Forest Ecology and Management, 1 (1977, published 1978) 255—265 255

FIRE AND FUEL DYNAMICS OF SIERRA NEVADA CONIFERS

JAMES K. AGEE*, RONALD H. WAKIMOTO** and HAROLD H. BISWELL**

**United States Department of the Interior, National Park Service, Western Region, San Francisco, Calif. (U.S.A.)*
***Department of Forestry and Resource Management, University of California, Berkeley, Calif. (U.S.A.)*

(Received 29 August 1977)

ABSTRACT

Agee, J.K., Wakimoto, R.H. and Biswell, H.H., 1978. Fire and fuel dynamics of Sierra Nevada conifers. *Forest Ecol. Manage.*, 1: 255—265.

Fuel dynamics were studied in a mixed-conifer forest in the Sierra Nevada. Accretion rates showed no apparent differences between species, but decomposition and caloric content of the forest floor did vary by species. Prescribed burning of the forest floor with a headfire at 10% analog fuel moisture reduced fine fuel loads 60—70%, depending on species and the loading of heavier branch and twig fuels. Pine fuels can effectively be reduced by spring, summer or fall burning, but white fir and giant sequoia fuels require drier summer or fall conditions. The implications of fire management in these ecosystems are discussed.

INTRODUCTION

Fire has been a recurrent natural phenomenon in Sierra Nevada mixed-conifer forest in California for thousands of years (Show and Kotok, 1924; Weaver, 1951). Studies of fire-scarred trees have revealed the frequency of fire to have been 4—8 years (Boyce, 1920; Wagener, 1961). The origins of these fires were both climatic (Van Wagtendonk, 1972) and cultural (Reynolds, 1959); the frequency of lightning alone in some areas could account for most of the fires, but it is known that the California Indians set wildland fires for a number of reasons.

Early California mixed-conifer forest fires were usually of low intensity (Muir, 1894), because fuel energy was periodically released before it built up to levels where a sudden large energy release could occur. The policy of suppressing all natural and man-caused forest fires, instituted early in the twentieth century, has allowed energy to accumulate over the years, ultimately being released by infrequent, damaging wildfires (Dodge, 1972). Fire is now being reintroduced to many forest environments to reduce fire hazards or recreate pristine conditions (Kilgore, 1970). The objective of this study was to quantify fuel buildups and fuel reduction by fire for four Sierra Nevada conifers.

STUDY AREA

The study was conducted at Whitaker's Forest in Tulare County, California, adjacent to Sequoia and Kings Canyon National Parks. Elevations range from 1640 to 1960 m, and the predominant soil series is Shaver sandy loam derived from granitic parent material. The dominant overstorey tree species are ponderosa pine (*Pinus ponderosa* D. Don.), sugar pine (*Pinus lambertiana* Dougl.), white fir (*Abies concolor* Lindl. & Gord.), giant sequoia (*Sequoiadendron giganteum* (Lindl.) Buchh.), and incense-cedar (*Calocedrus decurrens* (Torr.) Florin). The forest was manipulated, beginning in 1964, to reduce fire hazards (Biswell et al., 1968), enhance scenic values (Cotton and Biswell, 1973), to improve the wildlife habitat (Lawrence and Biswell, 1972), and to reduce competition for the larger trees. Much of the understorey, consisting of white fir and incense-cedar thickets which developed due to many years of fire suppression, was removed in the manipulation. The portion of the forest in this study now consists of a mosaic of even-aged groups of the four species studied. Much of the area was heavily disturbed by logging operations in the 1870's. Growth ring counts indicate that most white fir, incense-cedar, and young-growth giant sequoia became established after the logging operations were complete (Buchanan et al., 1966). The young-growth giant sequoia are small compared to mature stands (Fig.1), while the stands of the other species are mature. Stand basal areas over the study area average 130 m^2 ha^{-1}.

METHODS AND MATERIALS

Plots were established in areas dominated by pure stands of the fuel types ponderosa pine, sugar pine, white fir, and giant sequoia to compare litterfall, decomposition of fine fuel, caloric content of fuel, and fuel reduction from prescribed fires. Ten litter trays, each 1 m^2, were randomly placed under trees of each species studied and litter was collected at one month or longer intervals for two years. Decomposition packets, each containing several grams of litter or duff enclosed in polyester mesh, were placed in the appropriate litter or duff layers of the forest floor of each fuel type. Ten litter and ten duff packets from each species were removed after one year, and a duplicate set was removed after two years. Caloric contents with and without ash were determined for the litter, duff and branch-twig components of each fuel type, using standard procedure on a Paar 1242 calorimeter (Paar Instrument Co., 1971).

During the summer of 1971, prescribed headfires were applied to three 6-m^2 plots in each fuel type. One plot in each fuel type was comprised of fine fuel only (needles), while the other two plots had branch and twig fuels added at the rate of 450 and 900 oven-dry g m^{-2}. The fine fuels in each plot were measured before burning on 0.1-m^2 subplots, and each subplot was reconstituted with materials from off the plot. The plots were ignited when the moisture content of standard fuel moisture indicator sticks was 10%. This

Fig. 1. Whitaker's Forest, showing the stand structure of young-growth giant sequoia. The stump in the foreground is a remnant of a large diameter sequoia cut in the 1870's.

fuel moisture analog was used in his study to emphasize management application. Fuel moisture indicator sticks are still the most widely used estimators of moisture in medium (1—10 hour) timelag fuels. Residual fuel was measured on paired subplots because of the destructive sampling necessary to determine initial fuel weights. Where appropriate, statistical analysis using analysis of variance with orthogonal contrasts was applied. All results described as significant are statistically significant at $\alpha = 0.05$, $\beta = 0.10$, unless otherwise indicated.

RESULTS

Accretion and decomposition

Litterfall for each species is presented in Table I. The first year white fir recorded the highest litterfall, followed by ponderosa pine, giant sequoia, and sugar pine. The second year the order was reversed, due probably to a staggering of the litterfall cycles. The first year white fir had a heavy cone crop, which fell as deciduous scales and resulted in the high value for white fir. This effect was not apparent the second year. In both years the range of litter fall was similar and the two-year averages were quite close for all species.

TABLE I

Yearly litterfall mass (g m^{-2}) by fuel diameter class and species

	PP	SP	WF	GS
Year 1				
Below 6 mm diameter	356.8	302.2	380.3	328.8
Above 6 mm diameter	30.7	48.3	112.0	39.1
Total	387.5	350.5	492.3	367.9
Year 2				
Below 6 mm diameter	381.2	389.0	287.7	318.0
Above 6 mm diameter	28.2	109.3	99.3	121.4
Total	409.4	498.3	387.0	439.4

PP = ponderosa pine; SP = sugar pine; WF = white fir; GS = giant sequoia.

Average yearly decomposition of litter and duff packets over the two-year period is shown in Table II. Percent weight loss of the packets was statistically analyzed using a three-way nested factorial design, and significant differences due to fuel layer and packet exposure time were present. All litter

TABLE II

Average yearly percent decomposition of the forest floor by species

	PP	SP	WF[a]	GS
Litter	11.16	8.60	6.67	2.77
Duff	2.80	2.56	1.46	11.40

[a]White fir results affected by soil contamination.

layers lost a higher percentage of weight than duff layers, except for giant sequoia where the duff lost more. The packets remaining two years decomposed more than those remaining one year. The results for white fir are not reliable, as some of the packets in the first-year group actually gained net weight due to humus-soil contamination. This was not a problem for the other species. None of the second-year samples gained weight, but similar contamination reduced the second-year white fir weight loss.

Ash-free caloric content of the litter, duff, and branch-twig layers of the forest floor (Table III) was analyzed using a two-way nested design. Significant differences in caloric content were found. Fuels of ponderosa pine had higher caloric content than fuels of the other overstorey species. Caloric content of fuel layers within species also differed. The duff layers of ponderosa pine, white fir and giant sequoia had higher caloric contents than corresponding branch-twig components; caloric content of ponderosa pine duff also exceeded the litter caloric content for that species.

TABLE III

Ash-free caloric content (kcal g^{-1}) of fuels by species

	PP	SP	WF	GS
Litter	5.157	5.149	5.188	5.109
Duff	5.689	5.203	5.132	5.123
Branch-twig	5.016	5.122	4.939	4.936

Effects of burning

On the plots that were to be burned, initial fine fuel weights (Table IV) were analyzed, using a one-way analysis of variance (ANOVA) for litter, duff, and total fuel weight of each species. There were no significant differences between total fuel weights of ponderosa pine, white fir and sugar pine, but fuel weights of giant sequoia were significantly less than for white fir. These weights reflect not only fuel accretion but variable stand histories. Since these areas had been manipulated within the past decade, site disturbance may have affected the initial weights on these plots.

TABLE IV

Initial mass (g m^{-2}) of forest floor components by species

	PP	SP	WF	GS
Litter	1732	1673	2388	1563
Duff	3187	2763	2820	1497
Total	4919	4436	5208	3060

Actual weight loss and percentage weight loss from fire of litter, duff, and total fine fuel were analyzed using a two-way nested factorial design with fuel type and loading as the independent factors. Loading of branch and twig fuels and fuel type affected the weight loss of fuels, and percentage reductions are shown in Table V.

Under the fairly dry summer weather conditions, white fir and ponderosa pine fuels were reduced more than the fuels of sugar pine and giant sequoia, but possible statistical bias limited the testing to (n-1) contrasts. The litter reduction results indicated that fuel loss was higher for white fir than for ponderosa pine, and ponderosa pine fuel loss significantly exceeded that of sugar pine. Percent duff reduction was significantly greater for white fir and sugar pine than for ponderosa pine. Total percent loss was greater for white fir than ponderosa pine, while actual weight loss was greater for ponderosa pine than for sugar pine or giant sequoia.

The significant loading effect suggests that the amount of branch and twig fuels affects fine fuel reduction. This factor was statistically nested within fuel type because the branch and twig fuels were unique to each species and thus could not be randomly assigned regardless of species. No statistical interaction between species and loading could be tested due to their nested character. However, some non-statistical differences were observed in the field and the data. For the pines, all significant contrasts showed that increased loads of the medium size fuels increased fine fuel consumption. For white fir and giant seqoia, all significant contrasts showed just the opposite, that increased medium fuel loads decreased consumption of the fine fuels. The explanation lies in the nature of the fuel beds of the species. The loose, aerated fuel beds of the pines will carry fire over or around small branches and twigs at 10% fuel stick moisture. Fires tended to completely cover the pine plots, and ignition of branch-twig fuels aided further consumption of fine fuels. The white fir and giant sequoia fuel beds, being more compact, had lower flame heights. The fires were often restricted by the presence of medium fuels because the low flames would not carry over small branches and were forced to circumvent them. The low intensity fires could not provide the heat energy required to dry and ignite such fuels. Fine fuel consumption was still quite high in white fir and giant sequoia, but consumption did decrease as branch-twig weights increased.

Fuel buildup model

A computer simulation of fine fuel accumulation was developed to model short-term energy buildups in the absence of disturbance in three fuel types. The white fir fuel type was not considered because of the lack of acceptable decomposition data.

Since actual weights of the forest floor include ash, the caloric values with ash were used to compute energy in the litter and duff layers of each species. The fine fuel litterfall and decomposition rates found in the study were used

TABLE V

Percent fuel reduction of fuel layers by species and loading of branch and twig fuels

Branch and twig loading ($g\ m^{-2}$)	Litter reduction				Duff reduction				Total reduction			
	PP	SP	WF	GS	PP	SP	WF	GS	PP	SP	WF	GS
0	65.0	44.3	81.3	86.9	45.9	71.9	97.4	98.2	55.5	58.1	89.3	92.6
450	75.6	62.7	69.1	60.3	62.1	73.5	89.4	−14.6	68.9	68.1	79.2	22.9
900	79.4	79.5	75.5	87.1	74.4	95.7	59.5	82.4	76.9	87.6	67.5	84.8

to input energy to the litter layer, and it was assumed that one-sixth of the litter layer was transferred to the duff layer each year (Agee, 1973). An additional 2% caloric loss of the remaining litter was assumed, similar to the results of Stark (1973). Duff decomposition rates were those found in this study.

Yearly litter energy was calculated by subtracting from the previous year's litter energy the 2% loss, the fresh needle decomposition, and the amount transferred to the duff layer, and then adding in the annual needle input. Yearly duff energy was calculated by subtracting from the previous year's duff energy the amount decomposed, and adding the energy transferred from the litter, while total fuel energy was the sum of litter and duff energy. Because accretion initially exceeds decomposition, fuel accumulates until the percentage decomposition of the total equals the yearly addition. The program was run for a thirty-year period, beginning with an assumed total fuel energy of zero, and total fuel energy accumulation over the period is shown in Fig.2.

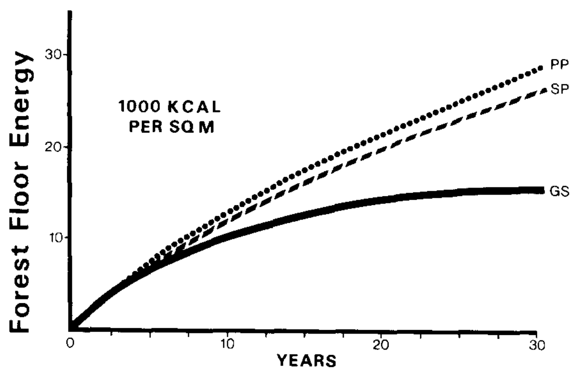

Fig. 2. Simulated forest floor energy buildup over time by species.

The simulated forest floor under ponderosa pine accumulated the most energy, followed closely by sugar pine, while the simulated accumulation under giant sequoia was much less. While the stands of the first two species were mature, the 100-year old giant sequoia stands were small compared to a 500—1000-year-old mature stand of sequoia. The assumed constant input of fine fuel was considered an underestimate of what would occur in a mature stand, so the model output is realistic only over the short run. The simulation shows that short-term accumulation of energy is not as rapid under the young sequoia as under trees of the other species, of the same size but physiologically more mature.

DISCUSSION AND CONCLUSIONS

The results are in many respects similar to other recent studies of fuel dynamics in the Sierra Nevada. The needlefall was similar to that found by

Van Wagtendonk (1972) in the Yosemite areas to the north. An earlier study of litterfall at Whitaker's Forest showed annual fall to be much greater (Biswell et al., 1966), primarily because the collecting trays were clustered around the bases of the sample trees. Decomposition of the two pine duff layers was almost identical to that found by Jenny et al. (1949). The high giant sequoia duff decomposition rate is likely due to the high cation content of giant sequoia needles (Zinke and Crocker, 1962). Once the rather large, coarse needles are partially decomposed, high nutrient availability and the ameliorating effect on pH provide a better environment for decomposition than is present in the forest floors of the other species.

Ash-free caloric values contrast with two other studies in the mixed-conifer forest. While this study showed the duff to have the same or higher ash-free caloric content than the litter, other studies have shown litter to contain more energy (Van Wagtendonk, 1972), or no significant differences (Agee, 1973). Though the results of these studies are in apparent conflict, the real differences between the caloric contents are small. When compared to the large differences in fuel loading between locations, the small differences in caloric contents of those studies are of little practical importance in determining energy contents.

Burning the forest floor under these four fuel types reduces fine fuel energy up to 60—70% if conducted in the summer at 10% fuel-stick moisture. Other studies in the same area have reported fuel reduction in the spring and fall months. Agee (1973) showed fuel reduction from spring burning to be less for white fir—giant sequoia than for ponderosa pine—incense-cedar, because of the more flammable nature of the latter fuel bed at that time of the year. Fall burning effectively reduces white fir and giant sequoia fuels. Kilgore (1972) noted an 85% reduction of fine fuels after fall burning. Fuels of the pines can effectively be reduced by spring, summer, or fall burning, but white fir and giant sequoia fuels required drier summer or fall conditions.

The fine fuel simulation indicated that ponderosa pine accumulates energy at a faster rate than sugar pine or giant sequoia. The differences between the pines are not large or important, but the sequoia forest floor may not accumulate energy nearly as fast as the forest floor under the other species. However, the giant sequoias studied eventually become much larger, increasing needlefall substantially over what was found in the present young stand; the forest floor energy at equilibrium in a mature stand may approach that of the other species. Zinke and Crocker (1962) noted that the litter and duff under old growth sequoia stands reached 13 000 g m^{-2}, or about 50 000 kcal m^{-2}, the model equilibrium that is eventually reached by mature ponderosa pine and sugar pine. The timeframe considered by the model precluded a long-term equilibrium simulation, but did indicate that in the short run, second-growth sequoia stands accumulate less energy than similar-sized pine stands.

Ecosystem dynamics appear to be more stable in a mixed-conifer ecosystem under a periodic fire regime. Historically, low decomposition rates and the flammable nature of the mixed-conifer forest floor ensured that frequent surface fires would occur, given an ignition source of lightning or man, periodically releasing stored energy. A cyclic stability was maintained, as described by Vogl (1970) in his consideration of the roles of fire in plant succession. When natural fires are suppressed, energy rapidly accumulates and species composition shifts from ponderosa pine, or giant sequoia with white fir, to a white fir—incense-cedar mix, because fir and incense-cedar seedlings are no longer eliminated by frequent surface fires. The new system is also less flammable, especially where ponderosa and sugar pines were once the dominant forest floor fuels, because fires will burn only in the driest months. The understorey tree fuels and forest floor fuels tend to accumulate and store energy, most of which is distributed as "ladder" energy connecting the energy on the forest floor with the energy stored in the overstorey tree crowns. When a wildfire occurs in dry weather under such fuel conditions, it is much more likely to develop crown fire behavior (Kilgore and Sando, 1975), killing many of the mature trees and seriously disrupting energy and nutrient cycle stability. This system state is inherently less stable than one dominated by a natural fire-maintained mixed-conifer forest.

The Sierra Nevada mixed-conifer ecosystems is intimately linked with its past fire history and present fire climate. Where the forest management system recognizes that fuel dynamics and fire are integral parts of this system, optimum fire management alternatives can be developed to accomplish the objectives of the forest manager.

ACKNOWLEDGEMENTS

This research was supported in part by Project Clean Air No. 6, Research Grant No. 2-017-1 from the State of California Air Resources Board.

REFERENCES

Agee, J.K., 1973. Prescribed fire effects on physical and hydrologic properties of mixed-conifer forest floor and soil. University of California Water Resources Center Contribution No.143, 57 pp.

Biswell, H.H., Gibbens, R.P. and Buchanan, H., 1966. Litter production by bigtrees and associated species. California Agriculture, 20(9): 5—7.

Biswell, H.H., Gibbens, R.P. and Buchanan, H., 1968. Fuel conditions and fire hazard reduction costs in a giant sequoia forest. National Parks and Conservation Magazine, 42(251): 16—19.

Boyce, J.S., 1920. Dry rot in incense-cedar. United States Department of Agriculture Bulletin No. 871. Government Printing Office, Washington, D.C., 58 pp.

Buchanan, H., Biswell, H.H. and Gibbens, R.P., 1966. Succession of vegetation in a cut-over Sierra redwood forest. Utah Academy of Science, Arts and Letters, 43(1): 43—48.

Cotton, L. and Biswell, H.H., 1973. Forest scape and fire restoration at Whitaker's Forest. National Parks and Conservation Magazine, 42(2): 10—15.

Dodge, J.M., 1972. Forest fuel accumulation — a growing problem. Science, 177 (4044): 139—142.

Jenny, H., Gessel, S.P. and Bingham, F.T., 1949. Comparative study of decomposition rate of organic matter in temperate and tropical ecosystems. Soil Science, 68: 419—432.

Kilgore, B.M., 1970. Restoring fire to the sequoias. National Parks and Conservation Magazine, 44(277): 16—22.

Kilgore, B.M., 1972. Impact of prescribed burning on a sequoia—mixed conifer forest. Tall Timbers Fire Ecology Conference Proceedings, 12: 345—376.

Kilgore, B.M. and Sando, R.W., 1975. Crown-fire potential in a sequoia forest after prescribed burning. Forest Science, 21(1): 83—87.

Lawrence, G. and Biswell, H.H., 1972. Effects of forest manipulation on deer habitat in giant sequoia. Journal of Wildlife Management, 36(2): 595—605.

Muir, J., 1894. The Mountains of California. Doubleday, Garden City, N.Y., 300 pp.

Paar Instrument Co., 1971. Oxygen bomb calorimetry and oxygen bomb combustion methods. Paar Instrument Co., Moline, Ill., 79 pp.

Reynolds, R., 1959. Effects upon the forest of natural fires and aboriginal burning in the Sierra Nevada. Unpublished M.S. thesis, University of California, Department of Geography, Berkeley, 262 pp.

Show, S.E. and Kotok, E.I., 1924. The role of fire in the California pine forest. United States Department of Agriculture Bulletin No. 1294. Government Printing Office, Washington, D.C., 80 pp.

Stark, N., 1973. Nutrient cycling in a Jeffrey pine ecosystems. Montana Forest and Conservation Experiment Station, University of Montana, Missoula, 389 pp.

Van Wagtendonk, J.W., 1972. Fire and fuel relationships in mixed-conifer ecosystems of Yosemite National Park. Unpublished Ph.D. thesis, University of California, School of Forestry and Conservation, Berkeley, 163 pp.

Vogl, R.J., 1970. Fire and plant succession. In: Intermountain Fire Research Council (Editors), The Role of Fire in the Intermountain West. Intermountain Fire Research Council, Missoula, Montana, pp. 65—75.

Wagener, W.W., 1961. Past fire incidence in Sierra Nevada forest. Journal of Forestry, 59(10): 737—747.

Weaver, H., 1951. Fire as an ecological factor in the southwestern ponderosa pine forests. Journal of Forestry, 49(2): 93—98.

Zinke, P. and Crocker, R.L., 1962. The influence of giant sequoia on soil properties. Forest Science, 8(1): 1—11.