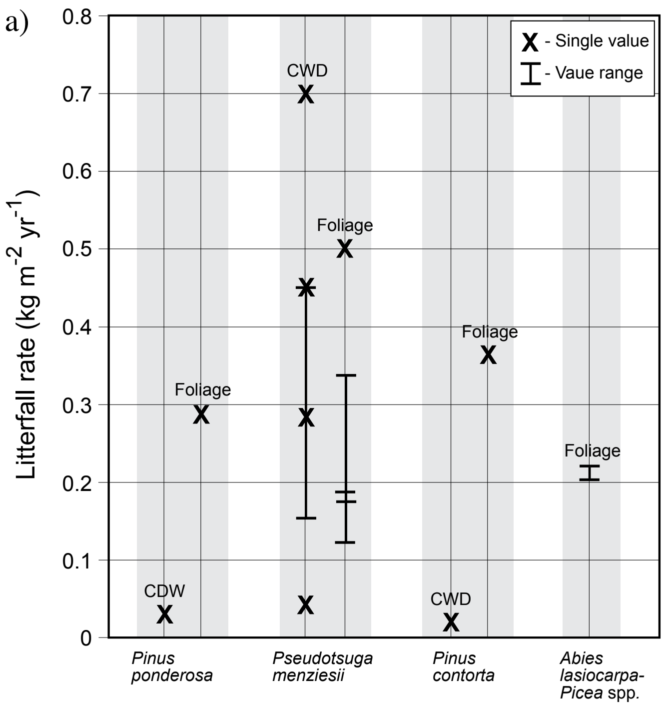
Fuel dynamics across managed landscapes are important to fire managers and researchers for many reasons. Rates of fuel buildup and decomposition can be used to define how long treatments will last and how long before an area needs fuel treatment (Fernandes and Botelho 2003). Fuel and fire modeling efforts often require estimates of deposition and decomposition rates to realistically simulate fuel dynamics across entire landscapes to compare alternative fuel treatment strategies (CH2MHill 1998; Keane and others 2002b). The rates can also be used as validation of simulated ecological processes in existing and future ecosystem process models (Botkin 1993; Keane and others 1996a; Keane and others 1989; Kercher and Axelrod 1984; Pastor and Post 1985; Vanderwel and others 2006).

In this study, the rates of deposition and decomposition were determined for several surface fuel components for major forest types of the northern Rocky Mountains, U.S.A. The study was specifically designed to quantify fuel dynamics parameters for use in complex landscape models of fire and vegetation dynamics (Keane and others 1996a, b; White and others 1998, 2000). Litterfall and decomposition rates are summarized by vegetation type and habitat type (Pfister and others 1977) and then their spatial and temporal properties are discussed in the context of fuel modeling and mapping. Since it was impossible to measure fuel dynamics for all stand types in all northern Rocky Mountain ecosystems, the measured litterfall and decomposition rates were correlated to a number of biophysical and vegetation variables in a companion paper (Keane 2008, in press). The environmental variables were either measured at the field sites or simulated with ecosystem process models so that fuel accumulation processes could be extrapolated across northern Rocky Mountains landscapes.

Background

Six surface fuel components are recognized in this study. Freshly fallen leaves and needles from trees, shrubs, and herbaceous plants are considered *foliage*, while all other non-woody material, such as fallen cones, bark scales, lichen, and bud scales, are lumped into a category called *other canopy fuels*. The woody material is sorted into four diameter classes using definitions required by the fire behavior and effects models (Anderson 1982; Burgan 1987; Fosberg 1970; Reinhardt and Keane 1998; Rothermel 1972). The smallest size class, called *twigs*, defines 1 hr timelag fuels with diameters less than 3 mm. *Branches* with diameters between 3 and 25 mm are 10 hr timelag fuels and *large branches* with diameters ranging from 25 to 75 mm are 100 hr timelag fuels. The *logs*, downed woody fuels greater than 75 mm in diameter, are often referred to as coarse woody debris and define the 1,000 hr timelag fuel component (Hagan and Grove 1999). We use the term litterfall to describe the process of fuel deposition so all fuels that hit the ground are called litter for simplicity and the devices used to measure fuel dynamics (litterfall and decomposition in this study) are referred to as litter traps and litter bags. We did not measure duff, tree, shrub, and herbaceous fuel dynamics in this study because duff is a byproduct of decomposition and many studies have already quantified the growth and mortality of live fuels.

Litterfall rates have been measured for many ecosystems of the world (Bray and Gorham 1964; Facelli and Pickett 1991; Harmon and others 1986a; Van Cleve and Powers 1995) and especially those of the Unites States Pacific Northwest (fig. 1). But, most studies only measured the rate of foliage or log deposition (Harmon and others 1986b, Vogt and others 1986). Small woody debris additions to the forest floor, such as twigs and branches, are rarely reported even though they may be the most important to fuels management and fire behavior prediction because they contribute most to fire spread (Albini 1976, Rothermel 1972). There are some exceptions, such as Ferrari (1999), who measured twigfall in hardwood-hemlock forests and Meier and others (2006), who measured fine woody material, along with other canopy litterfall, in an alluvial floodplain hardwood forest. Deposition



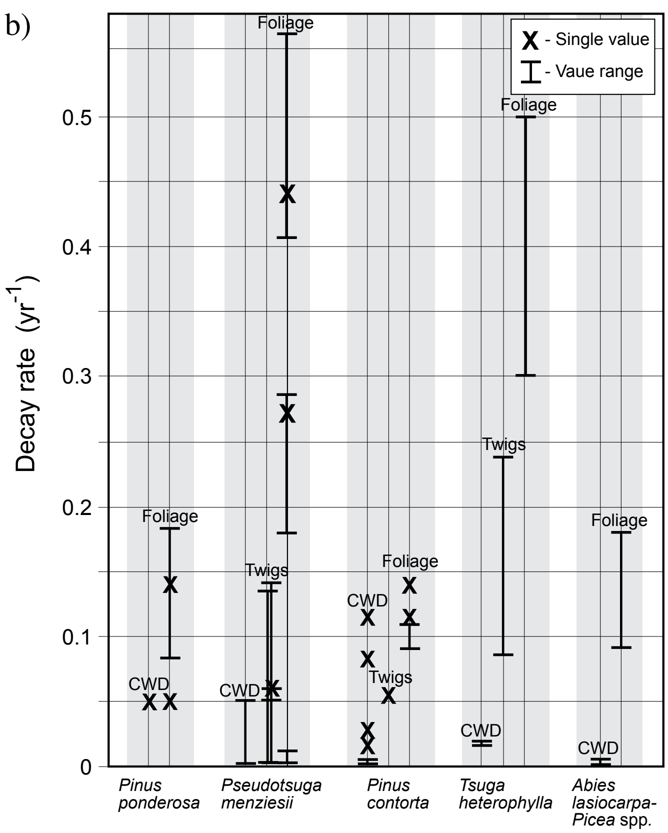


Figure 1. Ranges of a) litterfall and b) decomposition rates (decay constant k) as measured in the literature taken mostly from studies in the Pacific Northwest, U.S.A. Each mark (bar or x) identifies a separate study. These data were taken from the following sources: Alexander 1954; Avery and others 1976; Berg and Ekbohm 1993; Bray and Gorham 1964; Busse 1994; Christiansen and Pickford 1991; Dimock 1958;, Edmonds 1979, 1987, 1991; Edmonds and Eglitis 1989; Edmonds and others 1986; Fogel and Cromack 1977; Gottfried 1978; Graham 1982; Grier and Logan 1977; Harmon and others 1986a; Harmon and Hua 1991; Hart and others 1992; Keenan and others 1996; Klemmedson 1992; Klemmedson and others 1990; Kueppers and others 2004; Laiho and Prescott 1999; Maguire 1994; Means and others 1985; Pearson 1987; Prescott and others 1993, 2000, 2003; Sollins 1982; Sollins and others 1987; Spies and others 1988; Stohlgren 1988; Stump and Binkley 1993; Taylor and others 1991; Trofymow 1991; Turner and Long 1975; Wright and Lauterback 1958; and Yavitt and Fahey 1982.

rates for logs are usually measured from historical tree mortality and snag fall rates over time, but this assumes tree fall is the only input to log buildup. Large branches and tree tops, however, also contribute to log inputs to the forest floor in some ecosystems (Harmon and others 1986b).

Decomposition rates have also been documented for many ecosystems (Aber and Melillo 1980; Horner and others 1988; Millar 1974; Olsen 1963), but again, these rates are usually for the foliage and large log material, especially in the Western United States (fig. 1). The exceptions here are Edmonds (1987) and Taylor and others (1991), who measured decay of twigs, branches, and cones and Carlton and Pickford (1982) and Christiansen and Pickford (1991), who estimated small wood losses by sampling different aged timber slash.

The parameter k is often used to describe rates of decay because it is the parameter in the following exponential curve that if often used to describe decay over time (Olsen 1963; Robertson and Paul 2000).

$$\frac{A_0}{A_t} = e^{-kt} \qquad (1)$$

where A is the amount of material at time zero (A_0) and time t (A_t), and t is time. Decomposition is often expressed as an exponential function because organic material takes longer to decay as time progresses. Easily decomposed cellulose is quickly decayed, while the less digestible lignin remains and it decomposes slower (Kaarik 1974; Moorhead and Sinsabaugh 2006).

It is difficult and costly to measure surface fuel dynamics in the field because it requires extensive networks of litterfall traps that must be frequently monitored over long time periods (5 to 10 years or longer). The density and spacing of the collection devices are highly dependent on the type of fuel collected. Large fuels require installing larger traps across larger areas and are monitored for longer time periods, whereas small fuels require smaller and fewer traps that are frequently visited to minimize decomposition losses. Forest fuel accumulation is highly variable in space due to the clustered forest canopy and small scale canopy disturbances (Brown and Bevins 1986).

Methods

This study originated from two previous studies that explored the use of ecosystem modeling and gradient analysis to create digital maps of current and future landscape characteristics. In 1993, we installed a set of litter traps on two sites in western Montana to parameterize and validate two ecosystem models: Biome-BGC (White and others 1998) and Fire-BGC (Keane and others 1996b) (Sites CO and SB in table 1; fig. 2). Then, in 1995, we started an intensive project, called Gradient Modeling and Remote Sensing (GMRS), where measured and simulated environmental variables were used to map ecosystem characteristics, such as fuels, across landscapes (Keane and others 1997, 2002a; Rollins and others 2004). To parameterized and validate the various models used in both studies, we expanded the number of sites from two to six by establishing four new sites

Table 1. General description of the study sites and plots included in this study.

Study site	Plot	Cover type[a]	Habitat type[a]	Elevation (m)	Aspect[b]	Collection years	Basal[c] area (m^2 ha^{-1})	Tree[c] density (t ha^{-1})	Fuel[d] loading (kg m^{-2})	LAI[e] (m^2 m^{-2})
Coram (CO)	1	DF/WL	GF/CU	1,185	SW	1993 to 2005	29.87	296.4	27.26	1.75
	2	WC/WH	WH/CU	1,184	NW	1993 to 2005	50.44	741.0	1.84	2.24
	3	SF	SF/MF	1,937	NE	1993 to 2005	10.58	222.3	8.43	0.63
	4	WP	SF/XT	1,915	SW	1993 to 2005	34.34	938.6	18.45	3.10
Snowbowl (SB)	1	PP	DF/VS	1,680	NW	1995 to 2005	31.28	864.5	1.02	2.85
	2	DF	DF/PM	1,596	S	1995 to 2005	36.57	666.9	1.37	2.77
	3	LP	SF/XT	1,972	SW	1995 to 2005	30.11	988.0	2.61	1.74
	4	SF/WP	SF/MF	2,073	E	1995 to 2005	32.76	568.1	2.19	3.17
Red Mtn (RM)	1	PP	DF/CR	943	E	1995 to 2005	34.96	197.6	3.10	4.01
	2	WC/WH	WH/CU	942	E	1995 to 2005	55.68	395.2	28.12	3.38
	3	WP	SF/XT	1,988	SE	1995 to 2005	19.00	395.2	2.22	1.81
	4	SF	SF/MF	1,529	NW	1995 to 2005	31.31	395.2	8.42	2.47
Spar Lake (SL)	1	WC	WH/CU	1,090	SE	1995 to 2005	64.85	1,284.4	9.67	7.90
	2	DF	GF/XT	1,124	S	1995 to 2005	48.48	419.9	9.33	6.58
	3	WC	WH/CU	1,260	S	1995 to 2005	52.71	988.0	6.02	6.10
	4	WL	WH/CU	1,600	SE	1995 to 2005	68.22	617.5	19.87	7.02
Red River (RR)	1	PP	DF/LB	1,425	N	1995 to 2005	37.41	345.8	19.94	4.40
	2	GF/DF	GF/LB	1,407	SW	1995 to 2005	35.42	172.9	4.82	2.69
	3	LP	SF/XT	1,988	W	1995 to 2005	28.65	543.4	6.27	2.21
	4	LP	SF/XT	1,979	E	1995 to 2005	32.32	889.2	6.98	2.69
Keating Ridge (KR)	1	GF	GF/LB	1,041	E	1995 to 2005	46.53	518.7	20.09	8.39
	2	PP	PP/SA	1,340	W	1995 to 2005	47.35	345.8	10.12	3.01
	3	LP	SF/XT	2,004	W	1995 to 2005	51.31	1,630.2	2.35	4.41
	4	SF	SF/XT	2,078	E	1995 to 2005	70.72	1,654.9	5.20	6.59
Tenderfoot (TF)	1	LP	SF/VS	2,302	F	1997 to 2005	53.75	1,309.1	2.76	4.24
	2	LP/SF	SF/VS	2,299	F	1997 to 2005	44.26	839.8	0.47	3.31
	3	LP	SF/VS	2,143	F	1997 to 2005	25.95	716.3	0.71	2.23
	4	LP	SF/VS	2,158	F	1997 to 2005	38.23	1,284.4	0.77	3.38

[a] Cover type and habitat type species: trees are PP-ponderosa pine (*Pinus ponderosa* var. *ponderosae*), DF-Douglas-fir (*Pseudotsuga mensezii*), WL – western larch (*Larix occidentalis*), WC-western red cedar (*Thuja plicata*), WH-western hemlock (*Tsuga heterophylla*), LP-lodgepole pine (*Pinus contorta* var. *contorta*), WP-whitebark pine (*Pinus albicaulis*), SF-subalpine fir (*Abies lasiocarpa*), GF-grand fir (*Abies grandis*), and undergrowth species are CR-*Calamagrostis rubescens*, CU-*Clintonia uniflora*, LB-*Linnaea borealis*, MF-*Menziesia ferruginea*, PH-*Physocarpus malvaceus*, VS-*Vaccinium scoparium*, XT-*Xerophyllum tenax*. Habitat types are from Pfister and others (1977).

[b] Aspect codes are N-north, S-south, E-east, W-west, F-flat.

[c] Only overstory trees (greater than 10 cm DBH) were used to compute basal area and density.

[d] Fuel loading only includes downed dead woody fuels of all four size classes.

[e] LAI is projected leaf area index (m^2 m^{-2}) and was computed from foliar biomass equations, not the LAI-2000.

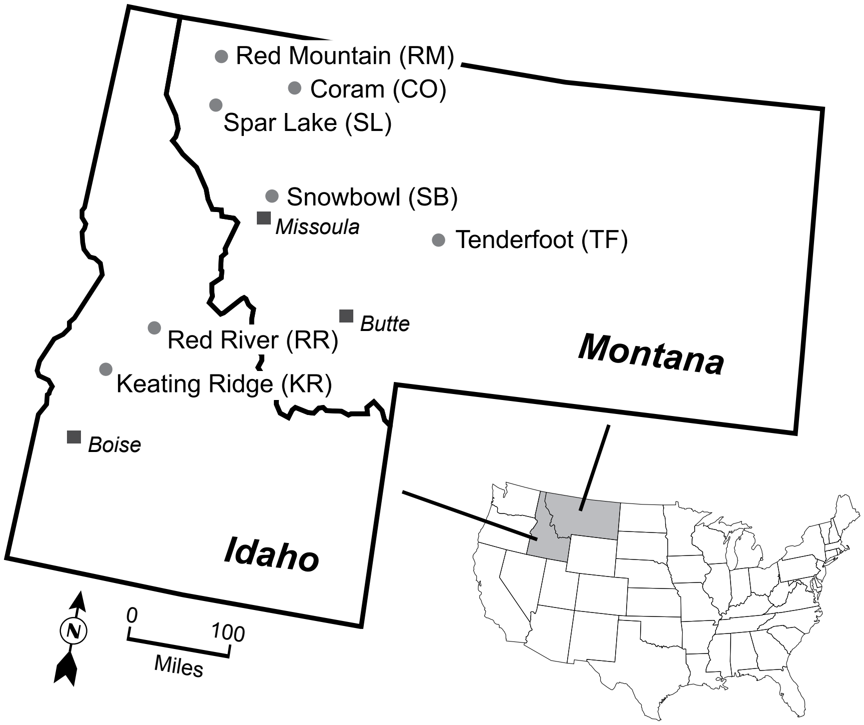


Figure 2. The geographic locations of the seven litter collection sites in the northern Rocky Mountains, USA.

along elevational and aspect gradients within the larger Northern Rockies study area (fig. 2). We only established plots in mature stands that had no evidence or record of disturbance for at least 20 years. Forest types represented by these sites include stands dominated by ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menzeisii*), western red cedar (*Thuja plicata*), subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*). In 1997, a site was established in the ubiquitous lodgepole pine (*Pinus contorta*) ecosystem that occurs east of the Continental Divide (Site TF in table 1; fig. 2).

Each site consisted of four plots established along major topographic gradients of elevation and aspect (fig. 3). We felt that establishing the plots in readily accessible areas at low and high elevations and on north and south aspects adequately described the diversity of the important direct environmental gradients such as productivity, moisture, and temperature (Keane and others 2002a). At each plot, we measured a number of topographic, vegetation, and ecosystem characteristics on 0.1 acre (0.04 ha) circular plots using the ECODATA sampling methodology (Hann and others 1988; Jensen and others 1994; Keane and others 2002a). An entire list of sampled attributes is given in Keane and others (2002a). The most important among them are an inventory of all trees within the plot to compute basal area, leaf area, and stand density, and

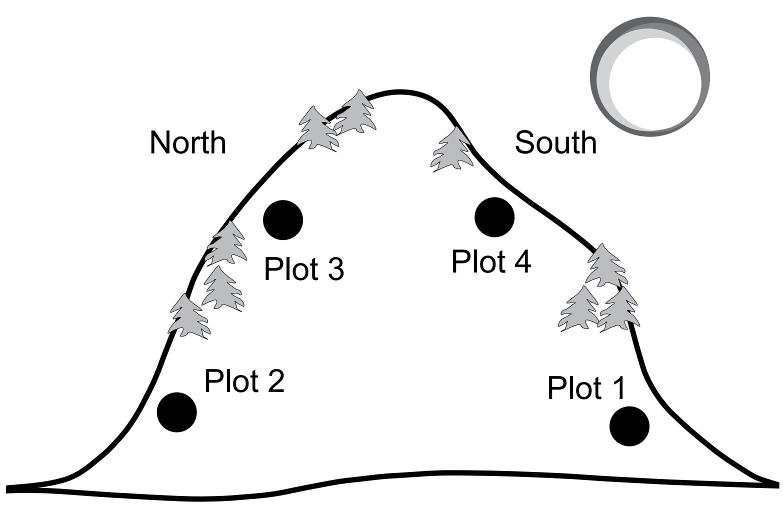


Figure 3. Four litter collection plots were established at each of the seven sample sites in figure 2. Plots were installed at high and low elevations and on north and south aspects for each site.

a network of 30-m fuel transects (Brown 1970) to estimate fuel loadings for five fuel components used in this study.

Measuring Litterfall

At each plot, we installed seven to nine litter traps in the pattern shown in figure 4 to collect fallen biomass. Nine litter traps were established on the two sites that were installed in 1993 (CO, SB; fig. 2, table 1) but a subsequent analysis of variance of fallen foliage showed that only seven traps were needed to adequately sample litterfall. The litter traps were constructed by creating a 1x1-m frame (inside dimensions) with 2x9-cm (1x6-inch) boards and then tacking a coarse grid hardware cloth on the bottom of the frame to allow water drainage and minimize losses from accumulated material due to decomposition and wind (fig. 5). We also tacked a plastic screen (mesh size 0.7 mm) on top of the hardware cloth to block fine material from falling through the coarse hardware grid and to facilitate efficient litter collection.

Each plot was visited once a month during the snow-free periods of the year and all material in each trap was placed into heavy paper bags that were labeled to identify site, plot, trap, and date. Woody fuel particles that lay partially out of the trap were sawed directly at the trap border as defined by the inside dimension of the trap boards. An estimate of projected LAI (Leaf Area Index, m^2 m^{-2}) was taken with a LiCor LAI-2000 (LI-COR 1992; Nackaerts and others 2000; Welles and Norman 1991) during each plot visit to document any major changes in the forest canopy. The frequent monthly visits were designed to minimize mass losses due to decomposition that occur as the newly fallen material sat in the traps, but we found that there was little decomposition occurring during the hot, dry months of summer. The most critical times for sampling were directly after snowmelt and just before the first autumnal snows. Therefore, starting in 2002, we only visited the plots during these two times.

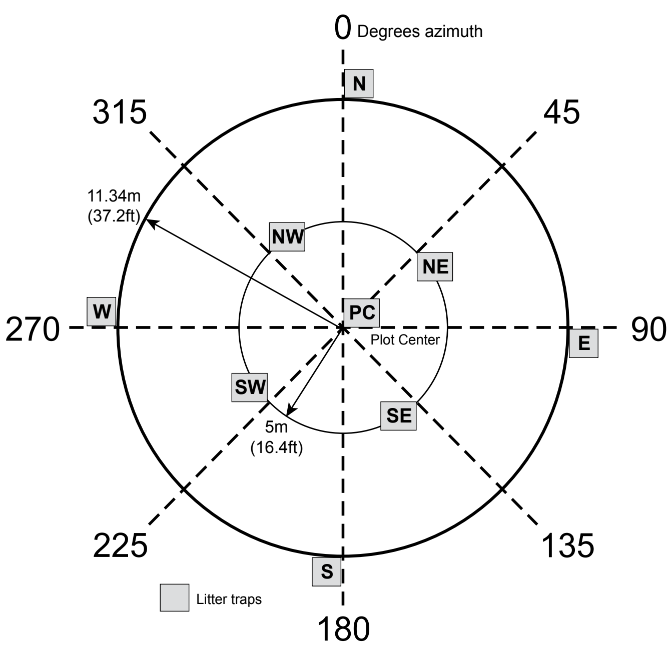


Figure 4. The location of the litter traps within a plot was in a cross-like pattern with nine litter traps at the Coram and Snowbowl sites (CO and SB in table 1) and seven traps per plot at the remaining sites (missing the NE and SW traps). Circles are at 11.6 m and 5 m radius from plot center and numbers represent azimuths. Acronyms reference compass directions: N-north, NW-northwest, NE-northeast, E-east, S-south, SE-southeast, SW-southwest, W-west, PC-plot center

Figure 5. One of the litter traps used in this study. These traps were 1x1 m inside dimensions and about 10 cm deep. Each trap was made of 2x9-cm (1x6-in) boards with hardware cloth tacked on the bottom. A screen was placed over the hardware cloth to catch the smaller material. The bottom of the trap was reinforced with 4x4-cm (2x2-in) boards for stabilization.

The collected materials were transported to the laboratory and the labeled bags were placed in an oven set at 90°C for 2 to 3 days. The dried litter was then placed in cake tins and sorted by hand into the six fuel components (foliage, twigs, branches, large branches, logs, and other canopy material). The weight of each fuel component was recorded to the nearest 0.01 g along with the date, site, plot, and trap information written on the bag. A small sample of the dried material was set aside for the decomposition experiment.

Measuring Fuel Decomposition

We used litter bags to estimate the rate of decay for four fuel components of freshly fallen foliage, twigs, branches, and large branches (Bocock and Gilbert 1957; Edmonds 1979; Johannsson 1994;

Prescott and others 2000; Preston and others 2000; Robertson and Paul 2000). These bags were made by sewing together a fiberglass screen with a pore size of about 2 mm for the top and a rumen bag or pool cover material with a pore size of 0.055 mm for the bottom using UV resistant thread (fig. 6a). One end of the bag was left open. Bags for foliage were roughly 170 mm square, while bags for the woody fuels were roughly 170 mm by 130 mm (0.0221 m^2). We put approximately 100 to 150 g of the material taken from the litter traps (see previous section) into each bag and then sewed the bag closed. We firmly attached a unique numbered tag to the side of the bag. The bags were then dried at 50^{o}C for 3 days and weighed to the nearest 0.01 g with the weight recorded by bag number. We did not measure decomposition rates for logs and other canopy material because of limited time, lack of appropriate equipment, and incompatible methods.

At each plot, we installed three sets of three bags for the three fine woody fuel components (1, 10, and 100 hr timelag) and three sets of six bags for the foliage material (fig. 6b). We placed one set from each of the four components near plot center, about 7 m (23 ft) northwest of plot center, and about 7 m southeast of plot center (fig. 6). We laid litter bags on top of the existing litter layer in late autumn and secured them with a wire that was sewn through each bag and attached to large 20-cm spikes driven into ground to a depth of 19 cm (7.5 in) to prevent movement down slope and ungulate damage. We flagged and staked the locations of each bag set. Decomposition was measured over 3 years by taking one foliage bag from each wire set every 6 months and one woody bag from each woody fuel set every 12 months. We cut the retrieved bags from the wire, and any material that had fallen onto the bag or became attached to the bottom of the bag was scraped off using a knife. We then placed the litter bags in paper bags, dried them at 50^{o}C for 3 days, and then weighed them to the nearest 0.01 g with the weight, tag number, and tag date recorded for analysis.

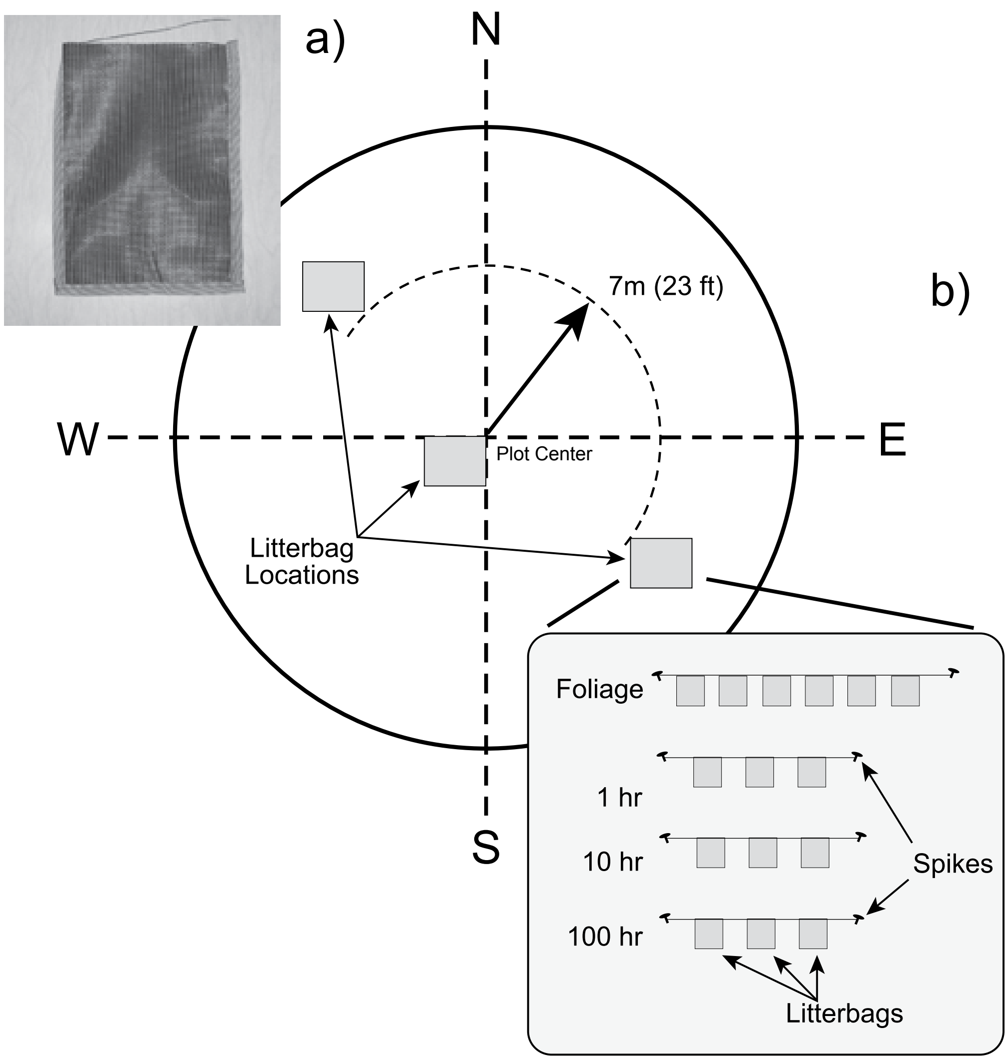


Figure 6. Details of the litterbags that were used in this study. a) picture of a litterbag and b) the locations of the litter bags on the plot representing each site. Litterbags were not placed at the Spar Lake (SL) and Red River (RR) sites due to lack of funding and resources.

Analyzing Collected Data

We summarized the measured deposition and decomposition rates by fuel component for each plot to create tables to use as reference for parameterization and validation of fuel dynamics models. We computed the annual litterfall rates (kg m^{-2} yr^{-1}) by dividing the total amount of accumulated material over all traps on a plot for the entire time period by the number of days in that time period, and then multiplied this daily flux rate by 365 to obtain an annual rate. We then summarized these rates by plot, cover type, and habitat type series (Pfister and others 1977) and correlated them with measured LAI.

Two estimates of decomposition were calculated. We estimated the parameter *k* by parameterizing the exponential decay function described in Equation 1. A mass loss rate (percent yr^{-1}) was also calculated from differences in bag weights over the 3-year period. Statistical summaries included an analysis of variance to determine the adequate level of sampling intensity and strength of the fuels flux estimates. We performed the analysis to determine the decomposition parameter *k* in the Olson (1963) equation in SPLUS using a linear mixed effects model whose form is as follows:

$$\ln\left(\frac{x_{ij}}{x_{i0}}\right) = (-k + b_i)t_j + \varepsilon_{ij} \qquad (2)$$

where x_{ij} is the weight of the *i*th trap at time j (t_j) and x_{i0} is the initial weight of the *i*th trap; b_i is the random effect of trap *i* representing the deviation of the slope from the fixed effect for trap *i*; and $\boldsymbol{\varepsilon}_{ij}$ are the random errors assumed to be independently distributed with a normal distribution.

An analysis of variance for litterfall was performed across all fuel components on each plot to determine if we had sufficient sampling rigor. First, we evaluated the variation of litterfall using a bootstrap method where traps were randomly removed from the analysis to determine the number of traps required to minimize variance. Then, we estimated the probability of detection for each fuel component over the entire length of the study and for 1 year to verify the results generated from the bootstrap variance calculations.

To address litterfall distribution across litter traps, we examined the skewness of the total accumulation of the traps for each plot (Hirabuki 1991). Since the skewness statistic is a measure of lack of symmetry, well distributed fuel components would have a fairly symmetric distribution for accumulation at each plot. However, if fuel distributions were spotty or clustered, then we would expect the distribution to be skewed. Skewness is equal to zero for symmetric or uniform distribution, negative when data are skewed left (more low litterfall years), and positive when data are skewed right (more high litterfall years).

We used cumulative sum (CUSUM) graphical plots to examine trends across time for each fuel component by trap and plot. CUSUM graphs are often used to monitor industrial processes but have been used to monitor environmental processes. CUSUM graphs show the accumulated deviations from the mean of that particular plot after sorting the plots in order of magnitude. This allows the detection of any systematic differences between the observed value and the expected value over the time span of collection.

Results

Litterfall Rates

Sampled rates of average annual fuel deposition for all fuel components across all plots in the study are shown in table 2 and figure 7. The highest rates were recorded for foliage, which also had the highest variability (fig. 7a) and these high rates tended to occur on plots with northern exposure, high basal area, and high LAI (fig. 7b). Rates for fine woody fuel and other canopy material components were similar across most of the sites (table 2). Log fall, which had the lowest rates, was recorded in only 47 percent (15 of 28) of the plots across all traps for the entire 10+ year recording period, but 90 percent of the plots experienced large branch fall and all plots recorded foliage, twig, branchwood, and other canopy material litterfall. Fallen foliage, twigs, and other canopy material were recorded in all traps for nearly all of the visits (99.8 percent). Annual variation of deposition rates were low (about 10 percent of annual mean) for fine woody fuel components, but tended to increase with increasing fuel size, probably because large fuels were rarely found in the traps (fig. 7a; table 2).

The mesic cover types with shade tolerant species, such as western red cedar (WC), grand fir (GF), and Douglas-fir (DF), usually had the highest litterfall rates (table 3). The low elevation, xeric cover types, such as ponderosa pine (PP) and Douglas-fir (DF), had nearly the same litterfall rates for all fuel components as the high elevation cover types such as whitebark pine (WP) and subalpine fir (SF). The pine cover types (WP, PP, LP) had a higher foliage to fine wood fuel litterfall ratio than all other species. The most productive habitat type series (Pfister and others 1977) had the highest litterfall rates, especially for foliar deposition (table 3). Since only mature stands were

Table 2. Litterfall rates for the six fuel components in this paper. Values in table are in kg m^{-2} yr^{1} dry weight biomass and values in parentheses are the standard error. Cells with dashes indicate that fuel was never sampled or collected on that plot. Cover type codes are defined in table 1.

Site	Plot-cover type	Foliage	1 hr (twigs)	10 hr (small branch)	100 hr (large branch)	1,000 hr (logs)	Other canopy material
Coram CO	1-DF	0.079 (0.005)	0.016 (0.001)	0.005 (0.001)	0.001 (0.001)	—	0.042 (0.005)
	2-WC	0.121 (0.011)	0.031 (0.004)	0.015 (0.004)	0.012 (0.006)	—	0.031 (0.003)
	3-SF	0.036 (0.005)	0.005 (0.001)	0.003 (0.001)	0.003 (0.003)	—	0.011 (0.001)
	4-WP	0.077 (0.011)	0.013 (0.006)	0.006 (0.003)	0.002 (0.002)	0.035 (0.024)	0.012 (0.004)
Snowbowl SB	1-PP	0.057 (0.003)	0.015 (0.003)	0.006 (0.002)	—	—	0.026 (0.005)
	2-DF	0.106 (0.013)	0.029 (0.008)	0.013 (0.005)	0.015 (0.015)	0.012 (0.012)	0.020 (0.002)
	3-LP	0.100 (0.005)	0.010 (0.001)	0.003 (0.001)	0.020 (0.016)	0.001 (0.001)	0.021 (0.002)
	4-SF/WP	0.094 (0.007)	0.029 (0.011)	0.030 (0.022)	0.015 (0.015)	0.158 (0.158)	0.028 (0.003)
Red Mountain RM	1-PP	0.110 (0.014)	0.006 (0.001)	0.019 (0.009)	0.011 (0.006)	—	0.042 (0.009)
	2-WC	0.135 (0.015)	0.032 (0.008)	0.011 (0.004)	0.003 (0.003)	—	0.056 (0.017)
	3-WP	0.061 (0.016)	0.003 (0.001)	0.001 (0.001)	—	—	0.021 (0.003)
	4-SF	0.058 (0.007)	0.012 (0.003)	0.007 (0.002)	0.023 (0.021)	—	0.022 (0.003)
Spar Lake SL	1-WC	0.144 (0.008)	0.043 (0.004)	0.026 (0.004)	0.054 (0.036)	0.080 (0.080)	0.035 (0.009)
	2-DF	0.132 (0.012)	0.035 (0.006)	0.032 (0.009)	0.067 (0.063)	0.117 (0.061)	0.045 (0.008)
	3-WC	0.150 (0.008)	0.032 (0.003)	0.021 (0.004)	0.039 (0.039)	0.058 (0.058)	0.050 (0.007)
	4-WL	0.230 (0.022)	0.060 (0.013)	0.033 (0.010)	0.026 (0.020)	—	0.075 (0.019)
Red River RR	1-PP	0.089 (0.015)	0.001 (0.0004)	0.008 (0.004)	0.002 (0.001)	—	0.023 (0.008)
	2-GF/DF	0.099 (0.014)	0.032 (0.008)	0.048 (0.030)	0.001 (0.001)	—	0.055 (0.012)
	3-LP	0.068 (0.009)	0.006 (0.001)	0.003 (0.001)	0.001 (0.001)	—	0.027 (0.004)
	4-LP	0.071 (0.008)	0.024 (0.009)	0.015 (0.006)	0.003 (0.002)	0.073 (0.073)	0.030 (0.004)
Keating Ridge KR	1-GF	0.134 (0.008)	0.034 (0.004)	0.018 (0.004)	0.002 (0.001)	0.192 (0.192)	0.020 (0.003)
	2-PP	0.129 (0.005)	0.002 (0.000)	0.012 (0.003)	0.001 (0.001)	—	0.045 (0.005)
	3-LP	0.094 (0.005)	0.025 (0.002)	0.016 (0.004)	0.006 (0.005)	—	0.061 (0.002)
	4-SF	0.157 (0.010)	0.048 (0.012)	0.038 (0.013)	0.001 (0.001)	0.0001 (0.0001)	0.062 (0.005)
Tenderfoot Forest TF	1-LP	0.131 (0.006)	0.024 (0.002)	0.003 (0.001)	—	—	0.061 (0.004)
	2-LP/SF	0.099 (0.006)	0.023 (0.010)	0.018 (0.013)	0.019 (0.019)	0.207 (0.164)	0.040 (0.007)
	3-LP	0.121 (0.004)	0.014 (0.002)	0.006 (0.002)	0.002 (0.002)	0.058 (0.058)	0.040 (0.003)
	4-LP	0.086 (0.009)	0.024 (0.004)	0.012 (0.002)	0.001 (0.001)	—	0.045 (0.004)

sampled, no differences in litterfall across stand age were evaluated.

Decomposition Rates

Decomposition measurements (k values and mass loss rates) were quite diverse across all plots in the study (table 4, fig. 8). Decay rates were higher for foliage (k = 0.085 to 0.283) than woody fuel (k = 0.045 to 0.125) (table 4), but foliage decay and mass loss rates were more variable (fig. 8a and 8b) and more closely tied to site conditions. Large woody fuels had lower decay and mass loss rates than the smaller size woody fuel classes, but many sites had the same woody decay rates across all woody size classes (table 4). The slowest decomposition occurred in the low elevation, south-facing forests, especially those with high LAI (fig. 8c). Decay rates were the highest in the most productive sites, namely those on low elevation north aspects or high elevation south aspects. In fact, the order of plots in figure 8c, from left to right, appears to correlate to a wet to dry moisture gradient (Keane 2008, in press). The most productive sites (SB-2, KR-2, and TF-2) had woody decay rates that were equivalent to foliage rates. The low variability of woody fuel decay might suggest little correlation with site environment.

Cover types with shade tolerant species usually had the highest decomposition rates (table 3). The most productive habitat type series (the most mesic) had the highest decomposition rates, especially foliar deposition (table 3). Again, the span of measured decomposition rates appears to correlate to an available moisture gradient. While dry site (PP, DF) decomposition of foliage was low compared to other mesic series (table 3), the woody fuel decomposition appears to be higher indicating a possible correlation to temperature.

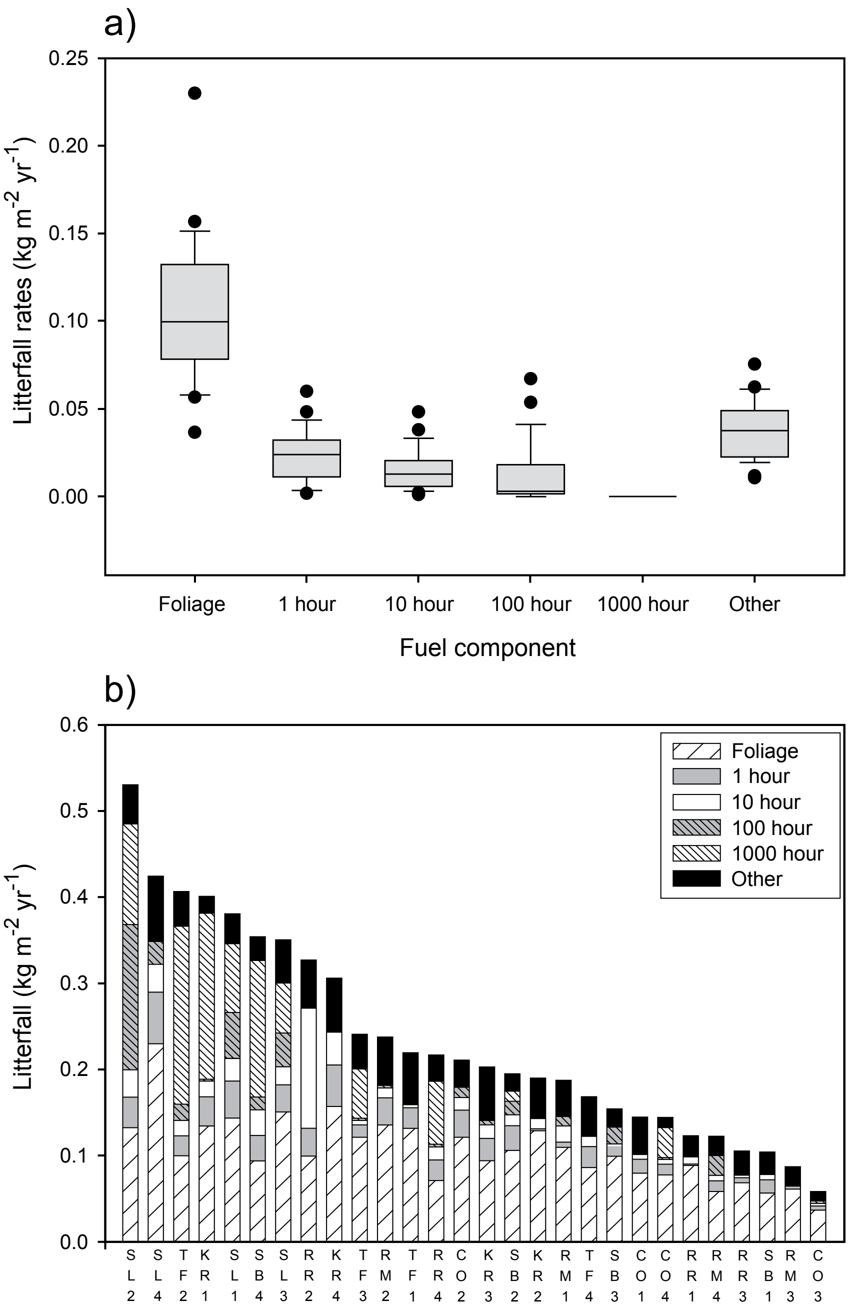


Figure 7. Distribution of litterfall rates (kg m^{-2} yr^{-1}) for all fuel collected in all litter traps by surface fuel components: a) distribution by fuel component across all plots and b) distribution across all fuel components for each plot.

Leaf Area Index (LAI)

Measurements of LAI using the LiCor LAI-2000 were much more variable than expected but proved valuable none the less, even with the high variability (fig. 9). The instrument appeared to have the sensitivity to detect the loss of foliage over the fall and winter and the subsequent leaf growth in the spring and early summer (fig. 10). Leaf area was the highest on those plots that were dominated by shade tolerant conifers (DF, WC, SF) and lower on the pine dominated plots (PP, LP) (fig. 9). The western larch (WL) plot in Spar Lake (SL4) had a high leaf area due to its high productivity and the abundance of shade tolerant conifers in the understory; LAI also tended to increase with increasing productivity and foliar litterfall. There does not appear to be any trends in LAI measurements across the 10+ years of the study (fig. 10), but there does appear to be some suspect measurements probably due to operator error (fig. 10d).

Discussion

Litterfall Rates

Litterfall rates in this study are slightly lower than those in other studies (compare fig. 1a with table 2)

Table 3. Litterfall and decomposition rates for each fuel component averaged across cover type and habitat type series. Types are arranged from low to high in foliage litterfall. Dashes indicate missing data because either logs were not detected on the plot or litter bags were never installed at that plot. Definitions for cover or habitat type acronyms are given in table 1 (Pfister and others 1977).

Cover type or habitat type series	Foliage		1 hr (twigs)		10 hr (branches)		100 hr (large branches)		1,000 hr (logs)	Other canopy material
	Litterfall	*k* value	Litterfall	*k* value	Litterfall	*k* value	Litterfall	*k* value	Litterfall	Litterfall
Cover type										
WP	0.069	0.226	0.008	0.083	0.003	0.069	0.002	0.050	0.035	0.017
SF	0.086	0.140	0.024	0.082	0.019	0.037	0.010	0.038	0.079	0.031
LP	0.096	0.195	0.019	0.093	0.010	0.045	0.007	0.041	0.085	0.041
PP	0.096	0.111	0.006	0.039	0.011	0.028	0.005	0.074	—	0.034
DF	0.106	0.120	0.027	0.084	0.017	0.031	0.062	0.142	0.064	0.036
GF	0.117	0.128	0.033	0.063	0.079	0.072	0.001	0.042	0.192	0.038
WC	0.138	0.165	0.034	0.093	0.018	0.047	0.027	0.023	0.069	0.043
WL	0.230	—	0.060	—	0.033	—	0.026	—	—	0.075
Habitat type series										
DF	0.090	0.098	0.013	0.034	0.012	0.024	0.009	0.014	0.012	0.028
SF	0.090	0.182	0.019	0.088	0.011	0.049	0.008	0.042	0.076	0.034
GF	0.111	0.142	0.029	0.074	0.049	0.059	0.043	0.092	0.154	0.041
PP	0.129	0.122	0.002	0.045	0.012	—	0.001	0.193	—	0.045
WH	0.156	0.165	0.040	0.093	0.021	0.047	0.027	0.023	0.069	0.050

Table 4. Measured decomposition rates for each of the plots averaged across all litter bag sets within a plot. Values in cells are estimates of mass loss (percent yr^{-1}) and the value k (yr^{-1}) with numbers in parenthesis are standard error estimates. Dashes indicate litter bags were never installed at that plot or they were missing from the plot at collection. Cover type codes are defined in table 1.

Site	Plot	Foliage		1 hr (twigs)		10 hr (branches)		100 hr (large branches)	
		Mass loss	*k* value	Mass loss	*k* value	Mass loss	*k* value	Mass loss	*k* value
Coram CO	1-DF/WL	0.126	0.156 (.007)	0.059	0.084 (.015)	0.034	0.046 (.007)	0.131	0.142 (.021)
	2-WC	0.137	0.191 (.011)	0.093	0.119 (.009)	0.057	0.051 (.007)	—	—
	3-SF	0.114	0.149 (.013)	0.084	0.113 (.011)	—	—	0.041	0.053 (.006)
	4-WP	0.121	0.169 (.011)	0.054	0.068 (.008)	0.068	0.083 (.009)	0.050	0.061 (.006)
Snowbowl SB	1-PP	0.095	0.102 (.018)	—	—	0.021	0.027 (.004)	0.023	0.016 (.006)
	2-DF	0.092	0.085 (.011)	—	—	0.018	0.016 (.005)	—	—
	3-LP	0.115	0.161 (.018)	0.093	0.125 (.011)	0.051	0.054 (.008)	0.031	0.043 (.005)
	4-SF/WP	0.148	0.183 (.011)	0.062	0.069 (.015)	0.062	0.041 (.015)	0.024	0.034 (.005)
Red Mountain RM	1-PP	0.077	0.108 (.016)	0.033	0.034 (.003)	0.024	0.029 (.005)	0.007	0.011 (.005)
	2-WC	0.097	0.140 (.011)	0.049	0.067 (.009)	0.026	0.044 (.009)	0.022	0.023 (.002)
	3-WP	0.168	0.283 (.027)	0.083	0.098 (.004)	0.047	0.056 (.006)	0.033	0.040 (.006)
	4-SF	0.075	0.110 (.007)	—	—	0.032	0.033 (.005)	—	—
Keating Ridge KR	1-GF	0.093	0.128 (.014)	0.053	0.063 (.008)	0.056	0.072 (.019)	0.033	0.042 (.015)
	2-PP	0.098	0.122 (.007)	0.047	0.045 (.004)	—	—	0.015	0.193 (.006)
	3-LP	0.079	0.104 (.006)	0.050	0.060 (.007)	0.030	0.032 (.005)	0.022	0.025 (.005)
	4-SF	0.081	0.118 (.010)	0.054	0.063 (.005)	—	—	0.024	0.027 (.005)
Tenderfoot Forest TF	1-LP	0.154	0.226 (.015)	0.056	0.082 (.012)	—	—	0.032	0.047 (.008)
	2-LP/SF	0.139	0.205 (.018)	0.063	0.106 (.027)	—	—	0.033	0.046 (.006)
	3-LP	0.167	0.247 (.008)	0.074	0.093 (.008)	0.037	0.047 (.006)	0.042	0.051 (.006)
	4-LP	0.154	0.229 (.008)	—	—	0.033	0.045 (.005)	0.029	0.036 (.004)

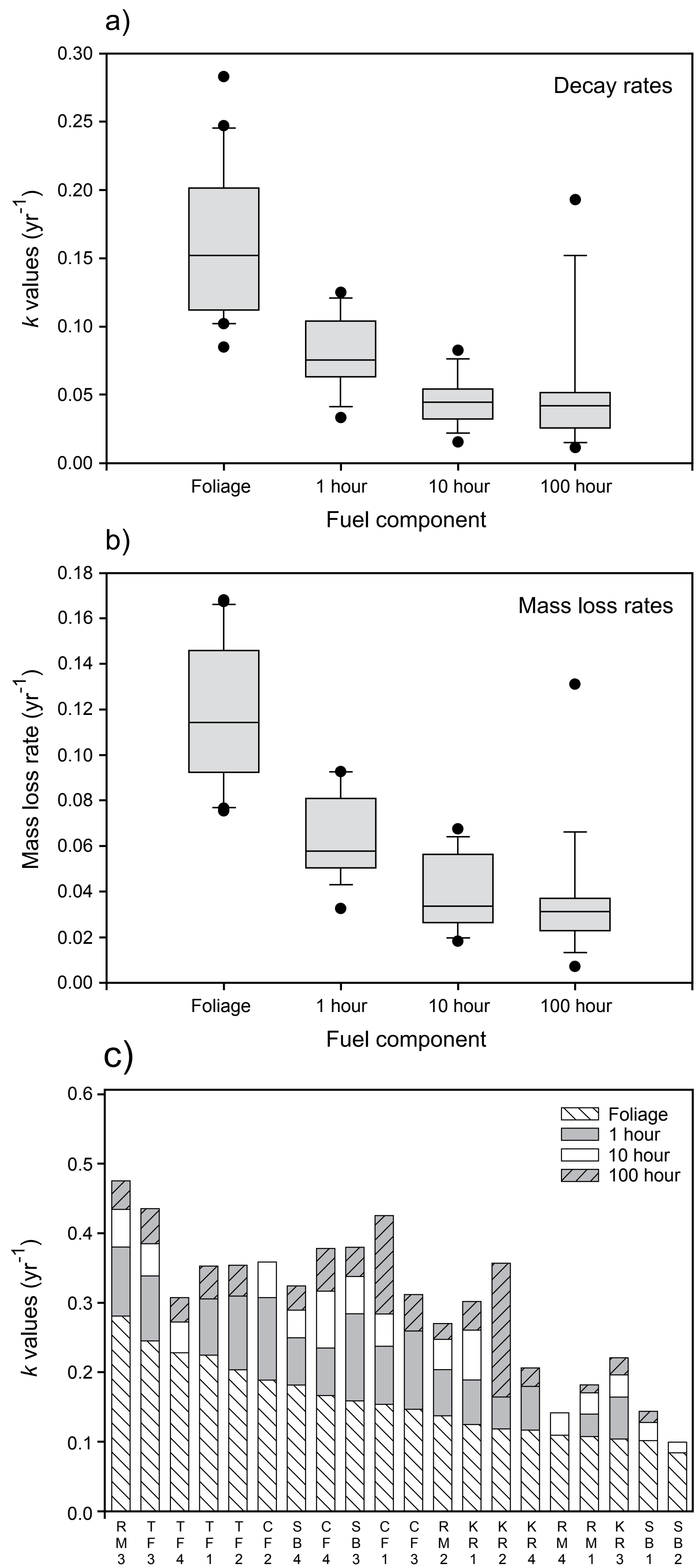


Figure 8. Distribution of a) decay rates (*k* value) and b) mass loss rates (percent loss) for all 28 plots in this study by four fuel components, and c) decay rates for all components arranged by plot from high to low foliage decomposition. We did not measure decay for logs and other canopy material due to time and cost constraints.

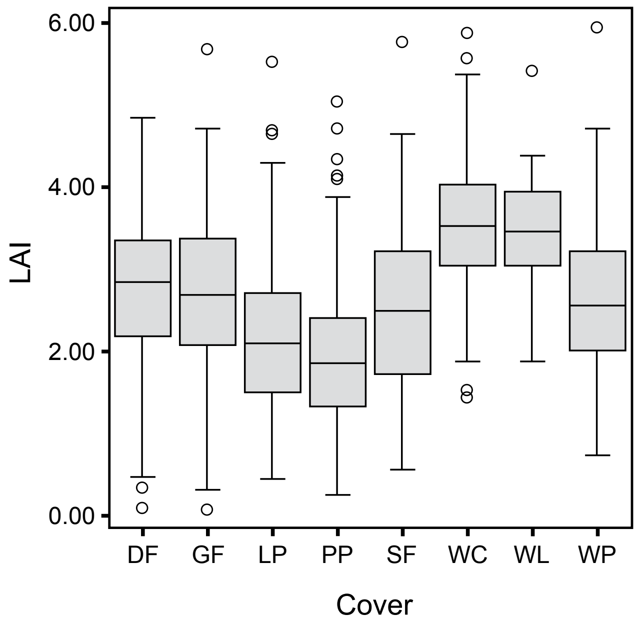


Figure 9. Distribution of LAI measurements, taken with the LiCor LAI-2000 instrument, across all plots classified to cover type. Note the high variation across and within cover types and plots. Cover types defined in table 1.

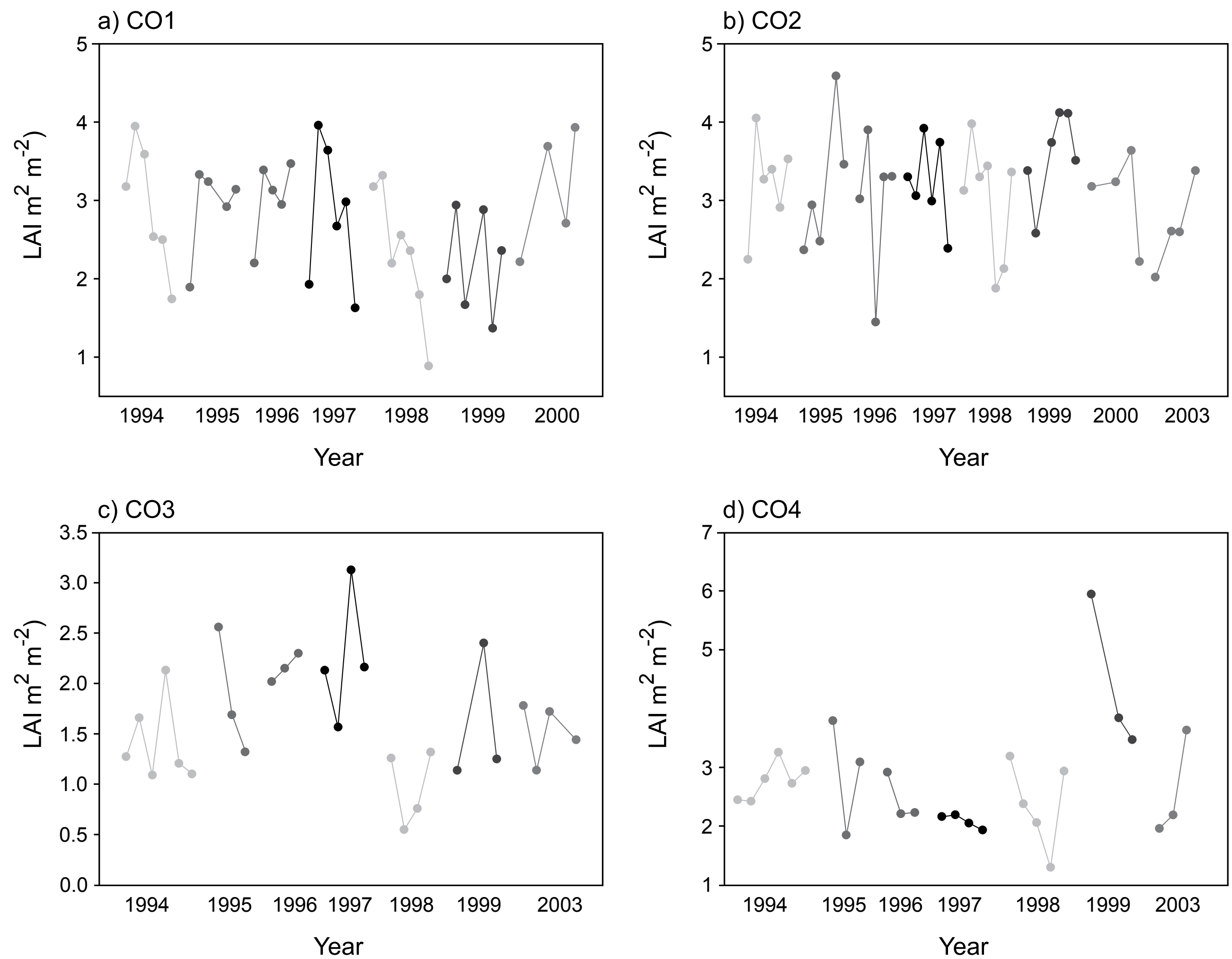


Figure 10. Broken time series of LAI measurements (taken with LiCor LAI-2000) for the four plots at the Coram Forest sample site: a) CO1 is the low elevation, south facing Douglas-fir plot, b) CO2 is the low elevation, north facing western hemlock plot, c) CO3 is the high elevation, north facing subalpine fir plot, and d) CO4 is the high elevation, south facing whitebark pine plot. Each year is a different color.

probably because the northern Rocky Mountain forests are less productive than the Pacific Northwest forests. The low elevation moist sites of this study (CO-2, RM-2, SL-1, SL-2, SL-3, and KR-1) are probably the most ecologically similar to the Douglas-fir study sites reported in figure 1 and the foliage deposition rates (0.12 to 0.15 kg m^{-2} yr^{-1}) are comparable to the minimum reported rates for Pacific Northwest Douglas-fir stands (0.17 to 0.50 kg m^{-2} yr^{-1}). Fine woody fuel litterfall rates measured in this study for those plots (0.001 to 0.139 kg m^{-2} yr^{-1}) also compare well with the Douglas-fir sites (0.005 to 0.129 kg m^{-2} yr^{-1}). Foliage litterfall rates of lodgepole sites (TF1 thru TF-4, RR-3, RR-4, and CO-3; 0.12 to 0.15 kg m^{-2} yr^{-1}) are about half of those reported for the lodgepole pine sites (0.362 kg m^{-2} yr^{-1}) in figure 1. Similarly, subalpine fir foliar litterfall rates in figure 1 are about double the foliage deposition rates (0.20 to 0.23 kg m^{-2} yr^{-1}) as the subalpine fir sites in this study (CO-3, SB-4, RM-4, KR-4) (0.036 to 0.157 kg m^{-2} yr^{-1}). Large woody fuel (logs, large branches) rates are highly variable in this study (0.0001 to 0.207 kg m^{-2} yr^{-1}) but they also seem to agree with those reported for all studies (0.02 to 0.30 kg m^{-2} yr^{-1}; fig. 1).

Foliage litterfall is highly correlated with fine woody litterfall and litterfall of other canopy material but it is not significantly correlated with large woody fuel (fig. 11). Correlation of foliage litterfall to other woody fuel components might be important because foliage deposition can then be used to predict the litterfall of other fuel components. Foliage is 1) easier to collect, 2) more homogeneously distributed across all litter traps (see later in this section) so fewer traps are needed, and 3) less variable across time so fewer years are needed to obtain an adequate sample (see later sections). Smaller woody fuels have the highest correlation because of the consistency of detection in the litter traps (fewer years where no fuels are collected) (figs. 11a and 11b). The high number of zero values for large branches and logs (none fell into traps) resulted in low correlations to foliage (figs. 11c and 11d). Other canopy material (buds, cones, scales) had high correlations with foliage litterfall. It appears that foliage litterfall can only predict fine fuel (twigs, other canopy material, and branches) deposition rates with suitable accuracy and consistency.

Another indirect way to estimate litterfall is to correlate the litterfall rates to a commonly measured stand attributes (Huebschmann and others 1999). We regressed the litterfall rates for the five fuel components to the LAI measured with LAI-2000 (averaged by plot across the entire 10 years) and tree basal area (trees larger than 10 cm DBH or 4 in DBH) and found high correlation in the fine fuels but low correlation in large fuels (branches and logs) (table 5). Again, this is mainly due to the inconsistency of sampling events in the time series for the large woody fuels, but it is also a function of the highly variable and difficult to measure LAI estimates. Equations in table 5 can be used to estimate litterfall rates across landscapes or stands to assess the longevity of fuel treatments.

Results of the bootstrap analysis of variance indicated that the seven litter traps used in this study were sufficient for most forest types (for example, see figure 12 for four plots that span the range of litterfall rates measured for our study). Plots with high litterfall rates appear to need more traps to obtain an adequate sample and the asymptotic variability at seven plots is also much higher than low litterfall rate plots. Large woody fuels (100 hr and 1,000 hr) had the highest variances and they were also the fuel components that needed more traps than the 7 to 9 used in this study (fig. 12). This was especially true for logs (fig. 12c) where most traps did not record fallen logs during the entire span of the study (table 2).

Since our study failed to describe large woody fuel (large branches, logs) deposition with statistical validity, it is important to determine better sampling strategy for measuring litterfall of these large fuel particles that fall so infrequently. The probability of detection (p_d) was calculated from the proportion of the seven or nine litter traps within a plot that recorded each fuel component for both the entire time period and across each year (fig. 13). For the entire 10+ year time period, the average estimated probability of detection across all 28 plots was high for foliage ($p_d = 1.0$), twigs ($p_d = 1.0$), and small branches ($p_d = 0.952$), but low for large woody fuels ($p_d = 0.27$ for large branches and $p_d = 0.0812$ for logs). Nearly the same results were found when p_d was computed by year, except that the large woody fuels were rarely detected ($p_d = 0.036$ for large branches and 0.0092 for logs). In an extension of this statistical analysis, it was found that over 30 plots of 7 to 9 traps each (>210 traps total) would be needed to achieve a p_d greater than 0.9 for logs for the entire 10+ year record (fig. 13a) and, for a single year, this estimate is so large that it could not be calculated with our data (fig. 13b). Obviously, this large number of traps would be quite costly and time-consuming to install and maintain. The tree life table and mortality rate approaches used by other studies (Harmon and Hua 1991, for example) appear to be more effective, especially in ecosystems with large, long-lived trees.

The spatial distribution of the fuel litterfall across the traps within a plot was uniform for only the foliage material (fig. 14). Results from the skewness analysis

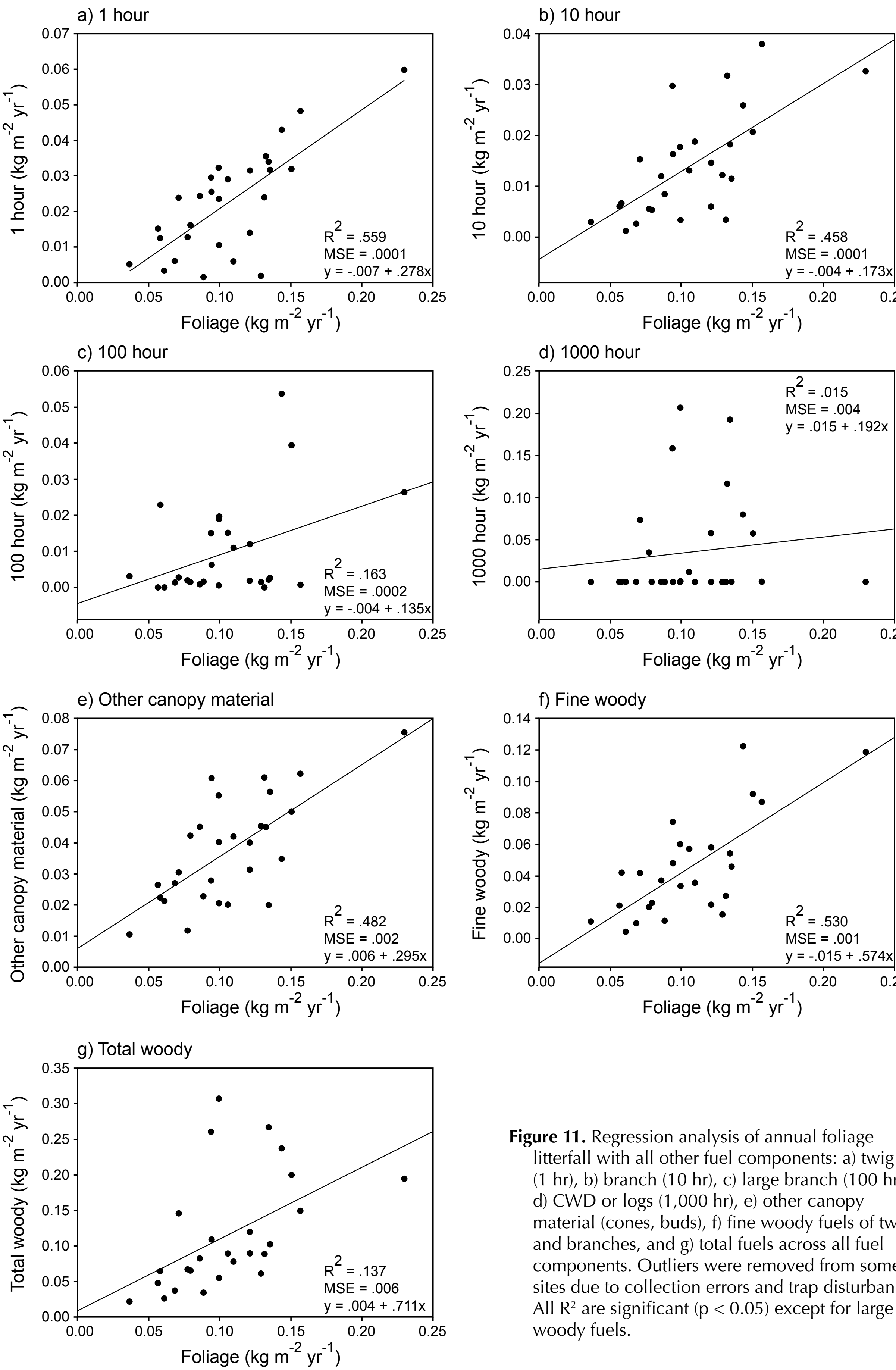


Figure 11. Regression analysis of annual foliage litterfall with all other fuel components: a) twig (1 hr), b) branch (10 hr), c) large branch (100 hr), d) CWD or logs (1,000 hr), e) other canopy material (cones, buds), f) fine woody fuels of twigs and branches, and g) total fuels across all fuel components. Outliers were removed from some sites due to collection errors and trap disturbance. All R^2 are significant ($p < 0.05$) except for large woody fuels.

Table 5. Regression equations that can be used to predict litterfall of the fine fuel components from basal area and LAI. Basal area is computed across all trees in the plot and LAI is measured using the LiCor LAI-2000 instrument.

Fuel component	Equation	Standard error of regression	R^2
	Basal Area ($m^2\ ha^{-1}$) for all trees		
Foliage	$\hat{y}$=.011+.0024 BA	.0216	.714
1 hour	$\hat{y}$=-.001+.0008 BA	.0094	.603
10 hour	$\hat{y}$=-.0037+.00046 BA	.0101	.308
100 hour	$\hat{y}$=-.006+.00044 BA	.0161	.137
Other	$\hat{y}$=.0038+.00082 BA	.0122	.494
Total	$\hat{y}$=.0186+.0053 BA	.0947	.402
	Leaf Area Index ($m^2\ m^{-2}$) as measured with LiCor LAI-2000		
Foliage	$\hat{y}$=.0168+.035 LAI	.0324	.355
1 hour	$\hat{y}$=-.020+.0166 LAI	.0097	.534
10 hour	$\hat{y}$=-.0093+.0095 LAI	.010	.292
100 hour	$\hat{y}$=-.021+.0129 LAI	.015	.263
Other	$\hat{y}$=.0121+.0099 LAI	.0157	.158
Total	$\hat{y}$=-.039+.107 LAI	.098	.362

showed that the skewness statistic tended to be close to zero for foliage (evenly distributed) but quite large and positive for the larger woody fuel (100 hr fuel and 1,000 hr fuel >2.0; fig. 13), indicating uneven fuel deposition. This means that these large fuel types are not detected in many traps after our annual visits. Results seem to agree with Hirabuki (1991), who found that heterogeneous litter distribution was related to the distribution of canopy structure. All fuel components had a tendency to have positive values for the skewness, which suggests that there was a tendency for one or two traps in a plot to have high litterfall while the rest of the traps have low litterfall. This again indicates that additional traps might have been needed to collect large fuels because smaller fuels are more evenly distributed across the traps but logs and large branches tended to accumulate in "jackpots" within the plot.

Results of the CUSUM analysis showed that there were few statistically significant differences between years for the fine canopy fuels of foliage, other canopy material, and fine woody material (fig. 15), but there were major annual differences in large branch and log material. Foliage accumulations for the CO1 plot declined slightly over the collection record (fig. 15a), but the highest accumulations of 1 hr fuels occurred for the years 1996 and 2001, which were more than double the accumulations of the two lowest years of 1994 and 2004 (rates for 1993 are low because the traps were installed in the middle of that year; figure 15b). For 10 hr branch fuels, 1996 had nearly triple the litterfall compared with all other years. An analysis of the climate data for these years did not reveal any statistically significant reasons why this occurred, but it is probably due to a late heavy snow or high wind event that caused extensive branch breakage.

There are some limitations and shortcomings in this study that might influence the litterfall results. Several times, it was impossible to empty litter traps on high elevation plots in autumn because of early snowfalls, so there may have been some decomposition losses as the litter sat in the traps under the snow through the winter. Additionally, large snow banks on access roads sometimes delayed spring trap visits for weeks, allowing the litter to sit in traps under warm and moist conditions that were ideal for decomposition. Many conifer tree species shed their foliage during the late fall and early winter after the last trap visit, so many of the fallen needles remained in the snow above the traps contributing to additional decomposition and wind losses. Several traps were vandalized during the summer causing gaps in the collection record for some plots. One ponderosa pine plot (KR2) experienced an autumn prescribed fire that burned all but one of the traps. The sorting of foliage from other canopy material was a difficult and tedious task and was probably inconsistently done by the 12 field technicians involved in the project over the 10+ years of the study.

Decomposition

The decomposition phase of this study did not match the rigor, detail, and scale of the litterfall phase. Decomposition was only measured over a 3-year time span, which was probably not long enough for

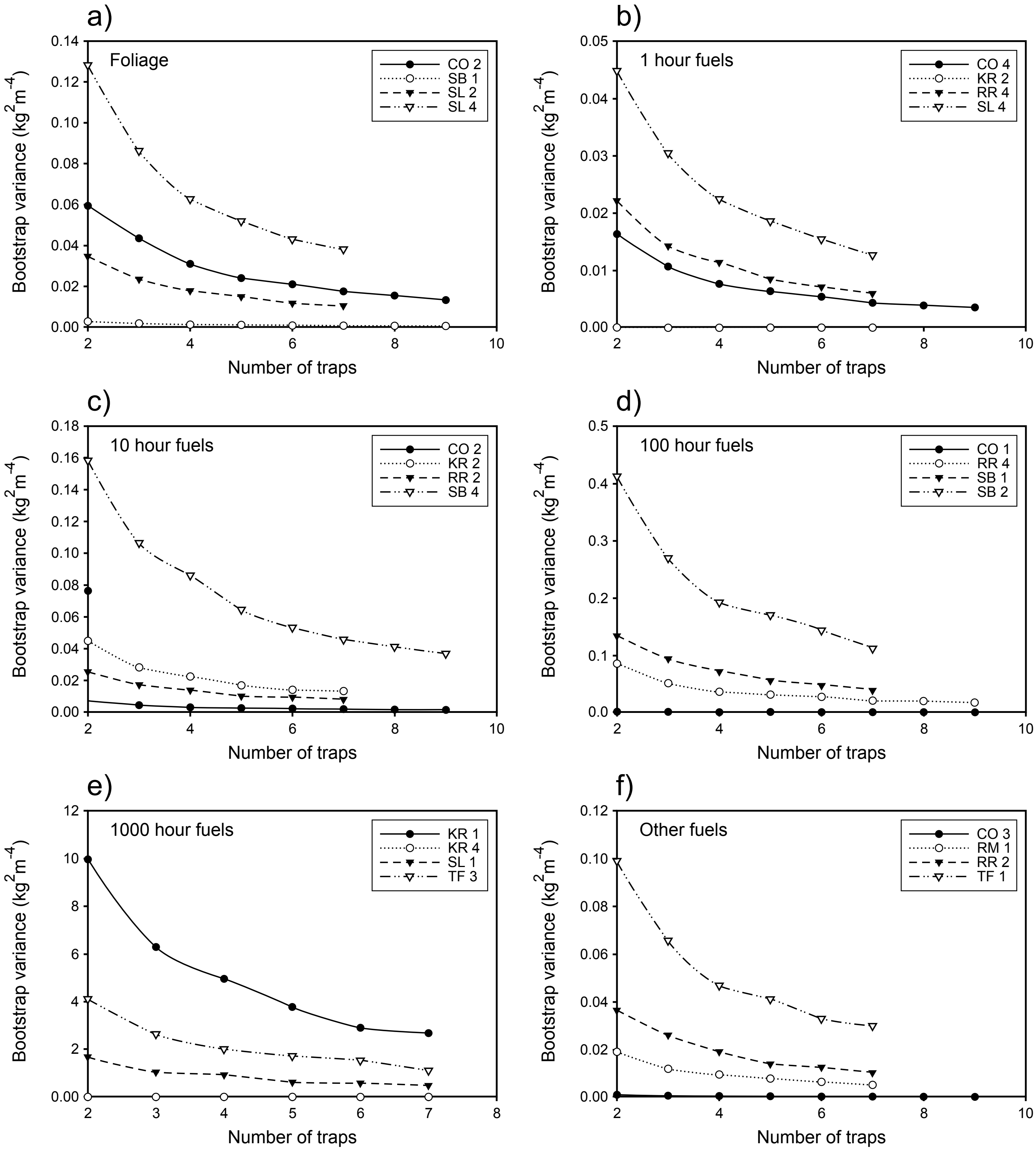


Figure 12. Bootstrap analysis of variance results for the four most disparate plots across each of the six fuel components. The asymptote can be used to determine the optimum number of traps to install at a plot for each fuel component: a) foliage, b) 1 hr fuels (twigs), c) 10 hr fuels (small branches), d) 100 hr fuels (large branches), e) 1,000 hr fuels (logs), and f) other canopy fuels (cones, bud scales).

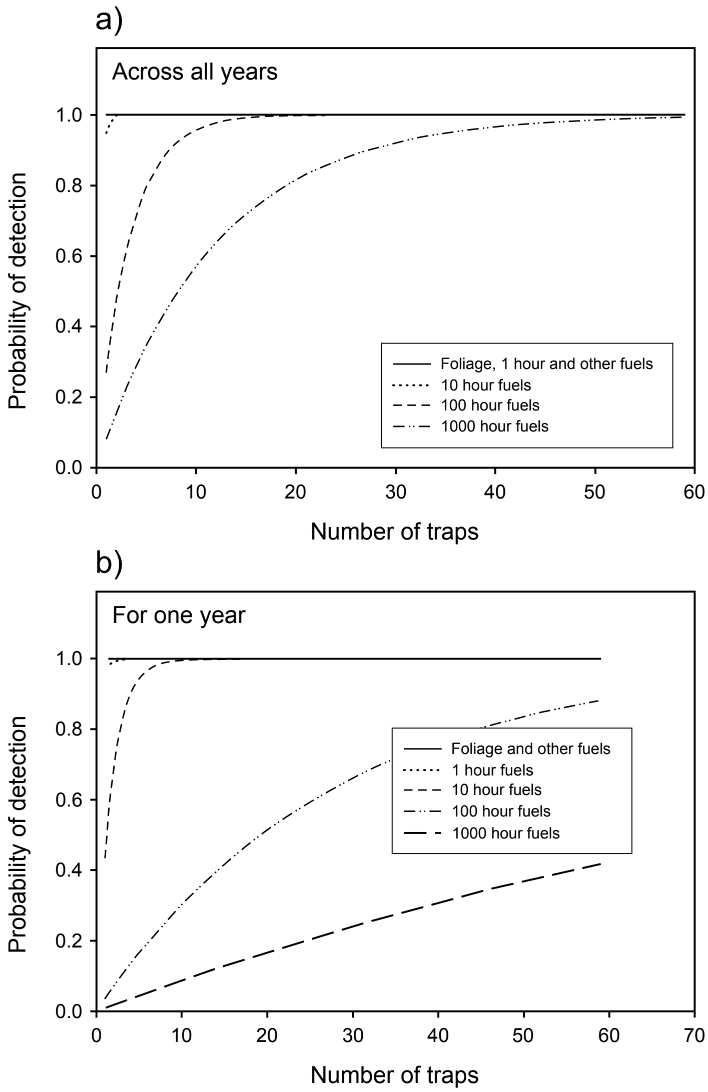


Figure 13. The relationship of the probability of detection of each fuel component with the number of traps as computed from the litterfall data collected in this study on all traps. The results are summarized a) across all years in the study and b) for 1 year.

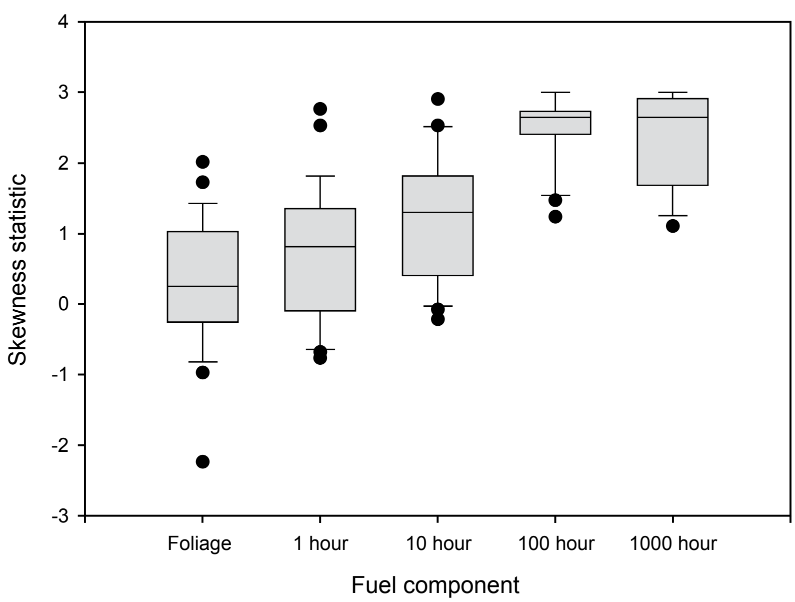


Figure 14. Spatial distribution, described by the skewness statistic, of surface fuel litterfall across the litter traps within a plot as analyzed across all 28 plots. Values of the skewness statistic near zero indicate even distribution across all traps in a plot. Positive values indicate one trap is receiving most of the fallen material

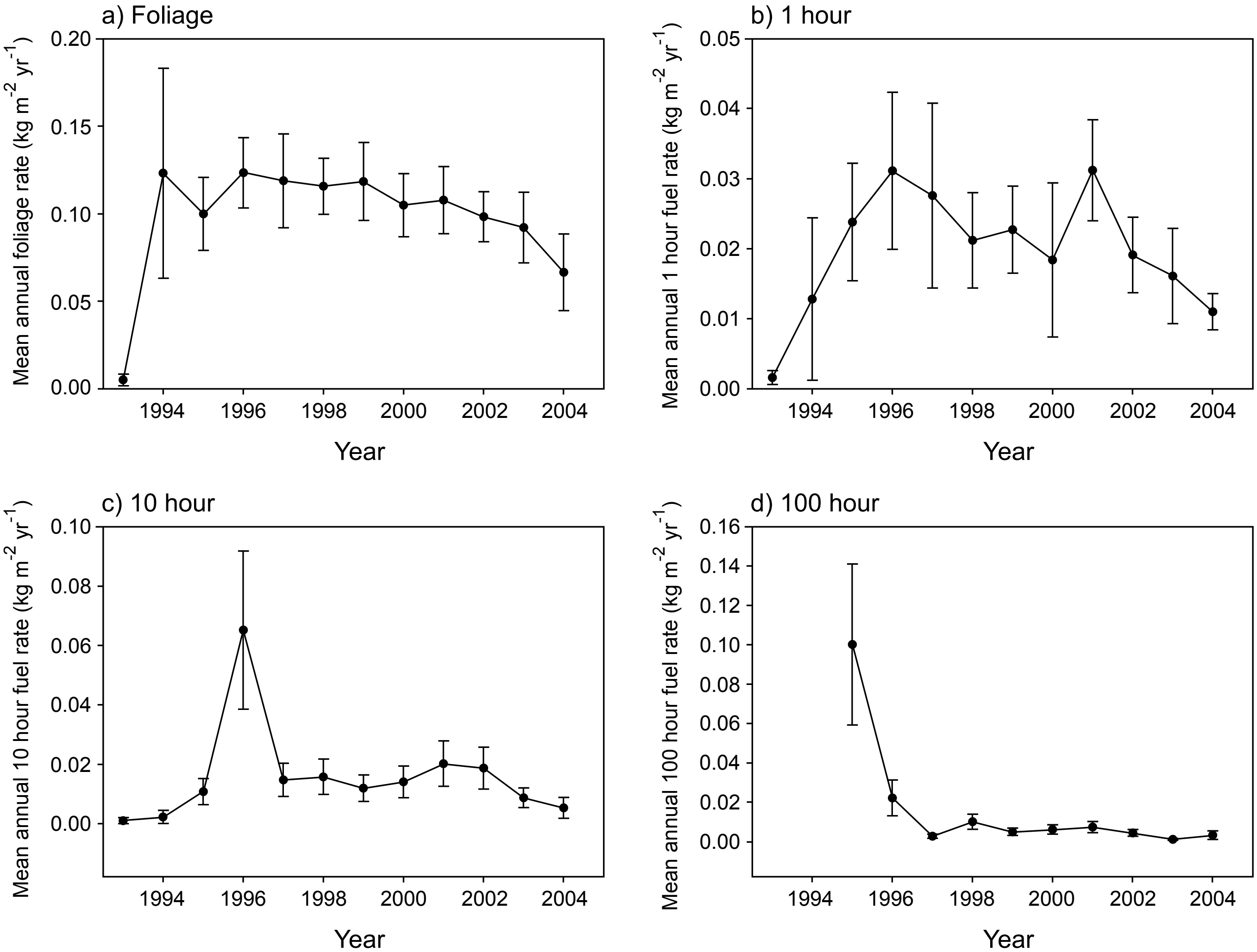


Figure 15. Annual surface fuel litterfall rates across the 10 years of record for the CO1 study site (low elevation Douglas fir): a) foliage, b) twig (1 hr), c) branch (10 hr), and d) large branch (100 hr). There were no differences between years for the foliage and twig fuel components ($p < 0.05$) excluding 1993, the first year of data collection. There was always 1 year for the large woody fuels that was significantly different ($p < 0.05$) than the others for nearly all plots.

the larger woody fuels. Decomposition was also only measured on five sites and it did not include logs and other canopy material. There were only three sets of litterbags installed at each site, so a comprehensive analysis of variance such as that done for the litterfall data was not possible with such a small sample. Moreover, it was difficult to remove the material that had fallen onto the litterbags over the 3 years while they were in the field. Freshly fallen needles and small materials sometimes worked their way into the bags through the coarse mesh, and we often found decomposing material below and on the top of the bags, and also brought into the bags by soil macrofauna. Some bags were chewed or torn apart by rodents and ungulates, while others were actually carried off site by unknown factors. We tried to separate the incorporated material from the original samples in the litterbags, but this was often difficult because of the small size of the particles. These limitations only affected around 16 percent of the samples.

Despite the limitations of the decomposition measurements, the measured rates seemed to compare quite well with those measured in other studies (compare fig. 1b with table 4). The range of *k* values for foliage decomposition measured in this study for the Douglas-fir sites (0.085 to 0.205 yr^{-1}) are similar to those in figure 1b (0.005 to 0.56 yr^{-1}). Similar results are found for the lodgepole (foliage: 0.104 to 0.247 yr^{-1} in this study and 0.09 to 0.14 yr^{-1} in table 1) and subalpine fir sites (0.110 to 0.169 in this study and 0.09 to 0.17 in fig. 1b).

This indicates that the values calculated from this study should be useful for future modeling efforts.

Management Implications

The primary objective of this study was to quantify fuel dynamics for the purpose of designing, parameterizing, and validating ecosystem models, and the data presented here appears to provide an extensive parameter set for constructing and testing models of fuel processes and dynamics. These data can also provide managers with valuable estimates of fuel deposition and decomposition rates that can be used to determine the longevity of fuel treatments and prioritize fuel treatment areas. This can be accomplished by using the fire behavior models to calculate how long it would take to accumulate enough surface fuels to ignite or support a crown fire or kill overstory trees using the fire behavior models. While the large woody fuel litterfall and decomposition estimates measured in this study may contain high error rates, the fine fuel dynamics, which is critically lacking in the literature, has been sufficiently estimated for use in models and management.

The major conclusions from this long-term study of fuel dynamics are:

- Litterfall rates are highest on productive plots with shade-tolerant conifers and plots with high LAI. The most productive habitat type series have the highest litterfall rates across all fuel components.
- While foliage litterfall rates vary widely across forest cover types and habitat type series, rates of woody fuel components are about the same across all plots and types, especially the largest woody fuels (large branches, and logs).
- Decomposition appears to be positively correlated to a moisture gradient where the highest decomposition rates occur on the most productive plots.
- The temporal and spatial distribution of fine fuels (foliage and twigs) is more homogeneous than large woody fuels (branches and logs) because of the consistent timing and distribution of the litterfall for these fine fuel components.
- Many litter traps are needed across a large area to adequately sample log (1,000 hr) deposition rates (>200) and this precludes efficient sampling for research and management. A better approach would be to quantify tree life tables to estimate eventual mortality and snag fall

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