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Fuel deposition rates of montane and subalpine conifers in the central Sierra Nevada, California, USA

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ABSTRACT

Fire managers and researchers need information on fuel deposition rates to estimate future changes in fuel bed characteristics, determine when forests transition to another fire behavior fuel model, estimate future changes in fuel bed characteristics, and parameterize and validate ecosystem process models. This information is lacking for many ecosystems including the Sierra Nevada in California, USA. We investigated fuel deposition rates and stand characteristics of seven montane and four subalpine conifers in the Sierra Nevada. We collected foliage, miscellaneous bark and crown fragments, cones, and woody fuel classes from four replicate plots each in four stem diameter size classes for each species, for a total of 176 sampling sites. We used these data to develop predictive equations for each fuel class and diameter size class of each species based on stem and crown characteristics. There were consistent species and diameter class differences in the annual amount of foliage and fragments deposited. Foliage deposition rates ranged from just over 50 g m^{-2} year^{-1} in small diameter mountain hemlock stands to ~300 g m^{-2} year^{-1} for the three largest diameter classes of giant sequoia. The deposition rate for most woody fuel classes increased from the smallest diameter class stands to the largest diameter class stands. Woody fuel deposition rates varied among species as well. The rates for the smallest woody fuels ranged from 0.8 g m^{-2} year^{-1} for small diameter stands of Jeffrey pine to 126.9 g m^{-2} year^{-1} for very large diameter stands of mountain hemlock. Crown height and live crown ratio were the best predictors of fuel deposition rates for most fuel classes and species. Both characteristics reflect the amount of crown biomass including foliage and woody fuels. Relationships established in this study allow predictions of fuel loads to be made on a stand basis for each of these species under current and possible future conditions. These predictions can be used to estimate fuel treatment longevity, assist in determining fuel model transitions, and predict future changes in fuel bed characteristics.

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1. Introduction

Fire history studies have shown that decades of fire suppression activities have, for all practical purposes, eliminated periodic fires from the forests of the Sierra Nevada in California, USA (Kilgore and Taylor, 1979; Swetnam, 1993; Lutz et al., 2009a; Scholl and Taylor, 2010). The exclusion of fire has led to a shift to fire intolerant and shade tolerant species in the understory and abnormally high fuel accumulations (Stephens and Finney, 2002). Excessive accumulation occurs when fuel deposition consistently exceeds losses from decomposition and fire consumption. As a result, when fires do occur, they are more intense and have more severe effects (Stephens, 1998; van Wagtendonk, 1985). Further complicating matters, projected changes in global climate could lead to even greater changes in fire regimes (Miller et al., 2008; Westerling et al., 2006). Although much of the change is directly related to predicted increases in temperature, changes in ignition sources and fuel conditions will also affect fire regimes (Lutz et al., 2009b).

Land managers in the Sierra Nevada use a variety of practices to treat fuels. Prescribed fire is the primary tool in areas where fuel accumulations and dense understories of shade tolerant species preclude allowing lightning fires to burn. In addition, manual or mechanical removal of fuel in areas adjacent to roads and developments is sometimes necessary to protect human values.

Recent concern about climate change has called into question the practice of prescribed burning because of the CO_2 released during consumption. Rather than losing carbon through emissions, Smithwick et al. (2002) suggested that carbon sequestration might be a means of mitigating the effects of climate change. Measured fuel deposition and decomposition rates can be used to approximate the contribution of fuel to the atmospheric carbon budget if they are burned (Thornton et al., 2002). Mitchell et al. (2009) used a simulation model and found that fuel treatments in the Pacific Northwest consistently reduced fire severity, but did little to reduce

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atmospheric CO_2. However, based on simulations of Sierra Nevada forests, Hurteau and North (2009) concluded carbon stocks were best protected by fuel treatments that produced low density stands of large pines. These simulations depend on accurate estimates of fuel deposition and decomposition.

Olson (1981) proposed four hypotheses relating to the carbon balance and fire regimes. In ecosystems where there is little or no fire, live and dead biomass inputs are balanced by rates of loss by decomposition and export, and carbon storage is maximized. Fire regimes with infrequent high intensity fires accumulate fuels until the eventual fire occurs, resulting in large fluctuations of stored carbon. Frequent, low intensity fires balance fuel accumulation with consumption, thereby maintaining carbon stores, albeit at less than the maximum level. Finally, in ecosystems where fires are frequent and intense, such as some grasslands, carbon stores are held at a minimum. In Sierra Nevada forests, a regime of no fires is not sustainable, and fires maintain a balance between accumulation and consumption (van Wagtendonk, 1985). Because fire frequency varies across the forests of the Sierra Nevada (van Wagtendonk et al., 2002), the rate of fuel deposition should be expected to vary inversely.

In the United States, the Rothermel (1972) fire spread equation is used as a basis for predicting the behavior of wildfires and prescribed fires (Andrews, 1986; Finney, 2005). Standard fuel models contain the information about fuels necessary to make fire behavior predictions (Albini, 1976; Anderson, 1982; Scott and Burgan, 2005). Fuel models contain values for load and surface-area-to-volume-ratio by fuel class and category, fuel bed depth, and moisture of extinction. Fuel categories are live and dead, and fuel classes correspond to fuel moisture time lag categories. Time lag is the amount of time necessary for a fuel class to reach 63% of its equilibrium moisture content (Fosberg, 1970). The 1 h time lag class includes foliage, fragments, and woody twigs that are less than 0.64 cm in diameter. Foliage includes needles and leaves, and fragments include bark flakes, cone scales, and other miscellaneous particles. Woody branches that range from 0.64 cm to 2.54 cm in diameter are considered 10 h fuels, and large woody branches from 2.54 cm to 7.62 cm in diameter are 100 h fuels. Woody logs between 7.62 cm and 20.32 cm diameter are considered 1000 h fuels.

In addition to their importance to fire behavior models, foliage and fragments are important components of ecosystem dynamics models and need to be differentiated from woody twigs (Keane et al., 1996). Because large woody logs do not contribute to the advancing fire front, they are not part of the fire behavior prediction systems, but are, rather, a component of fire danger rating system (Deeming et al., 1977). Although cones are not classified as fuels in the fire behavior and danger rating systems, they are important indicators of fire adaptations and are used in ecosystem models (Fonda and Varner, 2004).

The appropriate fuel model for a particular situation can change as fuels accumulate. Information on fuel deposition and decomposition rates can be used for determining when stands transition from one fuel model to another, insuring that fire behavior predictions are as accurate as possible (Davis et al., 2009). In situations when no standard fuel model is appropriate, fuel deposition rates combined with other fuel characteristics can be used to develop custom fuel models (van Wagtendonk et al., 1998a; Burgan and Rothermel, 1984). In areas that have been prescribed burned or mechanically treated, the length of time that treatments remain effective could be estimated using fuel deposition and decomposition rates (Vaillant et al., 2009; Agee and Lolley, 2006; Fernandes and Botelho, 2003).

Early work on fuel deposition rates for Sierra Nevada species was done by Biswell et al. (1966) who clustered collection trays at the bases of individual trees of giant sequoia (*Sequoiadendron giganteum*), ponderosa pine, sugar pine (*Pinus lambertiana*), white fir (*Abies concolor*), and incense-cedar (*Calocedrus decurrens*). Unfortunately, they did not record any information about tree characteristics, and collected fuels for only two years. Agee et al. (1977) randomly placed trays in pure stands of ponderosa pine, sugar pine, white fir, and giant sequoia. They collected for only two years, combined all woody fuels into two classes, and did not measure tree characteristics. In addition, their stands had been previously thinned and burned. The data used by van Wagtendonk (1985) to simulate montane fire cycles came from a single year, while van Wagtendonk and Sydoriak (1987) collected up to six years of fuel deposition data in prescribed burned areas that removed many twigs and branches from understory trees.

In ponderosa pine stands of Sequoia and Kings Canyon National Parks, Keifer et al. (2006) found that fuels accumulated to 84–88% of pre-fire levels 10 years after burning. In similar stands in Yosemite, they found that fuels accumulated to 150–180% of pre-fire values after 31 years. In these ecosystems, fire return intervals typically are from 10 years to 12 years, indicating that the Yosemite stands had departed from the historic fire return interval (Kilgore and Taylor, 1979).

Stohlgren (1988) pointed out the deficiencies of previous studies and conducted a four-year study in two mixed stands; one of giant sequoia, white fir, and red fir and the other of white fir, sugar pine, and incense-cedar. He found that deposition rates did not correlate well with stand basal area, stand density, and tree volume and speculated that deposition might better be related to individual tree basal area and the ratio between tree height and crown height. The high variability in deposition rates that Stohlgren (1988) observed was partially attributed to a severe winter, which caused green foliage and live branches to fall, indicating that a collection period longer than four years might be necessary to develop reliable estimates. Finally, Stohlgren (1988) combined the woody fuels into classes that were not compatible with the classes in Rothermel's (1972) fire spread model.

Deposition rates of ponderosa pine foliage have been studied in northern California by Biswell and Schultz (1956) and in Arizona by Gottfried and Ffolliott (1983), and deposition rates of ponderosa pine logs were measured in Arizona by Avery et al. (1976). Pearson et al. (1987) recorded deposition rates for lodgepole pine (*Pinus contorta*) logs in Wyoming, and Laiho and Prescott (1999) collected deposition rates for lodgepole pine logs and foliage in Alberta, Canada.

Keane (2008a, 2008b) studied deposition and decomposition rates for major forest types of the northern Rocky Mountains, USA. His sites included ponderosa pine, lodgepole pine, and whitebark pine (*Pinus albicaulis*) stands. He separated surface fuels into six classes including foliage, the four woody fuels that corresponded with the woody fuel classes in the Rothermel (1972) spread model, and other canopy material. He also related the annual rates to environmental and vegetation variables and found that deposition was best estimated by leaf area index, stand basal area, and tree height.

The first objective of our study was to determine if fuel deposition rates varied among four tree diameter size classes and 11 principal species that occur in montane and subalpine conifer ecosystems in the central Sierra Nevada. Secondly, we wanted to relate annual fuel increments to stem and crown characteristics.

2. Methods

2.1. Study area and site selection

Yosemite National Park is located in the central Sierra Nevada, California, USA. The park encompasses 3027 km^2 and ranges in elevation from 657 m in the foothills on the western boundary to 3997 m on the crest of the range. The vegetation of the Sierra Nevada occurs in broad zones in response to climate and multi-

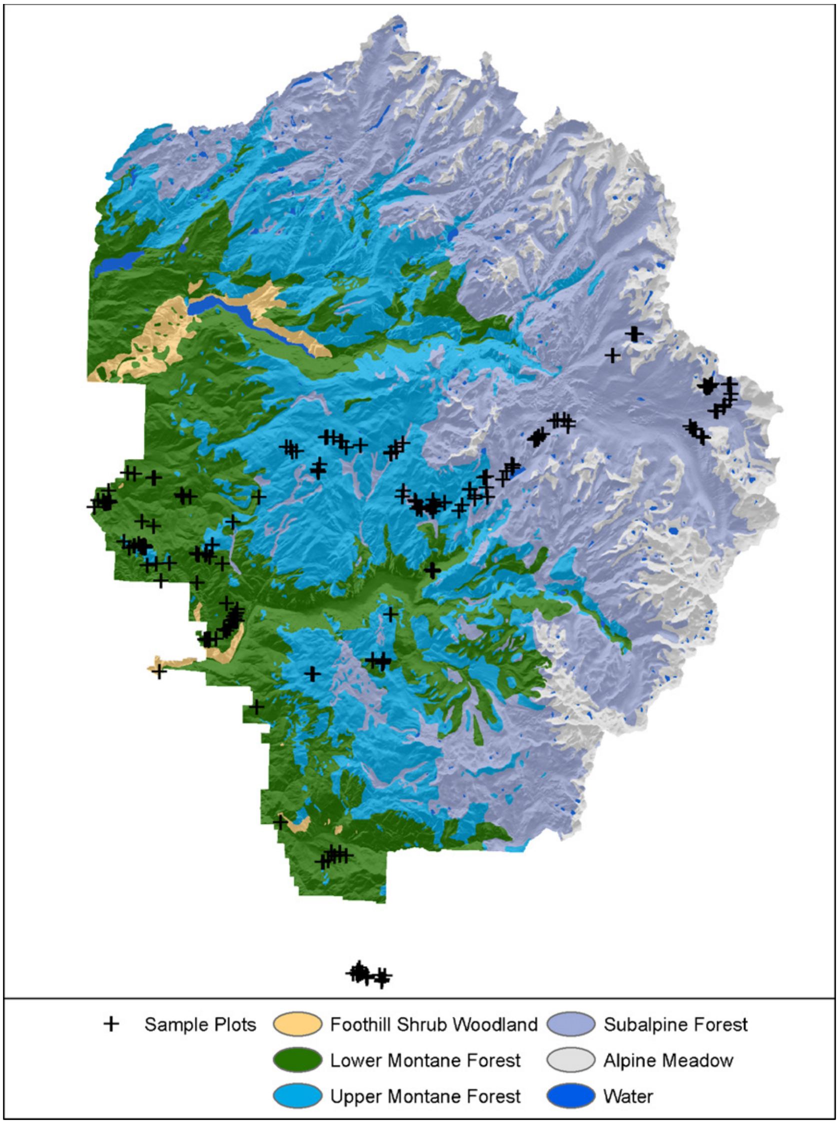

Fig. 1. Vegetation zones of Yosemite National Park, California, USA. The elevation range in the park is 657 to 3997 m and increases from left to right in the figure. All plot locations are in Yosemite National Park except for four plots of giant sequoias in the Nelder grove of the Sierra National Forest.

ple physical and biotic factors (Fig. 1). Chaparral and woodlands occur in the foothills, montane and subalpine forests cover the middle elevations, and alpine communities are found above tree line. Using a geographic information system, van Wagtendonk et al. (2002) found that the forests in Yosemite contain mixtures of 11 dominant or co-dominant conifer species roughly corresponding to elevation. Lower montane forests include ponderosa pine stands, which become mixed with incense-cedar, sugar pine, and white fir with increases in elevation. Giant sequoias occur in isolated groves within the lower montane forest. This mixture gives way to increasing amounts of red fir, western white pine (*Pinus monticola*) and Jeffrey pine (*Pinus jeffreyi*) in the upper montane zone. The subalpine forest is dominated by lodgepole pine, which, as treeline is approached, is replaced by mountain hemlock (*Tsuga mertensiana*) and whitebark pine. Three quarters of the park is forested with conifers, and the 11 species comprise 97% of those forests (van Wagtendonk et al., 2002) (Table 1).

Between the spring of 1987 and the summer of 1988, we established four replicate plots in each of four stem diameter size classes in representative stands of ponderosa pine, sugar pine, Jeffrey pine, giant sequoia, white fir, red fir, and incense-cedar (Table 1). In 1996, we established plots for an equal number of replicates and diameter classes of western white pine, lodgepole pine, mountain hemlock, and whitebark pine (Table 1). We established plots only in stands where at least 90% of the trees at a site were of the desired species and diameter class. For each species, our sampled stands represented four diameter classes from small to very large. Small stands had tree stems approximately 2.5 cm to 15.0 cm diameter at breast height (dbh); medium stands had stems 15.1 cm to 60.0 cm dbh; large stands had stems 60.1 cm to 120.0 cm dbh.; and very large stands had stems over 120.0 cm dbh. Because of their larger size, the diameter classes for giant sequoia were 2.5 cm to 54.0 cm, 54.1 cm to 108.0 cm, 108.1 cm to 300.0 cm, and greater than 300.0 cm. Similarly, because of their smaller size, the diameter classes for whitebark pine were 2.5 cm to 10.0 cm, 10.1 cm to 25.0 cm, 25.1 cm to 50.0 cm, and greater than 50.0 cm. The basal area of some of the very large stands dropped because only two or three trees were in those stands.

All of our plots were in Yosemite National Park, California, except giant sequoias (Fig. 1). Because the three sequoia groves in the park had been recently burned, we sampled giant sequoias in the Nelder Grove just south of the park in the Sierra National Forest. We located the plots in representative stands away from roads and signs of human disturbance such as trails or campsites.

Table 1
Average plot characteristics by species and diameter class and proportion of park by species. Within the pine and non-pine groups, species are listed by increasing elevation.

Species	Proportion of park[a] (%)	Diameter size class[b]	Plots (no.)	Stand basal area (m^2 ha^{-1})	Elevation (m)	Aspect (deg)
Ponderosa pine	8.34	Small	4	21.67	1627	160
		Medium	4	20.00	1531	171
		Large	4	47.50	1444	209
		Very large	4	50.00	1454	149
Sugar pine	2.05	Small	4	37.50	1983	215
		Medium	4	43.75	1889	145
		Large	4	67.50	1337	261
		Very large	4	58.75	1880	118
Jeffrey pine	12.5	Small	4	15.00	2225	117
		Medium	4	31.25	2234	177
		Large	4	13.75	2415	215
		Very large	4	27.50	2139	213
W. White pine	2.85	Small	4	16.25	2673	137
		Medium	4	25.00	2694	116
		Large	4	22.50	2665	216
		Very large	4	15.00	2653	155
Lodgepole pine	21.91	Small	4	40.00	2718	145
		Medium	4	63.75	2547	126
		Large	4	32.50	2515	154
		Very large	4	32.50	2577	221
Whitebark pine	4.51	Small	4	25.00	3003	242
		Medium	4	43.75	3044	260
		Large	4	52.50	3107	276
		Very large	4	25.00	3131	310
Incense-cedar	0.07	Small	4	31.67	1373	178
		Medium	4	50.00	1473	296
		Large	4	45.00	1548	167
		Very large	4	51.25	1473	119
White fir	5.00	Small	4	22.50	2213	165
		Medium	4	48.75	2021	136
		Large	4	43.75	2083	140
		Very large	4	85.00	2086	156
Giant Sequoia	0.03	Small	4	11.25	1784	218
		Medium	4	28.00	1661	117
		Large	4	105.00	1799	202
		Very large	4	76.67	1723	211
Red fir	11.05	Small	4	60.00	2498	169
		Medium	4	72.00	2421	203
		Large	4	70.00	2453	204
		Very large	4	70.00	2430	106
Mt. hemlock	4.70	Small	4	46.25	2718	47
		Medium	4	57.50	2757	194
		Large	4	47.50	2719	89
		Very large	4	13.75	2976	181

[a] Proportion of park area as determined by van Wagtendonk et al. (2002).
[b] Diameter size classes are: small, 2.5–15.0 cm; medium, 15.1–60.0 cm; large, 60.1–120.0 cm; and very large, 120.1 cm and larger. For giant sequoia, these classes are: small 2.5 cm to 54.0 cm; medium, 54.1–108.0 cm; large, 108.1–300.0 cm; and very large, 300.1 cm and larger. For whitebark pine, the classes are: small, 2.5–10.0 cm; medium, 10.1–25.0 cm; large, 25.1–50.0 cm; and very large, 50.1 cm and larger.

To insure that trees did not deposit fuels on more than one plot, we placed plots at least 30 m apart. This distance also precluded us from sampling the same tree in adjacent plots. If plots became altered by wildland fires or were disturbed by bears, we replaced them. We located replacement plots in stands as similar as possible to the original plots.

We placed a metal stake approximately equidistant between the trees of interest. At each site, we recorded the dominant tree species, the plant community in and near the plot, and topography. We used a prism with a metric basal area factor of five to characterize the basal area of the stand and to determine which trees contributed materials to a site. Trees meeting the diameter and distance criteria of the prism were most likely to drop foliage and branches on the plot. We measured dbh, tree height, distance from plot center, and height to live crown base of all selected trees using tapes and clinometers. We considered the height to live crown base to be the point of attachment of the lowest live branch.

We collected large woody fuels (large branches and logs) and cones on a 5 m × 5 m plot centered on the stake, and collected foliage, fragments, and small woody fuels (twigs and branches) on a 1 m × 1 m subplot consisting of a sheet metal tray placed within the 5 m × 5 m plot just northeast of the stake. Upon establishment of the plot, we completely cleared the 5 m × 5 m plot of all cones and woody debris greater than 2.5 cm in diameter. We collected up to 25 whole cones per species and dried and weighed them to derive an average dry weight. We applied this average to annual cone counts to determine the annual amount of cone biomass deposition.

2.2. Sample collection and processing

We collected fuel samples from the fall of 1988 through the spring of 1996 for montane conifers and from 1996 to 1999 for subalpine conifers. To minimize the time the fuels were exposed to possible disturbance, we collected twice per year. We began the first collection in April and progressed as areas became snow-free; the second collection started in September and lasted through October.

We calculated stand basal area by multiplying the number of selected trees as determined by the prism by the basal area factor of 5. We determined stem and crown characteristics from measurements made of the selected trees during the last collection year. We calculated stem basal area of each tree from its stem diameter and the average stem basal area as the average of all the selected trees. Crown height was the tree height minus the height to the live crown base. Live crown ratio was the crown height divided by the tree height.

We sorted all large branches and logs from the 5 m × 5 m plots by species and fuel class in the field before transporting them to the laboratory. We included only the portions of large branches and logs that fell within the plot perimeters. We sawed off portions extending outside plot perimeters. If the large branch and log material was too great to be transported to the lab, we obtained the gross weight of all the material in the field, weighed a subsample in each fuel class, and transported the subsamples to the laboratory to obtain dry weights. From the 1 m × 1 m subplot, we collected foliage, fragments, and small woody fuels in the twig and branch fuel classes for analysis in the laboratory. We used pruning shears to trim all fine material (foliage, fragments, twigs, and branches) to the edge of the collection tray. We counted cones with persistent woody scales (pines, giant sequoia, and mountain hemlock) by species and removed them from the plot. For species with deciduous cone scales (firs) and species with very small cones (incense-cedar), we included cone parts with fragments.

We sorted all woody fuels by species and fuel class and sorted foliage and cones by species before drying and weighing. We oven dried cones and large woody fuels at 50 °C until their weight did not change more than 0.1 g (or 10% for samples larger than 100 g) in a 24 h period. If we collected subsamples, we weighed them at the time of collection and after drying. By applying the ratio of dry weight to wet weight of the subsampled fuels, we calculated dry weight of large woody fuels weighed in the field. We combined all miscellaneous fragments, including fir and incense-cedar cone scales together for all species on a plot and then dried and weighed them. We then applied the average dry weight per cone of each species to the number of cones removed from each plot.

2.3. Statistical analysis

We used two-way analysis of variance to analyze annual mean weight per plot of each fuel class, with species and diameter size class as the independent factors. We then summarized the fuel results across diameter classes. Because observations between years within sites were not independent, we used the average across all years to get one value per plot. We applied $\alpha = 0.05$ to all of our significance tests.

To relate annual deposition rates of fuel classes for each species to stand characteristics, we used linear regression. We ran two sets of regressions, one through the origin and one with an intercept. We used five simple regressions (i.e. regressions on one covariate) based on each of three stem characteristics or two crown characteristics, and also six regressions based on combinations of two covariates (one stem and one crown characteristic). From the resulting 22 regression equations for each fuel class for each species, we chose the equation with the lowest corrected Akaike Information Criterion (AIC_c) score as the best model (Burnham and Anderson, 2002) We used corrected AIC scores because our sample size was small (Hurvich and Tsai, 1989). We also calculated the r-square, delta AIC_c, and Akaike weight (w_i) for each equation.

3. Results

We collected fuels data from 221 different plots, the original 176 plots plus 41 that had to be replaced once and four that had to be replaced twice because of bears or fires. We recorded stand characteristics in 173 of the final plots. Three plots burned just prior to obtaining stand characteristics; therefore, we excluded them from the stand data set.

3.1. Annual fuel deposition rate

Species differences in fuel deposition rates were significant for all fuel classes (Fig. 2, Table 2). Woody fuel class was significant except for the log class, where there was a great deal of variation among tree diameter size classes. Interactions among species and diameter size class were significant for all fuel classes except logs and foliage.

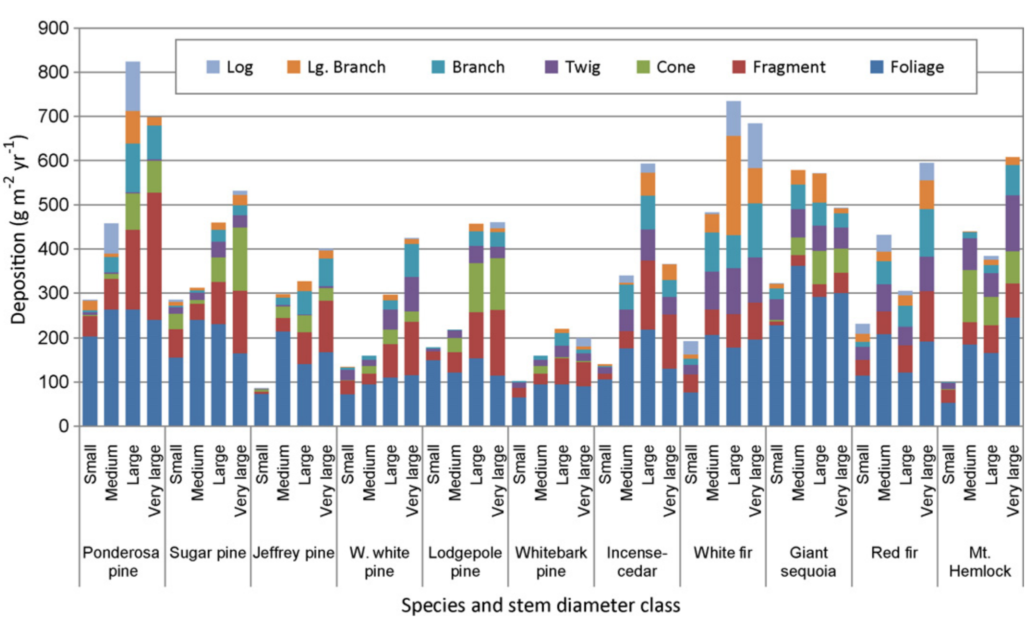

Fig. 2. Fuel deposition rates among species and stem diameter size classes for all fuel classes. Within the pine and non-pine groups, species are ordered by increasing elevation.

Table 2
Statistical values (*F*, *P*) for fuel components of 11 central Sierra Nevada conifer species as a function of species and stand diameter class.

Fuel component	Species		Diameter size class		Interaction	
	$F_{(10, 176)}$	P	$F_{(10, 176)}$	P	$F_{(10, 176)}$	P
Foliage	4.432	≤0.001	4.332	0.006	0.402	0.998
Fragment	8.374	≤0.001	42.813	≤0.001	2.215	0.001
Cone[a]	5.197	≤0.001	13.676	≤0.001	2.159	0.006
Twig	10.977	≤0.001	9.742	≤0.001	1.642	0.030
Branch	4.788	≤0.001	16.932	≤0.001	1.572	0.044
Large branch	10.048	≤0.001	14.487	≤0.001	3.575	≤0.001
Log	2.980	0.002	0.993	0.398	0.985	0.497

[a] *F* values for cones had 7 and 128 df for species, 3 and 128 df for stand diameter class, and 21 and 128 df for interactions.

For the small diameter size class stands, annual foliage increments ranged from a low of 53.3 g m^{-2} year^{-1} for mountain hemlock to a high of 227.7 g m^{-2} year^{-1} for giant sequoia (Table 3). Jeffrey pine had the least amount of fragment deposition, while sugar pine had the greatest. The average deposition of sugar pine cones was 33.6 g m^{-2} year^{-1}, while no cones were produced by small whitebark pines. Although Jeffrey pine had low annual increments in all woody fuel classes, lodgepole pine, whitebark pine, and mountain hemlock had no fuels accumulate in the large branch and log classes, and incense-cedar had none in the log fuel class (Table 3). Ponderosa pine woody fuels were also scant except in the large branch class, where it recorded the highest amount of any species. Giant sequoia, red fir, and white fir were the greatest producers of woody fuels in the small size diameter class stands with two to four times as much annual deposition as the other species. Red fir was consistently high in each of the woody fuel classes; the total averaged 80.0 g m^{-2} year^{-1}. Ponderosa pine had the greatest amount in the large branch fuel class, as did giant sequoia in the two smallest fuel classes.

Foliage, fragment, and cone fuel increments in medium diameter size class stands were greater than those in small diameter size class stands, although lodgepole pine foliage, western white pine fragments, and sugar pine fragments and cones were less (Table 4). Foliage deposition ranged from a low of 94.7 g m^{-2} year^{-1} for western white pine to 362.4 g m^{-2} year^{-1} for giant sequoia. Giant sequoia had the least fragments, while ponderosa pine had the most. Sugar pine cones averaged only 9.6 g m^{-2} year^{-1}, and mountain hemlock averaged 117.9 g m^{-2} year^{-1}. For medium diameter size class stands, the annual increment of woody fuels in the twig fuel class varied from 3.0 g m^{-2} year^{-1} for ponderosa pine to 86.1 g m^{-2} year^{-1} for white fir. White fir was also the biggest contributor to the branch and large branch fuel classes, recording 87.9 g m^{-2} year^{-1} and 42.4 g m^{-2} year^{-1}, respectively. Ponderosa pine had the largest amount of woody fuels in the log fuel class, while seven of the 11 species deposited no fuels in that class. Lodgepole pine had the least total woody fuel, and white fir had the most.

Although the amount of fragments for all species in large diameter size class stands was greater than in medium size class stands, foliage contributed less biomass in each case except for lodgepole pine, western white pine, and incense-cedar (Table 5). Cone drop was three times as great for large diameter size class stands with most of the increase coming from lodgepole pine and ponderosa pine with an average of 112.0 g m^{-2} year^{-1} and 82.5 g m^{-2} year^{-1}, respectively. For large diameter size class stands, the total annual average woody fuel (1–1000 h) increment was over four times as much as it was for small diameter size class stands and nearly twice as much as medium diameter size class stands. The largest increase was in the branch fuel class, where the average for all species was 49.3 g m^{-2} year^{-1}. Jeffrey pine and ponderosa pine had negligible woody fuels in the twig fuel class, while Jeffrey pine, sugar pine, lodgepole pine, western white pine, whitebark pine and giant sequoia had negligible or no fuel in the log fuel class.

The average annual foliage increment decreased slightly for five species between large diameter size class and very large diameter size class stands, and fragments increased by an average of 36% and cones varied (Table 6). Whitebark pine had the lowest foliage increment with 90.5 g m^{-2} year^{-1}, while giant sequoia had the most with 301.0 g m^{-2} year^{-1}. Sugar pine cone deposition was nearly double that of the average of all large diameter size class stands at 143.2 g m^{-2} year^{-1}. Total average annual increments of woody

Table 3
Mean and standard error of the mean (SE) of fuel deposition rates in g m^{-2} year^{-1} for small diameter size class (2.5–15.0 cm) stands of 11 conifer species, central Sierra Nevada, California. For giant sequoia, the small diameter size class is from 2.5 cm to 54.0 cm, and for whitebark pine, it is from 2.5 cm to 10.0 cm. Within the pine and non-pine groups, species are listed by increasing elevation.

Species	Litter Fuel						Woody Fuel[b]							
	Foliage (g m^{-2} year^{-1})		Fragment (g m^{-2} year^{-1})		Cone[a] (g m^{-2} year^{-1})		Twig (g m^{-2} year^{-1})		Branch (g m^{-2} year^{-1})		Lg. branch (g m^{-2} year^{-1})		Log (g m^{-2} year^{-1})	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Ponderosa pine	203.7	45.6	45.2	13.1	2.3	1.2	6.3	2.9	4.4	3.0	21.1	8.2	2.4	1.8
Sugar pine	155.9	44.4	64.4	18.2	33.6	29.0	14.8	6.2	3.4	1.9	8.4	6.2	4.1	4.1
Jeffrey pine	72.9	24.9	5.6	1.2	4.4	2.2	0.8	0.1	0.7	0.4	1.4	1.4	0.6	0.6
W. white pine	72.2	29.5	31.6	11.6	0.4	0.3	23.7	8.6	5.4	3.6	0.5	0.5	0.0	0.0
Lodgepole pine	149.4	22.0	20.0	7.8	0.6	0.5	5.8	1.5	3.0	2.8	0.0	0.0	0.0	0.0
Whitebark pine	65.5	20.1	22.1	5.9	0.0	0.0	11.4	1.9	3.1	1.0	0.0	0.0	0.0	0.0
Incense-cedar	106.9	31.2	12.8	1.6	–	–	14.0	2.4	3.3	2.6	3.1	2.6	0.0	0.0
White fir	76.6	17.2	41.1	11.5	–	–	21.2	13.9	14.5	13.5	9.0	7.0	30.0	30.0
Giant sequoia	227.7	42.3	8.8	2.6	3.6	0.9	46.6	5.4	24.7	11.8	10.3	7.5	1.1	1.1
Red fir	114.7	31.4	36.0	7.6	–	–	28.9	11.1	12.1	2.1	17.9	8.2	21.1	19.6
Mt. hemlock	53.3	10.6	29.6	7.8	1.1	0.6	14.4	3.8	1.0	0.4	0.0	0.0	0.0	0.0

[a] Cones of incense-cedar, white fir, and red fir disintegrate into cone scales and are included in miscellaneous fragments.
[b] Woody fuel size classes are: twig, 0.01–0.64 cm; branch, 0.65–2.54 cm; large branch, 2.55–7.62 cm; and log, 7.63 cm and larger.

Table 4
Mean and standard error of the mean (SE) of fuel deposition rates in $g\,m^{-2}\,year^{-1}$ for medium diameter size class (15.1–60.0 cm) stands of 11 conifer species, central Sierra Nevada, California. For giant sequoia, the medium diameter size class is from 54.1 cm to 108.0 cm, and for whitebark pine, it is from 10.1 cm to 25.0 cm. Within the pine and non-pine groups, species are listed by increasing elevation.

Species	Litter Fuel						Woody Fuel[b]							
	Foliage ($g\,m^{-2}\,year^{-1}$)		Fragment ($g\,m^{-2}\,year^{-1}$)		Cone[a] ($g\,m^{-2}\,year^{-1}$)		Twig ($g\,m^{-2}\,year^{-1}$)		Branch ($g\,m^{-2}\,year^{-1}$)		Lg. branch ($g\,m^{-2}\,year^{-1}$)		Log ($g\,m^{-2}\,year^{-1}$)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Ponderosa pine	263.8	29.4	68.6	13.3	12.2	5.3	3.0	1.2	34.5	15.8	7.6	2.3	67.7	39.1
Sugar pine	239.2	48.2	36.9	12.6	9.6	5.7	15.9	6.5	5.1	4.2	5.4	5.0	0.0	0.0
Jeffrey pine	214.4	48.6	29.6	3.0	26.0	6.4	3.8	2.4	16.5	14.4	6.9	4.5	0.0	0.0
W. white pine	94.7	13.0	24.8	4.5	17.4	4.4	13.5	6.3	9.3	6.7	0.0	0.0	0.0	0.0
Lodgepole pine	121.4	9.5	46.2	14.2	31.9	6.8	18.3	5.4	0.7	6.4	0.0	0.0	0.0	0.0
Whitebark pine	114.9	24.1	31.3	3.5	0.3	0.3	20.4	3.8	7.0	3.8	2.0	0.7	0.0	0.0
Incense-cedar	176.9	22.4	39.2	19.1	–	–	47.5	16.9	56.1	25.2	4.5	4.1	14.9	14.9
White fir	206.5	27.7	57.0	8.0	–	–	86.1	14.6	87.9	5.2	42.4	11.1	3.1	2.6
Giant sequoia	362.4	62.4	24.4	6.4	39.4	39.4	64.3	17.2	55.6	29.8	32.3	23.5	0.0	0.0
Red fir	208.8	18.0	49.9	6.3	–	–	62.3	8.3	51.1	19.6	22.6	7.8	36.3	32.1
Mt. hemlock	185.1	41.0	50.2	8.2	117.9	117.9	71.9	15.1	13.9	6.6	0.5	0.5	0.0	0.0

[a] Cones of incense-cedar, white fir, and red fir disintegrate into cone scales and are included in miscellaneous fragments.
[b] Woody fuel size classes are: twig, 0.01–0.64 cm; branch, 0.65–2.54 cm; large branch, 2.55–7.62 cm; and log, 7.63 cm and larger.

Table 5
Mean and standard error of the mean (SE) of fuel deposition rates in $g\,m^{-2}\,yr^{-1}$ for large diameter size class (60.0 cm stands of 11 conifer species, central Sierra Nevada, California. For giant sequoia, the large diameter size class is from 2.5 cm to 54.0 cm, and for whitebark pine, it is from 2.5 cm to 10.0 cm. Within the pine and non-pine groups, species are listed by increasing elevation.

Species	Litter Fuel						Woody Fuel[b]							
	Foliage ($g\,m^{-2}\,year^{-1}$)		Fragment ($g\,m^{-2}\,year^{-1}$)		Cone[a] ($g\,m^{-2}\,year^{-1}$)		Twig ($g\,m^{-2}\,year^{-1}$)		Branch ($g\,m^{-2}\,year^{-1}$)		Lg. branch ($g\,m^{-2}\,year^{-1}$)		Log ($g\,m^{-2}\,year^{-1}$)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Ponderosa pine	262.9	43.8	180.8	43.8	82.5	30.5	2.5	1.4	110.4	36.4	73.7	28.9	111.6	84.2
Sugar pine	230.6	55.8	95.2	28.6	55.7	7.7	35.8	5.3	26.1	6.5	16.6	9.3	0.0	0.0
Jeffrey pine	141.4	30.8	71.7	29.6	37.0	9.0	1.5	0.8	53.4	14.7	22.3	8.6	0.0	0.0
W. white pine	110.5	43.3	75.5	14.6	33.1	7.0	43.9	14.6	21.2	4.1	11.7	7.4	0.0	0.0
Lodgepole pine	154.7	28.8	102.1	16.3	112.0	19.2	38.0	8.9	33.6	11.6	16.6	11.0	0.0	0.0
Whitebark pine	95.0	14.0	59.3	14.9	2.2	0.9	26.1	8.6	28.6	10.9	8.9	7.2	0.0	0.0
Incense-cedar	219.2	28.3	154.8	25.6	–	–	70.6	7.6	76.5	19.7	51.8	11.6	20.2	11.6
White fir	178.3	55.1	74.4	15.3	–	–	104.6	26.4	74.4	37.4	224.1	63.3	78.2	76.0
Giant sequoia	291.4	89.2	28.5	13.3	76.0	31.0	57.4	16.3	52.4	11.9	65.0	26.4	0.1	0.1
Red fir	122.3	26.3	61.5	8.6	–	–	41.6	9.8	46.5	12.4	23.3	10.1	9.3	9.3
Mt. hemlock	166.2	15.5	61.6	17.8	64.3	8.9	53.7	7.6	18.7	5.6	11.6	6.4	7.8	7.8

[a] Cones of incense-cedar, white fir, and red fir disintegrate into cone scales and are included in miscellaneous fragments.
[b] Woody fuel size classes are: twig, 0.01–0.64 cm; branch, 0.65–2.54 cm; large branch, 2.55–7.62 cm; and log, 7.63 cm and larger.

Table 6
Mean and standard error of the mean (SE) of fuel deposition rates in g m^{-2} yr^{-1} for very large diameter size class (120.1 cm and larger) stands of 11 conifer species, central Sierra Nevada, California. For giant sequoia, the very large diameter size class is 300.1 cm and larger, and for whitebark pine, it is 50.1 cm and larger. Within the pine and non-pine groups, species are listed by increasing elevation.

Species	Litter Fuel						Woody Fuel[b]							
	Foliage (g m^{-2} year^{-1})		Fragment (g m^{-2} year^{-1})		Cone[a] (g m^{-2} year^{-1})		Twig (g m^{-2} year^{-1})		Branch (g m^{-2} year^{-1})		Lg. branch (g m^{-2} year^{-1})		Log (g m^{-2} year^{-1})	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Ponderosa pine	239.3	53.0	288.9	59.9	72.1	20.6	3.0	0.6	76.9	9.6	18.1	6.5	0.0	0.0
Sugar pine	165.2	16.0	140.9	37.3	143.2	40.0	27.3	3.6	22.9	5.8	22.9	4.8	8.7	8.2
Jeffrey pine	167.6	50.8	116.2	26.8	28.1	20.7	4.2	1.3	62.5	39.6	18.3	8.4	3.6	3.6
W. white pine	115.7	43.5	119.8	47.1	24.1	11.4	77.1	29.1	75.3	28.7	10.9	5.2	2.0	2.0
Lodgepole pine	114.7	13.0	147.9	40.0	117.2	17.7	26.0	6.9	32.7	19.1	9.0	2.4	12.7	12.7
Whitebark pine	90.5	19.0	55.3	9.6	2.5	0.9	17.4	3.8	8.6	3.8	6.8	5.9	17.8	17.8
Incense-cedar	130.2	41.9	121.9	17.6	–	–	39.7	7.8	38.0	8.8	35.7	15.5	0.1	0.1
White fir	196.4	17.6	82.9	11.1	–	–	102.1	13.9	121.6	33.9	80.2	34.8	101.6	59.6
Giant sequoia	301.0	262.3	45.1	37.9	54.5	34.9	48.5	40.2	31.6	27.1	11.3	7.8	1.1	1.1
Red fir	192.3	27.4	113.0	19.1	–	–	77.3	11.6	107.6	24.6	65.8	20.6	38.5	22.4
Mt. hemlock	245.3	110.7	77.3	16.2	72.5	13.0	126.9	61.0	68.6	44.9	17.5	7.8	0.0	0.0

[a] Cones of incense-cedar, white fir, and red fir disintegrate into cone scales and are included in miscellaneous fragments.
[b] Woody fuel size classes are: twig, 0.01–0.64 cm; branch, 0.65–2.54 cm; large branch, 2.55–7.62 cm; and log, 7.63 cm and larger.

fuels for very large diameter size class stands were slightly less than for large diameter size class stands as a result of reduced amounts of fuel deposition in the two larger fuel classes. In particular, ponderosa pine and Jeffrey pine had small amounts of woody fuel in the twig fuel class, white fir amounts were greatly reduced in the large branch fuel class, and woody fuels in the log fuel class for ponderosa pine, incense-cedar, and mountain hemlock were largely absent. White fir and red fir were the largest contributors in nearly all woody fuel classes, totaling an average of 405.5 g m^{-2} year^{-1} and 289.2 g m^{-2} year^{-1}, respectively.

3.2. Relation of annual fuel increment to stand characteristics

All of the regressions with the lowest AIC_c scores had a single variable and went through the origin. As such, these equations are considered the best among the models evaluated for predicting fuel increments. Because single-variable models through the origin minimize the number of parameters, they are both simple and parsimonious. The regressions are all in the general form:

$$\text{Deposition Rate} = \text{Coefficient} \times \text{Characteristic}$$

For the six pine species, the probability that the models were the best among the 22 candidate models, as measured by w, ranged from 0.340 for lodgepole pine cones to 0.071 for ponderosa pine fragments and western white pine large branches (Table 7). Crown height was the most frequent characteristic included in the best models for the six pines, followed by crown ratio and tree stem diameter. Crown ratio was included in all of the models for predicting foliage deposition rate. Tree stem diameter was the best predictor of cone deposition rates for four of the six pines, and crown height was the best predictor of large branch deposition for three of the pines. There was no consistent predictor for fragments, twigs, or logs.

For the five non-pine species, the range of w values was narrower than for the pines with a maximum probability of 0.269 for incense-cedar foliage to 0.107 for red fir twigs (Table 8). The live crown ratio was the most frequent characteristic in the best models for the five non-pine species, followed by crown height. Crown ratio was the best predictor of foliage deposition for all five species and twig deposition for three species. There was no consistent pattern for the other fuel classes.

4. Discussion

In general, deposition was higher for larger stem diameter size class stands. Foliage was the greatest contributor to total fuel deposition; while logs, because of their infrequent deposition, usually contributed the least. Lower elevation species such as ponderosa pine and white fir had greater deposition rates than Jeffrey pine and red fir, which occur at mid elevations. At treeline, whitebark pine had the lowest total deposition rates of all species.

Woody fuels increased from the small diameter size class through the very large diameter size class, although there was some variation in the two largest diameter size classes. This is primarily due to the high amounts of large branches deposited by white fir in the large diameter size class and the lack of log debris for many species in the very large size class. Woody fuel deposition differed among species. Jeffrey and ponderosa pine consistently had less woody fuel in the smallest fuel class, likely a function of their branch morphology. The large quantities of log-sized limbs of medium and large diameter ponderosa pine stands were possibly a result of self pruning in these stands. The dense branching habit, vertically and horizontally, of the firs probably contributed to the large amounts of woody debris they deposited in each fuel class.

Table 7
Regression equations for estimating fuel increments in g m^{-2} year^{-1} for six central Sierra Nevada pine species as a function of mean stem or crown characteristics, where w = Akaike weight, SE = standard error of the coefficient, and R^2 is the coefficient of determination. Species are listed by increasing elevation.

Species	Fuel class[a]	w	Characteristic	Coefficient[b]	SE	R^2
Ponderosa pine	Foliage	0.156	Crown ratio	35.093	4.169	0.845
	Fragment	0.071	Crown height	6.599	0.582	0.908
	Cone	0.182	Stem diameter	0.938	0.159	0.729
	Twig	0.145	Crown ratio	0.675	0.200	0.466
	Branch	0.181	Crown height	2.735	0.464	0.728
	Lg. branch	0.212	Crown ratio	3.888	1.021	0.527
	Log	0.168	Crown ratio	0.570	0.266	0.261
Sugar pine	Foliage	0.258	Crown ratio	31.915	3.974	0.811
	Fragment	0.121	Stem height	3.031	0.539	0.679
	Cone	0.241	Stem basal area	99.249	12.573	0.806
	Twig	0.101	Stem height	0.802	0.132	0.169
	Branch	0.223	Stem height	0.583	0.087	0.747
	Lg. branch	0.144	Stem diameter	0.180	0.042	0.553
	Log	0.180	Stem basal area	5.893	2.523	0.267
Jeffrey pine	Foliage	0.150	Crown ratio	20.854	3.557	0.696
	Fragment	0.174	Stem diameter	0.787	0.098	0.810
	Cone	0.162	Crown height	1.218	0.235	0.641
	Twig	0.134	Stem diameter	0.028	0.009	0.401
	Branch	0.158	Crown height	2.020	0.453	0.570
	Lg. branch	0.197	Crown height	0.690	0.137	0.628
	Log	0.178	Stem basal area	2.164	0.905	0.276
W. White pine	Foliage	0.211	Crown ratio	12.464	1.957	0.730
	Fragment	0.228	Crown height	4.453	0.789	0.680
	Cone	0.200	Stem diameter	0.305	0.046	0.746
	Twig	0.177	Crown height	2.808	0.526	0.656
	Branch	0.229	Stem basal area	57.713	11.336	0.633
	Lg. branch	0.071	Crown height	0.488	0.131	0.479
	Log	0.136	Crown height	0.042	0.031	0.109
Lodgepole pine	Foliage	0.201	Crown ratio	17.316	1.479	0.901
	Fragment	0.210	Stem diameter	1.831	0.265	0.761
	Cone	0.340	Stem diameter	1.652	0.167	0.867
	Twig	0.236	Stem diameter	0.496	0.068	0.779
	Branch	0.231	Stem basal area	87.398	18.146	0.607
	Lg. branch	0.195	Stem basal area	33.433	9.528	0.451
	Log	0.141	Crown height	0.269	0.227	0.086
Whitebark pine	Foliage	0.238	Crown ratio	11.556	1.286	0.843
	Fragment	0.239	Stem height	4.936	0.485	0.485
	Cone	0.275	Stem diameter	0.050	0.009	0.670
	Twig	0.143	Crown ratio	2.398	0.332	0.777
	Branch	0.170	Stem height	1.477	0.372	0.512
	Lg. branch	0.118	Crown height	0.868	0.258	0.431
	Log	0.146	Stem diameter	0.235	0.124	0.194

[a] Woody fuel size classes are: twig, 0.01–0.64 cm; branch, 0.65–2.54 cm; large branch, 2.55–7.62 cm; and log, 7.63 cm and larger.
[b] Units for the coefficient of the characteristics are: crown ratio, dimensionless; crown height, m; stem height, m; stem diameter, cm; stem basal area, cm^2.

The annual deposition of foliage for each species was the lowest for the small diameter size class stands. Once trees entered the medium size class, foliage deposition reached a peak and dropped only slightly in the two largest diameter size classes stands. However, fragments and foliage increased in almost every case as the stands matured, and there were consistent species differences in the amount deposited. For example, ponderosa pine deposited more foliage than white fir in every diameter size class.

Annual variability in deposition of foliage, fragments, and cones within species and diameter size class was probably due in part to winter storm severity and precipitation. Differences in site productivity could also have affected fuel production. The magnitude of overall variability and within-species variability of all deposition appeared to increase with the diameter size class and the class of woody fuels. This affected the ability to detect differences among groups, especially for cone fuel, and underlined the importance of long term observations. For example, heavy cone crops of the pines of California are known to occur every 3–7 years (Fowells and Schubert, 1956).

Crown height and live crown ratio were the best predictors of annual fuel increments for most species, diameter size classes, and fuel classes. The live crown ratio takes into account the proportion of the tree's height that is photosynthesizing. Live crown ratio was not the best characteristic for predicting annual increments of the largest woody fuel class.

Comparisons of our results with previous studies of fuel deposition rates in the Sierra Nevada was difficult because fuel classes were combined into different categories (Biswell et al., 1966; Agee et al., 1977; Stohlgren, 1988) or were not differentiated by species (Stohlgren, 1988). The one possible comparison was for cones collected by Stohlgren (1988), which showed deposition rates for giant sequoia and sugar pine cones to be similar to the rates we observed.

Keane (2008a) reported results for the three conifers common to both the northern Rocky Mountains and the Sierra Nevada. His stands were most comparable to our large diameter size class. Our values for foliage in that size class were 1.5 times greater for lodgepole pine, 2.5 times greater for ponderosa pine, and nearly equal for whitebark pine compared to his results from the northern Rocky Mountains. The deposition rates of all other fuel classes were from 2 to 10 times greater in the Sierra Nevada, except for ponderosa pine twigs, which were twice as great in the Northern Rocky Mountains. When comparing Pacific Northwest forests studied by Harmon et al. (1986), Keane (2008a) attributed the lower depositions rates he found to less productive growing conditions. Forests on the western slope of the Sierra Nevada, with higher total precipitation and

Table 8
Regression equations for estimating fuel component increments in g m^{-2} yr^{-1} for five non-pine central Sierra Nevada conifer species as a function of mean stem or crown characteristics, where *w*: Akaike weight, SE: standard error of the coefficient, and R^2 is the coefficient of determination. Species are listed by increasing elevation.

Species	Fuel class[a]	w_i	Characteristic	Coefficient[b]	SE_b	R^2
Incense-cedar	Foliage	0.269	Crown ratio	33.825	4.296	0.816
	Fragment	0.244	Stem height	4.385	0.369	0.910
	Twig	0.165	Crown ratio	8.942	1.786	0.642
	Branch	0.155	Stem height	2.111	0.564	0.501
	Lg. branch	0.187	Stem diameter	0.503	0.143	0.469
	Log	0.143	Stem diameter	0.108	0.060	0.187
White fir	Foliage	0.130	Crown ratio	24.393	3.442	0.770
	Fragment	0.118	Stem height	2.257	0.228	0.867
	Twig	0.232	Stem height	2.917	0.339	0.831
	Branch	0.238	Stem height	2.894	0.444	0.739
	Lg. branch	0.185	Crown height	5.428	1.290	0.542
	Log	0.205	Stem basal area	118.100	35.669	0.451
Giant sequoia	Foliage	0.161	Crown ratio	44.744	10.550	0.545
	Fragment	0.170	Crown height	1.034	0.247	0.539
	Cone	0.189	Crown height	1.726	0.312	0.671
	Twig	0.160	Crown ratio	8.154	1.763	0.588
	Branch	0.170	Crown ratio	6.167	1.796	0.440
	Lg. branch	0.162	Stem height	0.659	0.209	0.399
	Log	0.137	Stem basal area	0.095	0.057	0.154
Red fir	Foliage	0.255	Crown ratio	26.539	2.880	0.850
	Fragment	0.153	Stem diameter	1.020	0.112	0.847
	Twig	0.107	Stem diameter	0.775	0.115	0.753
	Branch	0.180	Stem diameter	0.921	0.159	0.691
	Lg. branch	0.231	Stem basal area	73.140	14.041	0.644
	Log	0.132	Stem basal area	46.833	20.509	0.258
Mt. hemlock	Foliage	0.267	Crown ratio	20.609	3.914	0.649
	Fragment	0.111	Crown ratio	6.844	0.922	0.786
	Cone	0.229	Crown ratio	8.271	2.459	0.430
	Twig	0.217	Crown ratio	8.554	2.146	0.514
	Branch	0.153	Crown ratio	3.282	1.510	0.239
	Lg. branch	0.176	Stem diameter	0.140	0.040	0.455
	Log	0.126	Stem height	0.142	0.100	0.118

[a] Woody fuel size classes are: twig, 0.01–0.64 cm; branch, 0.65–2.54 cm; large branch, 2.55–7.62 cm; and log, 7.63 cm and larger.
[b] Units for the coefficient of the characteristics are: crown ratio, dimensionless; crown height, m; stem height, m; stem diameter, cm; stem basal area, cm^2.

a longer growing season than the Northern Rockies, may differ for similar reasons.

Although the rates determined in this study were derived from Sierra Nevada forests, they should prove useful both there and in similar ecosystems of the western United States. Information on fuel deposition rates should prove useful to both managers and scientists. By measuring mean stem and crown characteristics, users can develop deposition rates for their stands. For example, if the mean crown ratio in a ponderosa pine stand was 0.5, the regression equation would predict a foliage increment of 17. 5 g m^{-2} year^{-1}:

$$\text{Deposition Rate} = \text{Coefficient} \times \text{Characteristic}$$

$$17.5 = 35.093 \times 0.5$$

The equations could be used to estimate fuel loads which help determine appropriate fuel models and develop custom fuel models. Care must be taken to not assume a direct relation between fuel load estimates and the values in fuel models (Burgan and Rothermel, 1984). The estimates are starting points in a procedure that relates fuel model values to fire behavior characteristics (Burgan, 1987).

Deposition rates can be used to determine when an area is ready to burn. For instance, fuels begin to accumulate after an area has burned, eventually reaching the upper end of historical variability. That point is determined by the historical fire return interval and rate of accumulation, which is directly related to deposition and decomposition rates. The regression equations presented here will allow managers to make deposition rate predictions at the local scale using stand characteristics. The equations will also prove useful for modeling fuel processes across landscapes and vegetation types.

When combined with decomposition rates, these predictions can be used to determine priorities for burning. The historical range of variability in fuel loads can be calculated and compared to measurements of fuel load made in the field or from remotely sensed data (Matlu et al., 2008). In conjunction with other factors, those areas that are most divergent in fuel load could then be assigned a high priority in a prescribed burning program.

The move to consider forests as carbon stores to offset climate change effects makes it critical to have accurate information on fuel deposition rates. As Hurteau and North (2009) report, returning fire to Sierra Nevada forests may be the best policy in the long run for maximizing sequestered carbon. The contribution forest fuels can make to stored carbon can be calculated from their deposition rates and heat contents (van Wagtendonk et al., 1998b).

A better understanding of fuel dynamics should help land mangers restore natural processes and manage wildlands consistent with ecological principles. This study has contributed to that understanding with the hope of aiding managers in that task. To expand this information to the landscape scale and to other regions, further research will be needed.

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