EFFECTS OF PRESCRIBED FIRE IN GIANT SEQUOIA-MIXED CONIFER STANDS IN SEQUOIA AND KINGS CANYON NATIONAL PARKS

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ABSTRACT

Many national parks have incorporated the use of management-ignited prescribed fire in their management plans. Soil and cambium heating, forest floor fuel reduction, and soil nutrient increases have been measured on eight independent, planned management fires over a 9-year period in Sequoia and Kings Canyon National Parks. Findings show that instantaneous lethal temperature (150°F [66°C]) can be reached in the soil and within the cambium of giant sequoia (*Sequoiadendron giganteum*) and sugar pine (*Pinus lambertiana*) trees during prescribed burning. Mortality has not occurred to any of the giant sequoia trees examined but has occurred to some of the sugar pine trees examined. Available nitrogen in the soil is increased substantially and persisted for up to 4 years after prescribed burning.

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INTRODUCTION

Giant sequoia has been an awe-inspiring botanical specimen since its discovery by Euro-Americans in the mid-19th century. Known to be the largest tree species in the world, it occurs in a limited range in the central and southern Sierra Nevada and has been given protective status after lumbering eliminated several groves. Efforts by local conservationists led to protection of prime, uncut groves (Hartesveldt et al. 1975). Where stands of giant sequoia have been preserved, their protection has been so complete as to preclude the very natural forces that are required for the perpetuation of the species (Harvey et al. 1980). Not the least of these forces is fire, which has been suppressed and, therefore, not allowed to perform its natural function of reducing flammable surface fuels, thinning forest trees, stimulating sprouting of shrubs and other hardwoods, releasing seeds and preparing seedbeds favorable for germination of giant sequoia, efficiently recycling nutrients, and influencing insect and disease populations (Kilgore 1972, Harvey et al. 1980).

Fire history data in a number of forms indicate the existence of periodic fires in all temporal phases of the giant sequoia-mixed conifer ecosystem (Kilgore and Taylor 1979, Tweed 1987). Continuation of the ecological fire process for the long-term maintenance of the ecosystem is essential (van Wagtendonk 1983, Parsons et al. 1986). By the late 1960's, the National Park Service had begun a program of prescribed burning in the giant sequoia groves to reduce the hazardous fuel buildup, hoping to avoid catastrophic wildfire, while at the same time restoring fire to a more natural role (Bancroft et al. 1985). There is little question that this ecosystem has been changed by fire suppression activities. Some uncertainty exists, however, as to the most effective way of reversing those changes (Bonnicksen and Stone 1985, Parsons et al. 1986, Lemons 1987, Parsons 1990).

As a result of the prescribed fire program at Sequoia and Kings Canyon National Parks, many questions have surfaced with regard to both objectives and methods. The general goal in the park's burning program is "to restore or maintain natural fire regime to the maximum extent possible so that natural ecosystems can operate essentially unimpaired by human interference." Because of public concerns regarding the park's burning program, a panel was assembled in 1987 "to evaluate the effectiveness of the National Park Service fire management program" in the sequoia-mixed conifer forests of the Sierra Nevada (Christensen et al. 1987). The review panel supported the general premise and direction of the program while recommending the need to more clearly articulate objectives for individual burns, as well as the expansion of the monitoring and research programs (Christensen et al. 1987). As part of the park's expanded research program, we initiated a study to examine tree cambium and rooting-zone soil temperatures during prescribed burns and the effects thereof.

From an extensive prescribed fire research study started in 1976 in northern Arizona (Sackett 1980), it was determined that after the initial burns in unusually heavy natural fuels, something other than crown scorch was severely weakening and eventually killing some of the large mature trees. After a cursory investigation, we decided to monitor root mortality and cambial damage during burns that reduced litter on the forest floor. A temperature monitoring system was developed for use in Arizona on ponderosa pine (*Pinus* *ponderosa*), to investigate soil and cambium heating generated by burning forest floor material (Sackett and Haase 1992). After monitoring the soil and cambium heating on a number of fires, it was determined that elevated temperatures at the root collar and in the soil rooting zone might, in fact, be the cause of large tree mortality. It was this information that led the park to request a similar study of prescribed fires in the giant sequoia-mixed conifer ecosystem and the initial results of this ongoing study are presented here.

METHODS

The study of fire effects requires the basic knowledge of pre-existing fuel loadings on the site being investigated. To do this effectively without disturbing and altering the burning characteristics of the specific study site, forest floor samples and depth measurements are collected on an area representative of the study area. Prediction equations to estimate total forest floor accumulation and woody material ≤ 1 inch (2.54 centimeters) in diameter, are developed for each species using simple linear regression analysis of fifty 1 square foot (0.09 square meter) samples taken in the proximity of sugar pine trees (*Pinus lambertiana*) and again in the proximity of giant sequoia trees. Forest floor depth gauges are then used to define total forest floor depth, consumption depth, and the residual forest floor depth near temperature sensing sites. Forest floor depth-weight prediction equations for the two species are very good (Figure 1), presumably because of the relatively closed stand conditions and heavy snow packing during the winter. These prediction equations are then used to estimate the fuel loading (tons per acre [tonnes per hectare]) of each soil temperature site and around the base of the individual sample trees.

Soil Temperatures

A survey is made of each prescribed burn unit. Individual specimens of giant sequoia and sugar pine are selected that represent the burn unit, and are accessible. Selected trees need to be within 150 to 200 feet (45.7 to 61.0 meters) of a protected area (fireline) to accommodate the thermocouple cable length. Soil temperature sites are randomly selected that represent forest floor fuel conditions near the bole of each selected tree, midway to the drip line, and near the drip line. Since the overstory canopy is virtually closed in giant sequoia-mixed conifer stands, forest floor depth is relatively uniform from point-to-point for a given site, and hence forest floor weight. In contrast, forest floor weight decreases to very low levels just beyond the dripline of mature southwestern ponderosa pine trees. Sites are avoided where there is excessive disturbance by wildlife and/or people.

Once the six soil temperature sites are selected, holes are dug by hand and thermocouples are installed while kneeling on a piece of plywood to protect the site. A 6 × 18 inch (15.2 × 45.7 centimeter) rectangle is cut in the forest floor down to mineral soil and it is removed intact. As each hole is dug, the forest floor material and soil are placed on a sheet of plastic to further protect the site. Initially, holes were dug to a soil depth of 12 inches (30.5 centimeters), but after the first fires, it was determined that heating was substantial at that depth and subsequent holes are dug down to 20 inches (50.8 centimeters).

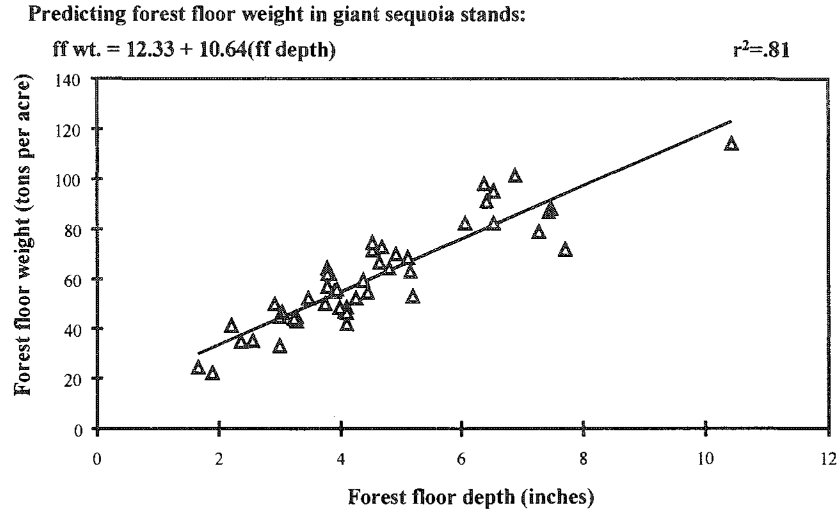
After the rectangular hole is dug to a sufficient depth, 12 inch (30.5 centimeter) long, 3/16-inch (0.48 centimeter) diameter stainless steel grounded, chromel-alumel thermocouples are inserted horizontally into the vertical soil wall at 18-, 12-, 8-, 4-, and 2-inches (45.7-, 30.5-, 20.3–10.2-, and 5.1-centimeters) below the soil and duff interface. The sixth thermocouple is positioned at the soil-duff interface. Once each set of six thermocouple probes is installed, each thermocouple is joined to the connection box of the extension cable, and the millivolt values on the micrologger are checked to confirm the integrity of the system. The hole is then filled, and the forest floor put back in place. Thermocouple extension cables are suspended out to a fireline on 8-foot (2.4 meter) tall support posts. A more complete description of the thermocouple installation process is found in Sackett and Haase (1992) and an example of the soil temperature data collected for one soil site profile is shown in Figure 2.

Soil moisture content samples are taken in 2-inch (5.1 centimeter) increments at the same time the hole is being dug. These soil samples are sieved to 0.079 inch (2 millimeter), placed in soil tins, sealed and identified for further processing. Postburn soil moisture content samples are taken in the undisturbed probe sampling area. Initially, soil moisture samples are weighed in the field, and then taken back to laboratory facilities to be dried at 221°F (105°C) until weight loss is no longer detected. The samples are removed from the oven, capped and sealed, and allowed to cool to room temperature before weighing again. Soil moisture content is determined using the oven dry weight basis (O.D. basis). Five forest floor consumption pins are installed in a horseshoe pattern beyond the ends of the thermocouple probes.

Measurements of the original forest floor depth, consumption depth, and the depth of the residual forest floor are made after each burn. By using the prediction equations in Figure 1, consumption weights are determined for each site.

Cambium Temperatures

To assess potential damage to tree boles, cambium temperatures are measured using 18-inch (45.7 centimeters) long, 1/8-inch (0.32 centimeter) diameter stainless steel sheathed, grounded, chromel-alumel thermocouple probes. Six locations around the base of the sample tree are selected. In sugar pine, a 2 × 5 inch (5.1 × 12.7 centimeter) rectangle is cut in the bark down to the cambium using the tip of a chainsaw while working from a piece of plywood to protect the temperature site. The notch is pried out with a long-handled, wide wood chisel. The thermocouple probe is then inserted downward inside the cambium with



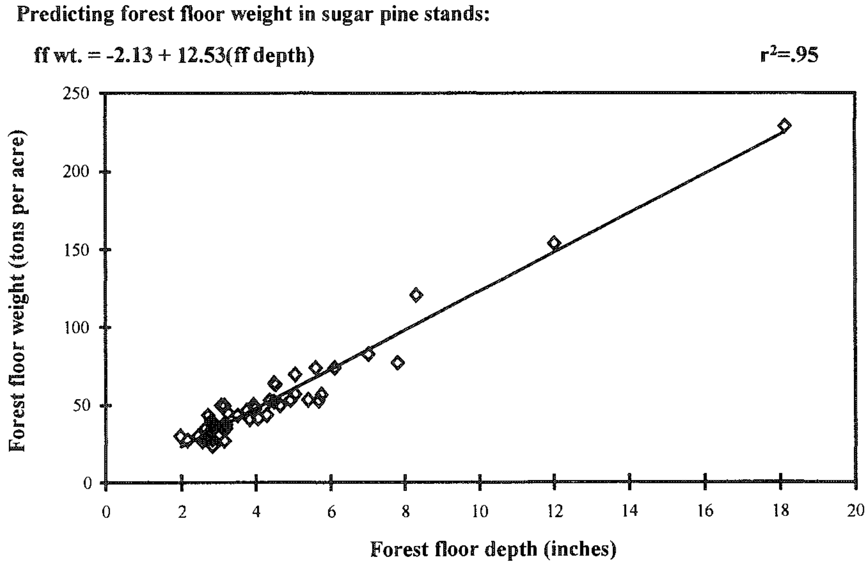


Fig. 1. Indirect method of predicting forest floor weight by measuring undisturbed forest floor depth for sugar pine and giant sequoia stands in Sequoia and Kings Canyon National Parks (tonnes per hectare = 2.247 × tons per acre and millimeters = inches × 25.40).

the help of a locking-pliers and hammer. In each case, an attempt is made to position the end of the thermocouple probe in the cambium corresponding to midway of the forest floor depth found directly outside the tree. A protective cover is placed over the reinstalled bark chunk and thoroughly insulated with fiberglass insulation. The bottom of the protective cover is in line with the top of the forest floor to provide a reference to measure forest floor depth after the burn. New techniques use a single vertical cut through the bark to insert cambium thermocouples.

In giant sequoias, the task is much more difficult because the bark can be as thick as 18 inches (45.7 centimeters). A new approach was developed, where the thermocouple probe is inserted at an angle through the bark so as to hit the cambium somewhere below the top forest floor level. Because the bark is so soft and fibrous, the method works very well. Many of the first measurements of giant sequoia cambium temperatures were lost because of the unusual bark characteristics of the species. In sugar pines, the bark is rigid which causes the thermocouple to stay at the cambium and bark interface each time.

Extension cables connect each thermocouple probe to an extension cable connection box that is suspended on a bracket attached to the tree. Again, a coaxial extension cable is suspended by poles to the protected area outside the fireline. A complete description of the system for soil and cambium temperature data acquisition is outlined by Sackett and Haase (1992)

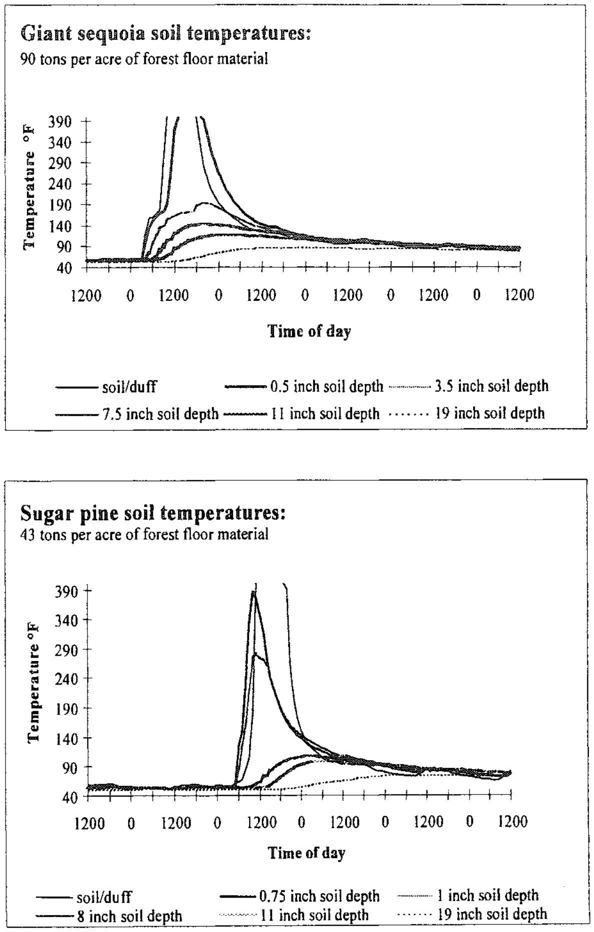


Fig. 2. Examples of temperature traces of individual soil site profiles during a prescribed fire in Sequoia and Kings Canyon National Parks (tonnes per hectare = 2.247 × tons per acre, millimeters = inches × 25.40 and °C = 0.556(°F−32)).

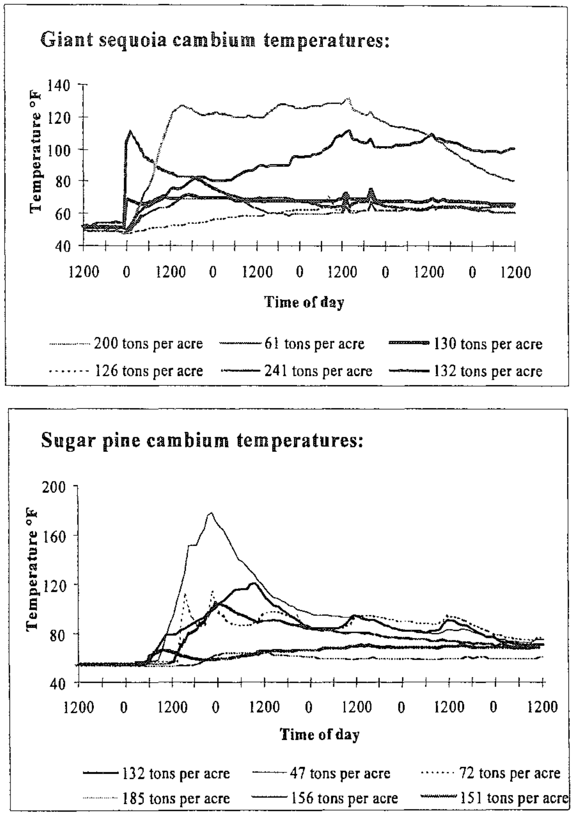


Fig. 3. Examples of temperature traces for cambium temperatures around individual trees during a prescribed fire in Sequoia and Kings Canyon National Parks (tonnes per hectare = 2.247 × tons per acre and °C = 0.556(°F−32)).

and an example of cambium temperature data that is collected for one particular tree is shown in Figure 3.

RESULTS

Fire Behavior

Eight prescribed fires (seven in Giant Forest and one in Grant Grove) have been documented since 1988. All have included the same general mix of giant sequoia, sugar pine, white fir [*Abies concolor* (Gord. & Glend.) Lindl.] and incense cedar [*Calocedrus decurrens* (Torr.) Florin]. Generally speaking, if an area will ignite and the fire carries over the surface forest floor, complete consumption of the litter and duff will occur over most of the area. This phenomenon occurs in duff moisture contents of 7 to 200+%. The wetter fuels burn for a longer period of time before burning out, often as long as five or more days. Fire burning in the forest floor is relatively unspectacular with flame lengths generally 6 inches (15.2 centimeters) or less, and lasting only a short time before glowing combustion takes over in the more densely matted fuel. Only when fire would run up the dry lichen of a fir or the bark of a giant sequoia would there be any unusual fire behavior.

Burning Conditions

Burns documented in the park were accomplished both during the summer and fall. Ambient air temperatures ranged from 54°F to 77°F (12°C to 26°C), while ignition time relative humidity ranged from 26 to 66%. Soils at burn sites in the Giant Forest area are classified as Umbrepts, mesic. They are shallow to very deep soils formed on hillsides in materials weathered from acid igneous intrusive rock (Huntington and Akeson 1987). They generally lack significant subsoil development and rest on weathered or unweathered parent rock at depths ranging from 12 inches (30.5 centimeters) to more than 59 inches (150 centimeters). Soil moisture at temperature sensing sites varied greatly from site to site, and vertically in the soil profile. It has ranged from 4.0 to 26.4% moisture content (O.D. basis). Duff moisture content, which has had little to do with the amount of forest floor material consumed except in two cases, has ranged from 7.4 to 218% (O.D. basis). Higher duff moisture content merely slowed the combustion process.

Forest floor fuel loading equivalents (including woody material ≤ 1 inch [2.54 centimeter] diameter) at soil temperature measuring sites around giant sequoia have ranged from 38 to 137 tons per acre (85

Table 1. Mean and median maximum soil temperatures at five different soil depths measured on eight management burns where complete consumption of forest floor material occurred in Sequoia and Kings Canyon National Park, 1988–1995.

	Soil depths in inches (centimeters)				
	2 (5.1)	4 (10.2)	8 (20.3)	12 (30.5)	18 (45.7)
Giant Sequoia					
Number of observations	15	16	15	12	5
Range of maximum temperature:					
°F	114–588	102–310	88–260	70–237	81–153
°C	46–309	39–154	31–127	21–114	27–67
Mean maximum temperature:					
°F (standard deviation)	236 (126)	174 (61)	136 (44)	116 (44)	101 (30)
°C (standard deviation)	113 (70)	79 (34)	58 (25)	47 (25)	38 (16)
Median maximum temperature:					
°F	196	157	118	102	88
°C	91	70	48	39	31
Sugar Pine					
Number of observations	14	17	16	13	3
Range of maximum temperature:					
°F	152–695	114–362	107–231	81–217	69–87
°C	67–369	46–183	42–111	27–103	21–31
Mean maximum temperature:					
°F (standard deviation)	271 (148)	182 (64)	143 (34)	120 (34)	77 (9)
°C (standard deviation)	133 (82)	83 (35)	62 (19)	49 (19)	25 (5)
Median maximum temperature:					
°F	223	160	133	111	76
°C	106	71	56	44	24

to 306 megagrams per hectare) (mean of 72 tons per acre [161 megagrams per hectare]). Consumption was complete on 21 of 23 sites. At the two soil temperature sites having incomplete consumption, 45 of 55 tons per acre (101 of 123 tonnes per hectare) and 16 of 57 tons per acre (36 of 128 tonnes per hectare) of forest floor material were consumed.

Forest floor fuel loading equivalents (including woody material ≤ 1 inch [2.54 centimeters] diameter) at soil temperature measuring sites around sugar pine have ranged from 34 to 128 tons per acre (76 to 286 tonnes per hectare)(mean of 69 tons per acre [154 tonnes per hectare]). Consumption was complete on 24 of 26 sites. There were two sites where partial or no consumption occurred and these weights were not included in the mean or range of forest floor weights.

Soil Temperatures

Soil temperature probes at the 23 individual sites near giant sequoia trees were placed at six depths from

Table 2. Duration (hours) of soil temperatures exceeding four temperature limits at five different soil depths on eight management burns in Sequoia and Kings Canyon National Parks, 1988–1995.

	Giant sequoia					Sugar pine				
	Soil depth in inches (centimeters)					Soil depth in inches (centimeters)				
Temperature limit	2 (5.1) (n=15)	4 (10.2) (n=16)	8 (20.3) (n=15)	12 (30.5) (n=12)	18 (45.7) (n=5)	2 (5.1) (n=14)	4 (10.2) (n=17)	8 (20.3) (n=16)	12 (30.5) (n=13)	18 (30.5) (n=3)
>80°F (27°)										
average (hrs.)	88	90	84	81	63	88	90	85	77	16
range (hrs.)	37–120	36–120	8–150	0–151	31–94	44–92	31–114	43–111	6–106	0–49
median	100	104	100	99	73	51	91	90	82	0
>100°F (38°C)										
average (hrs.)	49	50	45	29	18	51	53	46	34	0
range (hrs.)	8–110	4–107	0–107	0–107	0–89	24–89	7–105	13–92	0–86	—
median	40	55	39	18	0	49	48	45	32	0
>120°F (49°C)										
average (hrs.)	31	30	22	16	17	35	33	23	12	0
range (hrs.)	0–108	0–104	0–104	0–104	0–83	12–81	0–79	0–62	0–51	—
median	21	21	0	0	0	31	31	22	0	0
>140°F (60°C)										
average (hrs.)	18	21	18	15	11	26	22	8	2	0
range (hrs.)	0–98	0–98	0–100	0–101	0–56	5–61	0–62	0–34	0–23	—
median	14	9	0	0	0	24	18	0	0	0

Table 3. Mean available soil nitrogen in milligrams nitrogen per kilogram of soil and standard deviations ( ) found over time in the top two inches (5.1 centimeters) of soil in giant sequoia-mixed conifer stands in Sequoia and Kings Canyon National Park, 1988–1995.

	Giant Sequoia		Sugar Pine	
Sample period	Ammonium-nitrogen	Nitrate-nitrogen	Ammonium-nitrogen	Nitrate-nitrogen
	milligrams nitrogen per kilogram of soil			
Before burn (n=8)	1.90 (1.28)	0.55 (0.39)	1.66 (0.86)	0.60 (0.56)
After burn (n=8)	68.63 (25.25)	0.51 (0.36)	62.71 (20.59)	0.46 (0.35)
1st spring after burn (n=7)	41.09 (13.64)	2.52 (2.48)	48.87 (12.75)	2.06 (2.41)
2nd spring after burn (n=7)	15.43 (10.63)	5.70 (2.55)	16.25 (8.01)	7.96 (3.53)
3rd spring after burn (n=5)	3.63 (2.14)	1.40 (1.19)	7.94 (7.01)	3.81 (2.58)
4th spring after burn (n = 5)	1.24 (0.25)	0.76 (0.58)	3.09 (2.05)	1.67 (1.40)
5th spring after burn (n=5)	1.54 (0.43)	0.36 (0.22)	1.60 (0.51)	0.57 (0.36)
6th spring after burn (n=4)	1.87 (1.10)	0.36 (0.22)	1.24 (0.51)	0.65 (0.57)
7th spring after burn (n=2)	1.12 (0.21)	0.22 (0.11)	1.52 (0.36)	0.72 (0.50)

the soil-duff interface down to 20 inches (50.8 centimeters). Because of the difficulty of inserting probes in the soil, standard depths were often not maintained. To most accurately represent the temperature changes in the soil profile, only the 21 sites having complete consumption are summarized here. The most complete records of maximum temperatures, were at 2-, 4-, 8-, 12-, and 18-inches (45.7-, 30.5-, 20.3-, 10.2-, and 5.1-centimeters) below the soil surface and are presented in Table 1. Average maximum temperatures at these levels were 236°F, 174°F, 136°F, 116°F, and 101°F (113°C, 79°C, 58°C, 47°C, and 38°C), respectively.

Twenty-six individual soil temperature probe sites were located near sugar pine trees in a like manner to that of giant sequoia. Again, the most complete temperature profiles were 2-, 4-, 8-, 12-, and 18-inches below the soil surface and are presented in Table 1. Average maximum temperatures at those depths for the 24 sites with complete consumption of the forest material were 271°F, 182°F, 143°F, 120°F, and 77°F (133°C, 83°C, 62°C, 49°C, and 25°C), respectively.

Coagulation (death) of protoplasm in plant tissue is generally in the range of 113° to 147°F (Baker 1929, Lorenz 1939, Nelson 1952, Kayll 1963). For purposes of our research we conservatively consider 150°F (66°C) to be an instantaneous lethal temperature for giant sequoia and sugar pine roots.

Instantaneous lethal temperatures (150°F [66°C]) occurred in the rooting zone down to 18 inches (45.7 centimeters) in one case, but more often occurred in the upper 4 inches (10.2 centimeters). Durations of temperatures over 80°F (27°C) are summarized in Table 2. Temperatures lower than the instantaneous lethal temperature but sustained for some period of time may be just as lethal to root systems. Since ambient soil temperatures are generally 50°F (10°C), soil temperatures of 80°F (27°C) or 90°F (32°C) for a few hours may be just as deadly as 150°F (66°C). A study is underway now to further define this time-temperature relationship to root mortality.

Cambium Temperatures

Until the new method was developed to insert cambium temperature probes in giant sequoia trees, meaningful temperature measurements were difficult to obtain. The average maximum cambium temperature during the eight fires investigated was 105°F (41°C) and ranged from 62°F (17°C) to 182°F (83°C). Forest floor fuel loadings around the base of giant sequoia trees is substantially greater than that found away from the trees, hence the difference from the soil temperatures shown previously. In the last two burns where measurements were most reliable, forest floor weight equivalents ranged from 46 to 240 tons per acre (103 to 537 tonnes per hectare). Maximum cambium temperatures associated with those loadings ranged from 69°F to 139°F (21°C to 59°C) with an average of 90°F (32°C) (n = 12). Much, but not nearly all, giant sequoia bark is burned away as the forest floor is consumed. Much of this burned band at the root collar was burned away by natural fires many years ago.

Average maximum cambium temperature measured in the cambium of the selected sugar pines was

Fig. 4. Root system of windthrown giant sequoia tree in Sequoia and Kings Canyon National Parks.

Fig. 5. Detail photo of root mass directly below a giant sequoia tree in Sequoia and Kings Canyon National Parks.

108°F (42°C) and ranged from 63°F (17°C) to 198°F (92°C). Forest floor weight equivalents around the base of these sugar pines ranged from 23 to 165 tons per acre (51 to 369 tonnes per hectare), which are quite different from weights found on the soil temperature sites. Temperatures measured were generally more reliable than in giant sequoia and 43 individual cambium sample points have been recorded.

Soil Nutrients

Inorganic soil ammonium-nitrogen levels are known to be low in most forest soils (Cochran 1979, Heidmann et al. 1979, Powers 1980). Giant sequoia-mixed conifer soils are no different. Because ammonium-nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N) are the two forms of nitrogen available to plants, our sampling is directed to study changes in their concentrations due to burning. Mean preburn ammonium concentrations in the upper levels of soil (0–2 inches [0–5.1 centimeters]) averaged 1.66 milligrams NH_4^+-N per kilogram of soil on sugar pine sites and 1.90 milligrams NH_4^+-N per kilogram of soil near giant sequoia. Immediately after burning when soils had cooled, the mean soil ammonium-nitrogen concentrations rose to 62.71 milligrams NH_4^+-N per kilogram of soil near sugar pines and 68.63 milligrams NH_4^+-N per kilogram of soil near giant sequoias (Table 3). Nitrate-nitrogen, in general, is not directly affected by fire and changes in nitrate-nitrogen concentrations do not appear until soil microorganisms begin converting ammonium to nitrate. Increases are generally seen the first or second spring after a fire and are shown in Table 3.

DISCUSSION AND CONCLUSIONS

Even though fire-induced soil and tree cambium temperature increases are adequate to damage root and cambium tissue during prescribed fires in unnaturally heavy fuels, mortality has not been observed in the giant sequoia trees over the 26-year burning history (personal communication, Larry Bancroft, National Park Service). None of the giant sequoia trees monitored for either soil nutrients or temperatures have died to date. High cambium temperatures are very intermittent around the base of the giant sequoia trees. This would allow deep roots extending from undamaged cambium areas to survive. Soil samples taken one or two years after the initial fire, have shown new roots are regenerated at concentrations that may be greater than before burn levels. This would be expected with the improved soil moisture relations and especially with the soil nitrogen surge that occurs from the fire. This is now being looked at more closely by going back to the previously burned areas where we have soil and tree cambium temperature data and determining the current amount of live root material. The root reserve is probably located directly under the bole, where soil heating does not take place. We have observed root systems of wind thrown trees in the park (Figures 4 and 5) and the root mass is substantial, especially when the basal area of such large trees is considered. Regrowth from this protected root reserve is probably responsible for the survival of giant sequoia. Mutch and Swetnam (1995) found that mean width of giant sequoia tree rings following a fire are significantly larger than growth rings of giant sequoia trees growing in areas not burned.

Sugar pine trees appear to be more susceptible to uniform cambium heating and root damage from soil heating. The 67% mortality of the sugar pine trees monitored for either nutrients or temperatures is suggestive of their inability to resist temperatures generated from burning these levels of natural forest floor fuel loadings.

The random mortality of sugar pine may be a price that the manager may have to pay in order to reintroduce fire back into this ecosystem. Observations in areas that were burned 10–15 years ago show regeneration of sugar pine and giant sequoia that does not appear in unburned areas. This negative effect appears to be short-lived and other benefits of the management decision to burn would appear to outweigh the cost of not burning. Also, techniques are now being developed to mitigate cambial heating as a way of moderating the total heat load on individual sugar pine trees.

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