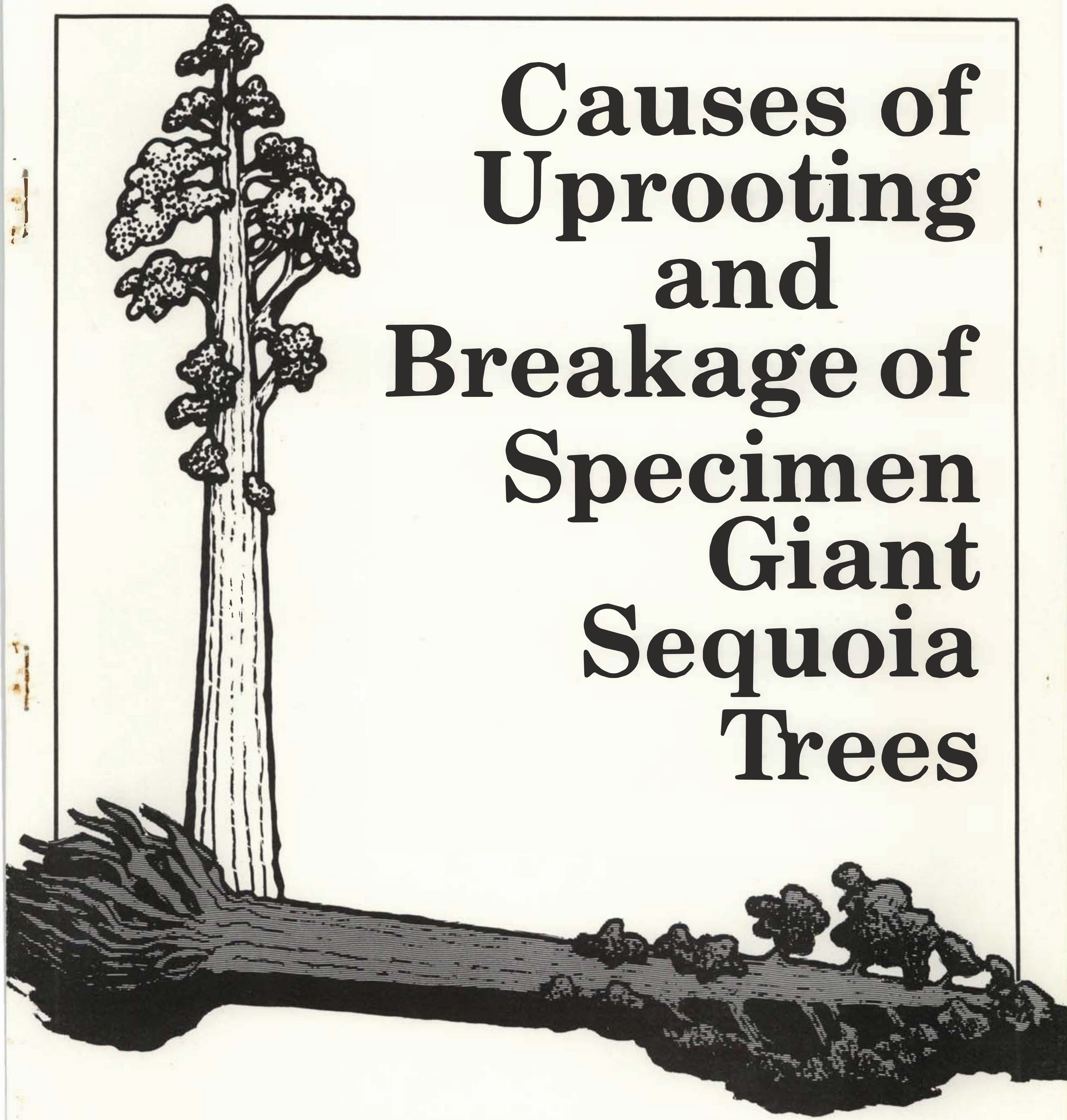
Causes of Uprooting and Breakage of Specimen Giant Sequoia Trees



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Causes of Uprooting and Breakage of Specimen Giant Sequoia Trees[1]

Abstract

A study of the causes of uprooting and stem failure in old-growth giant sequoia (*Sequoia gigantea* [Lindl.] Decne.) indicated many factors, depending upon the type of failure (by root, stem, or earth). Advanced decay and fire scars were the most frequently associated with failure. In 21 of 33 study trees, one-third or more of the roots were judged too decayed to provide support. Twenty-seven study trees possessed basal fire scars, and 26 fell toward the scarred side. Nine Basidiomycetes, including *Fomes annosus, Poria albipellucida, Poria incrassata*, and *Armillaria mellea*, were associated with decayed wood. Carpenter ants were found in or adjacent to the failure zone of nearly half of the study trees. Physical disturbances (e.g., roads, trails, streams) were associated with 22 tree failures, but their role in initiating failure requires further investigation.

Introduction

Giant sequoia (*Sequoia gigantea* [Lindl.] Decne.),[2] one of the earth's oldest and largest living organisms, may be one of the least understood. Many generalizations have been made about it, leading people to believe it is not subject to the same natural forces that affect other tree species.

Probably the most misleading generalization, since the tree's first recorded discovery by the Joseph Walker party, was by John Muir (1894) when he wrote: "I never saw a Bigtree [giant sequoia] that had died a natural death; barring accidents they seem to be immortal, being exempt from all diseases that afflict and kill other trees."

Hartesveldt (1962) perpetuated this concept, stating: "Sequoia's longevity and great size have been attributed by nearly all writers, popular and scientific, to its few insect and fungus parasites and the remarkable resistance of the older trees to damage or death by fire." He went on to say: "There is no record of an individual sequoia living in its natural range as having been killed by either fungus or insect attack."

This absence of reported mortality may be because few detailed studies of the effects of disease and insects on giant sequoia have been conducted until recently.

The impact of man on forests is becoming alarming. With nearly 4 million people per year visiting Yosemite and Sequoia-Kings Canyon National Park, considerable concern has been expressed by park managers, naturalists, and the public about the uprooting and stem breakage of giant sequoia trees in areas of high recreational use. The severity of the problem is shown in a case involving the death of an elderly woman in the Hazelwood area of Sequoia-Kings Canyon National Park. As she picnicked with friends, a giant sequoia fell, striking another tree which in turn fell and struck her. Several hours later another large, old-growth giant sequoia fell within the same area. At the time of the Hazelwood incidents, Jack Hickey, a National Park Service naturalist, suggested that carpenter ant excavation might be responsible for the failure of old-growth giant sequoia trees.

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[1] This paper is based on results presented in a Ph.D. dissertation submitted by Douglas D. Piirto to the Graduate Division of the University of California, Berkeley. W. Wayne Wilcox was chairman of the dissertation committee.

[2] The correct scientific name for giant sequoia is currently a subject for disagreement. The common name, giant sequoia, and the scientific name, *Sequoia gigantea*, will be used in this paper. Justification for this is detailed in Piirto (1977). The common name, coast redwood, will refer to *Sequoia sempervirens* (D. Don) Endl.

The Hazelwood case raised three important issues:

1. The potential hazard of falling giant sequoias to unsuspecting tourists.
2. The loss of giant sequoia trees that required centuries to grow.
3. The lack of sufficient information to describe the factors associated with tree failure of giant sequoia.

These three issues, along with the question generated by the Hickey hypothesis, were the impetus for determining the underlying causes of uprooting and stem breakage in giant sequoia trees.

Literature Review

Giant sequoia occupies approximately 75[3] mixed conifer grove communities (Rundel, 1972a) on the western slope of the Sierra Nevada. Its range is a narrow belt, 260 miles long, from Placer County through Tulare County, California (approximately between latitudes 36° and 39°N). Most of the groves occur at elevations between 4,500 and 7,000 feet. In contrast to coast redwood, giant sequoia grows in a colder and drier climate with the average annual precipitation between 45 and 60 inches, most of it snow. The temperatures to which giant sequoia is subjected occasionally drop to -12° F in winter and seldom exceed 100° F in summer.

Giant sequoia grows best on moist, deep, well-drained soils of pH 6. Seed germination and survival depend upon a seedbed of bare mineral soil. The density levels of giant sequoia and its associated brush and tree species (e.g. white fir, *Abies concolor* (Gord. & Glend.) Lindl.; sugar pine, *Pinus lambertiana* Dougl.; incense cedar, *Libocedrus decurrens* Torr.; ponderosa pine, *Pinus ponderosa* Laws.; and California black oak, *Quercus kelloggi* Newb.) have been influenced greatly by fire history. More specific details and pertinent citations regarding the silvics and ecology of giant sequoia can be found in Biswell, 1961; Schubert and Beetham, 1962; Fowells, 1965; Stark, 1968a, 1968b; Little, 1971; Rundel, 1971, 1972a, 1972b, 1973; Hartesveldt, *et al.* 1975; Kilgore, 1975; Kilgore and Taylor, 1979; Piirto, 1977; Bonnicksen and Stone, 1978; Harvey, *et al.* 1980; Parsons and DeBenedetti, 1979.

[3] The number of giant sequoia groves is listed differently by various authors.

Factors associated with failure of coniferous trees (e.g., uprooting, breakage, windthrow) (Persson, 1975) include: weather (wind, precipitation, temperature); season; topography; geographical situation; soil (type, depth, drainage); silviculture (species, spacing and density, age and height of stand, cleaning, thinning, clear felling, method of regeneration, degree of mechanization); decay and insects. Little is known about the role these and other factors (e.g., human disturbance, roads, fire, resource management policies) play in initiating tree failure of giant sequoia.

Several potentially dangerous forest pathogens (*Armillaria mellea* (Fr.) Quel.; *Fomes annosus* (Fr.) Cke.; and *Poria incrassata* (Berk. & Curt.) Burt.) and insects (termites, *Zootermopsis nevadensis*; carpenter ants, *Camponotus* sp.) have been associated with giant sequoia (DeLeon, 1952; USDA, 1960; Bega, 1964; Hepting, 1971; Piirto, Parmeter and Cobb, 1974; Piirto, Parmeter, and Wilcox, 1977).

Studies on wood properties and methods of detecting decay in giant sequoia have been made (Piirto, 1977; Piirto and Wilcox, 1977; Piirto and Wilcox, 1981). Little, however, is known about the relative impacts and distribution of these and other forest pests within the giant sequoia ecosystem, particularly with relation to mechanical failure of large old-growth giant sequoia trees.

Materials and Methods

Factors possibly responsible for tree failure in giant sequoia have been identified in our review of the literature and in Piirto (1977). Which of these actually played a role in the observed tree failures is, however, not known. Thirty-three fallen trees and their surrounding stands were surveyed with each factor in mind to determine those causally associated. Evaluating each was approached by:

1. Surveying all recent giant sequoia tree failures to detect similarities or trends indicative of factors associated with tree failure.
2. Evaluating the growth rate during the last two centuries of 10 recently fallen, old-growth, giant sequoias.
3. Isolating and identifying Basidiomycetes associated with visibly decayed sapwood and heartwood of recent giant sequoia tree failures.
4. Determining in laboratory tests the capacity of the isolated Basidiomycetes to decay wood.

5. Microscopically examining discolored and normal heartwood associated with advanced decay and carpenter ant galleries in fallen, old-growth, giant sequoia trees.

6. Determining whether carpenter ants vector decay fungi.

7. Determining whether carpenter ants prefer to excavate in decayed wood.

Field survey

Thirty-three recently fallen old-growth giant sequoia trees that failed within the last 10 to 15 years were examined for:

1. Presence of decay at the failure zone and in other portions of the tree.

2. Type and extent of decay at the failure zone (visual estimate). Where possible, photographs of it were made, the photographic image of the zone was cut out of a black and white print and weighed, the portion of the image representing decay was cut out, the remaining image was reweighed, and the percentage of decay calculated to confirm the visual estimates.

3. Evidence of wood decay fungi (mycelial fans, rhizomorphs or sporophores). The identities of sporophores were confirmed by Basidiomycete taxonomists.

4. Presence of carpenter ant galleries in the failure zone or in adjacent wood. The proportion of the failure zone containing galleries was assessed visually.

5. Presence and extent of fire scars.

6. Direction of fall with respect to the fire scar and slope.

7. Presence of such physical disturbances as roads, trails, and streams.

The 33 trees studied were located in such areas as Sequoia-Kings Canyon National Park, Yosemite National Park, Whitaker's Forest, Sierra National Forest, and Mountain Home State Forest. Their history and location are shown in Piirto (1977).

Growth rates

To determine whether a significant change in growth rate occurred before tree fall, which could indicate loss of health or vigor, a wedge was removed from the lower 20 feet of 10 trees above the butt swell. Depth of the wedge cut was approximately 1 foot. Measurements of the number of rings per inch were made on the wedges for the last 200 years of the tree's life. Comparisons were made between centuries and between 25-year intervals.

Basidiomycete fungi: Their decay capacity

Isolations were made to identify the fungi associated with the various types of decay visible in sapwood and heartwood of the fallen trees. Decayed wood was collected from 14 of the trees examined. Following aseptic laboratory procedures, two or three chips of wood (approximately 0.25 x 0.25 x 0.125 inches) were placed on plates containing potato dextrose agar and on plates containing water agar. The plates were examined periodically and representative fungi transferred to tubes containing potato-dextrose agar.

Soil-block tests in decay chambers, prepared according to ASTM Standard D-2017 (1974), were conducted to determine the capacity of the isolated Basidiomycetes and *Poria monticola* Murr. (from Madison 698) to decay sapwood and adjacent outer heartwood from the stem of a recently fallen giant sequoia. Test specimens were selected from the mid-stem of a single tree to assure unformity of sample material. Three sugar pine (*Pinus lambertiana* Dougl.) sapwood blocks were used as reference blocks for each fungus and 10 test blocks each of giant sequoia heartwood and sapwood were employed for each fungus. All test and reference blocks were conditioned to 12 percent equilibrium moisture content before initial and final weights were recorded. Because of the slow growth of some of the isolated fungi, the test was extended to 14 weeks rather than to 12 weeks as recommended by the Standard.

Microscopic examination of heartwood near carpenter ant galleries

In three of the six trees containing carpenter ant galleries in the failure zone, microscopic examinations were made of discolored wood and, where present, nondiscolored wood associated with the galleries. A sliding microtome was utilized to prepare radial, tangential, and cross sections at a thickness of 20 micrometers.

Carpenter ant-fungus interaction

Four trials were conducted to determine whether carpenter ants vector wood decay fungi and whether carpenter ants prefer to excavate in decayed wood. All ants were collected in Sequoia-Kings Canyon National Park.

Trial A involved collection of 80 ants (*Camponotus modoc*) from galleries associated with decayed wood of a recently fallen giant sequoia in the Hazelwood area of the park's Giant Grove. Isolations were made from the ants as follows:

1. Twenty dead ants were individually placed on 10 plates containing water agar and on 10 plates containing potato dextrose agar (PDA).

2. Forty dead ants were surface-sterilized in a Clorox solution for 10 minutes. Twenty of these were individually placed on 10 plates containing water agar and on 10 plates containing PDA. Twenty others were dissected into three regions (head, thorax, and abdomen) and then each group of three pieces was placed on plates containing water agar or PDA (10 plates per medium).

3. Twenty living ants were individually placed on 10 plates containing water agar and on 10 plates containing potato dextrose agar.

The plates were examined at regular intervals and representative fungi were placed in tubes containing PDA.

Trial B involved the use of freshly cut, debarked Monterey pine (*Pinus radiata* D. Don) discs (3¼-inch diameter, ⅜-inch thickness) as a selective medium for *Fomes annosus*. Fifty living ants (*Camponotus modoc*) were taken from a white fir stump (in the Round Meadow area of Giant Grove) showing evidence of *Fomes annosus* (sporophores, laminated-stringy rot) and then individually placed into plates containing moist filter paper and a Monterey pine disc. The discs were examined at regular intervals for development of conidiophores of *Fomes annosus*.

Two trials (**Trial C** and **Trial D**) were conducted to determine whether carpenter ants prefer to excavate in decayed rather than in sound wood. A plexiglas box (2.25 inches wide, 1.75 inches deep, and 8.5 inches long) served as the test chamber into which matched blocks (1 x 1 x ⅜ inches), one decayed and one nondecayed, and conditioned to an equilibrium moisture content (EMC) of 12 percent, were placed side by side across the width of the box; grooves in the sides, top and bottom of the box held the blocks in place (Figure 1). A small, tapered hole was made in the face at the bottom of each test block to encourage burrowing activity. The test blocks were alternately positioned on the right and on the left side of each test chamber.

The carpenter ants (*Camponotus modoc*) used in Trials C and D came from a nest in a park bench made of giant sequoia heartwood in the Round Meadow area of Giant Grove. Carpenter ant trails extended from the nest to nearby white fir and giant sequoia trees. Twenty carpenter ants from the nest were individually placed into the test chambers containing the sound and decayed test blocks. Ideally, the ant would begin burrowing into one of the two blocks to get to the other side of the box. The chambers were then taken to a nearby cabin where behavior was periodically observed for 48 hours. At the end of the 48 hours blocks were examined and the extent of excavation was evaluated. The two trials were organized as follows:

Trial C: Twenty decayed blocks were compared with 20 nondecayed blocks, all of which were of old-growth, giant sequoia, outer heartwood from one tree (Specimen R-1). Twenty-five decayed blocks were obtained from soil-block test chambers prepared essentially by the procedures outlined in ASTM Standard D-2017 (1974), except that the moisture content in the bottled soil was 140 percent of the moisture holding capacity and white fir feeder blocks were used. The 25 blocks were exposed to the decay fungus *Poria monticola* (from Madison 698) for 12 weeks. Five test blocks were used to evaluate weight loss. All blocks were conditioned to 12 percent equilibrium moisture content before exposure to the carpenter ants.

Trial D: Twenty decayed blocks were compared with 20 nondecayed blocks, all of which were of white fir (*Abies concolor* [Gord. & Glend.] Lindl.) sapwood from one tree. Twenty-five white fir decayed blocks were prepared following the same procedures outlined in Trial C. The white fir blocks were exposed to the decay fungus *Poria monticola* (from Madison 698) for 4 weeks. As in Trial C, five of the test blocks were used to evaluate weight loss and all blocks (decayed and nondecayed) were conditioned to 12 percent equilibrium moisture content before exposure to the carpenter ants.

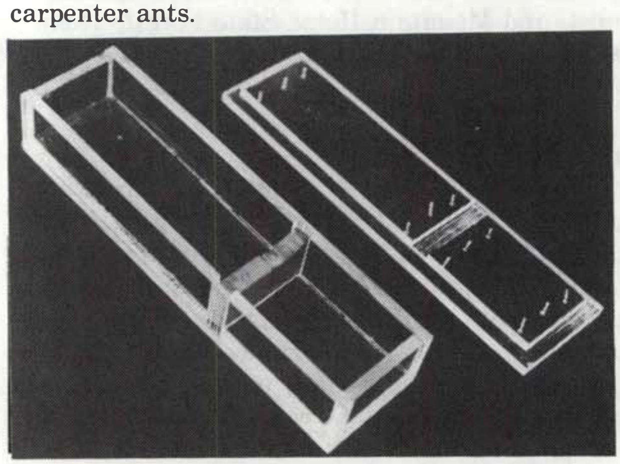

Figure 1. Carpenter ant excavation test chamber.

Results and Discussion

Field survey

Results of the field survey follow (for details see Table 1):

1. Three categories of tree failure were identified:

   Root failures (Figure 2): 22 trees (67 percent)
   Earth failures (Figure 3): 7 trees (21 percent)
   Stem failures (Figure 4): 4 trees (12 percent)

2. A stringy rot (Figures 2 and 5) was the most frequently encountered decay in the failure zone of 30 study trees (91 percent). A brown cubical rot was also seen in the failure zone of 15 (45 percent), but it usually was not as extensive as the stringy rot.

3. In 21 study trees (64 percent), one-third or more of the wood in the failure zone had advanced decay. Average extent of decayed wood in the failure zone of the 22 root failures was 53 percent, and in some cases as much as 80 percent of the root failure zone provided virtually no structural support. Average extent of decayed wood in the failure zone of the four stem failures was 29 percent. Extent of decay in roots of the seven earth failures could not be assessed visually because the roots were covered with soil.

4. Decay also occurred in other locations in the tree, besides in the failure zone (Table 1). Heartwood stringy rot, when present, was primarily restricted to the lower bole and butt of the tree, whereas sapwood stringy rot, when present, occurred in both the upper and lower parts of the stem. Heartwood cubical rot, when present, was observed in snag tops, broken upper crown branches, and in the tree's butt. Further research is needed to better characterize the within-tree ecological relationships of wood decay fungi for giant sequoia.

5. Carpenter ant galleries were found near the failure zone in 16 study trees (48 percent). However, only six of these trees (18 percent of the total) contained carpenter ant galleries in the actual failure zone (Figure 6).

6. Twenty-two (67 percent) of the study trees were exposed to one or more of the following physical disturbances: roads, 7 trees; trails, 9 trees; streams, 8 trees; road and trail, 1 tree; road and stream, 1 tree.

7. Seventeen study trees (52 percent) fell on level ground, 4 (12 percent) fell across slopes, 7 (21 percent) fell uphill, and 5 (15 percent) fell downhill.

8. Twenty-seven study trees (82 percent) had fire scars. Of these, 26 (96 percent of the fire scarred trees) fell toward the side bearing the largest fire scar.

9. A large volume of branch and wood debris was commonly associated with all 33 study trees, a potential fire hazard (Figure 7). Whereas this wood debris may make a beneficial contribution of organic matter to the soil, it may also increase the fire hazard, provide a breeding ground for forest insects and diseases, and impede regeneration.

The field survey defined factors associated with failure of giant sequoia, including root decay, soil disturbance, and fire scars. Continued research is needed, however, to verify and extend our understanding of the many factors and interrelationships involved.

The fact that a number of recent tree failures have occurred in the Redwood Mountain Grove area of Sequoia-Kings Canyon National Park is cause for concern. This area possesses a very dense understory of white fir, as do most other giant sequoia groves. Perhaps, with changes in stocking levels of associated trees and shrubs, a change in the microfloral population occurs. The amount of wood debris and litter associated with the now dense mixed conifer-giant sequoia forest at Redwood Mountain Grove might also be important in this relationship because of a possible effect on regeneration and on insect and microfloral populations.

Growth rates

From the data in Table 2 it was not possible to determine a characteristic growth pattern in old-growth giant sequoias during the 200 years preceding tree fall, primarily because of fluctuating growth rates. During the 25 years just before failure, six study trees demonstrated a slight to definite decrease in growth rate and four had a slight to definite increase in growth rate. Because two trees with decreased growth rate were earth failures—presumably less influenced by the condition of the tree than root failures—the data appear to be balanced between increasing and decreasing growth rate before failure. The eight root failures contained substantial amounts of decay in the trees' roots and lower butt. These data suggest that such long-term stress conditions as attacks by decay fungi and insects or such physical disturbances as roads, trails, and streams may not have easily discernible effects on growth rate patterns when rings per inch measurements are the only criteria evaluated. This result can be explained on the basis of the many other variables (e.g., site characteristics, climatic conditions, tree age) which affect growth patterns of giant sequoias.

Thus, studies (e.g., Hartesveldt, 1962) utilizing growth characteristics, such as rings per inch of old-growth giant sequoia, must be viewed judiciously; the tree may well be under stress without demonstrating a noticeable or predictable change in the rings per inch measurements.

Basidiomycete fungi

Thirty groups of isolates, nine of them Basidiomycetes, were recognized from the total number of isolates obtained from decayed giant sequoia wood. Of the nine, five have the reputation or potential for being very serious forest pests: *Fomes annosus, Poria albipellucida, Poria incrassata, Armillaria mellea* and *Polyporus schweinitzii*. Distribution of these forest pests within the giant sequoia ecosystem and their relationships to forest composition and succession require further study. Synonymy, cultural details, and other specific information on the nine Basidiomycetes are given in Pirto (1977).

The fungi isolated cannot be viewed as indicative of all the fungi associated with decay in giant sequoia sapwood and heartwood nor can they be accurately interpreted on a quantitative basis, because of the subjective manner of isolation. Quantitative interpretation of the isolations of decay fungi is made difficult by contamination, inability of some decay fungi to compete with other fungi in culture, sampling methods, the largely mycelial nature of decay fungi in wood, autolysis, fungal succession and death, as well as other problems. Consequently, data concerning the fungi associated with decay of giant sequoia sapwood and heartwood must be considered qualitative only.

TABLE 1. Field Survey Data on 33 Recently Fallen Old-Growth Giant Sequoia Trees

Characteristic	Failure classes*			Total number of study trees
	A	B	C	
Total number of study trees	22	7	4	33
Number of trees containing root decay				
Stringy rot	22	4	—	26
Cubical rot	11	1	—	12
Number of trees containing stem decay				
Stringy rot	16	7	4	27
Cubical rot	12	3	3	18
Number of trees showing evidence (sporophores, rhizomorphs, cultural characters) of:				
Fomes annosus	7	5	0	12
Poria albipellucida	2	2	0	4
Armillaria mellea	2	0	1	3
Naematoloma capnoides	2	1	0	3
Poria incrassata	2	0	0	2
Stereum hirsutum	1	1	0	2
Polyporus schweinitzii	0	1	0	1
Polyporus versicolor	1	0	0	1
Unknown No. 23B	1	0	0	1
Number of trees in which one-third or more of the failure zone was no longer structurally functional as a result of decay, fire, etc.	19	0	2	21
Number of trees containing carpenter ant galleries in the failure zone	3	0	3	6
Number of trees containing carpenter ant galleries in wood adjacent to failure zone	10	2	4	16
Number of trees exposed to the following physical disturbances:†				
Road	5	0	2	7
Trail	6	2	1	9
Stream	6	2	0	8
Number of trees falling:				
On level ground	9	4	4	17
Across slope	4	0	0	4
Uphill	6	1	0	7
Downhill	3	2	0	5
Presence of fire scar	18	5	4	27
Fell on fire scar	18	4	4	26

*Failure classes:
A: root failure
B: earth failure (root system covered with soil)
C: stem failure
†Within presumed root system.

Figure 2. Root failure (Specimen R-4) in the Redwood Mountain Grove area of the Sequoia-Kings Canyon National Park. Note the extensive fire scar and the advanced decay (stringy rot) in 66 percent of the root system. Tree fell in winter 1968-1969. Approximate dimensions of root system: Height, 14 feet; width, 25 feet.

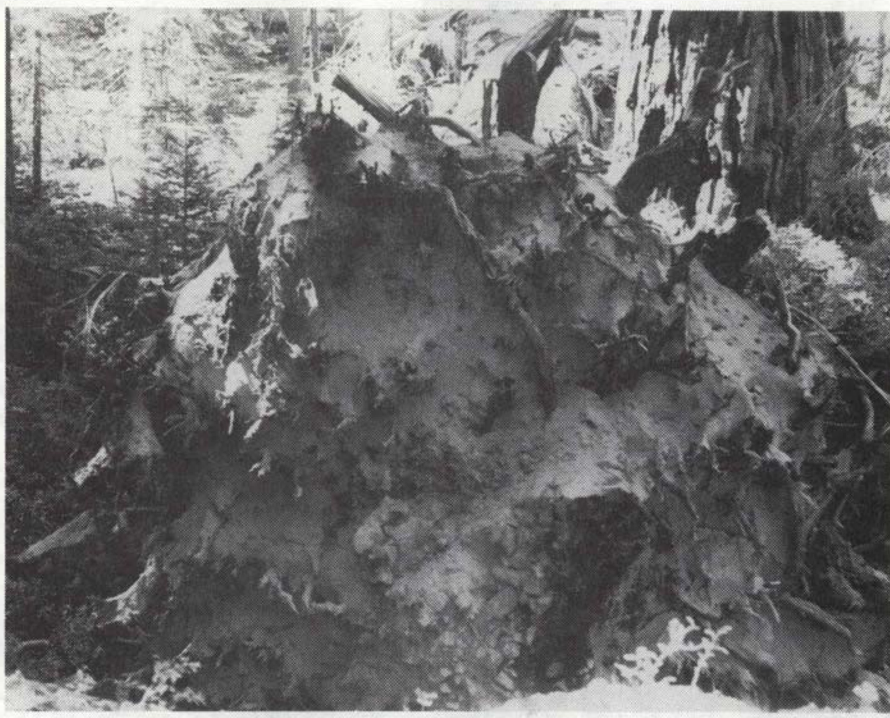

Figure 3. Earth failure (Specimen R-3) in the Redwood Mountain Grove area. Stream erosion of the soil beneath the root system is presumed to be the major factor associated with tree failure. However, decay (stringy rot) was observed in some supporting roots, suggesting that a combination of factors may have been involved. Sporophores of the decay fungus *Fomes annosus* were observed growing from decayed stem sapwood. Tree fell in winter 1968-1969. Approximate dimensions of root system: Height, 20 feet; width, 28 feet.

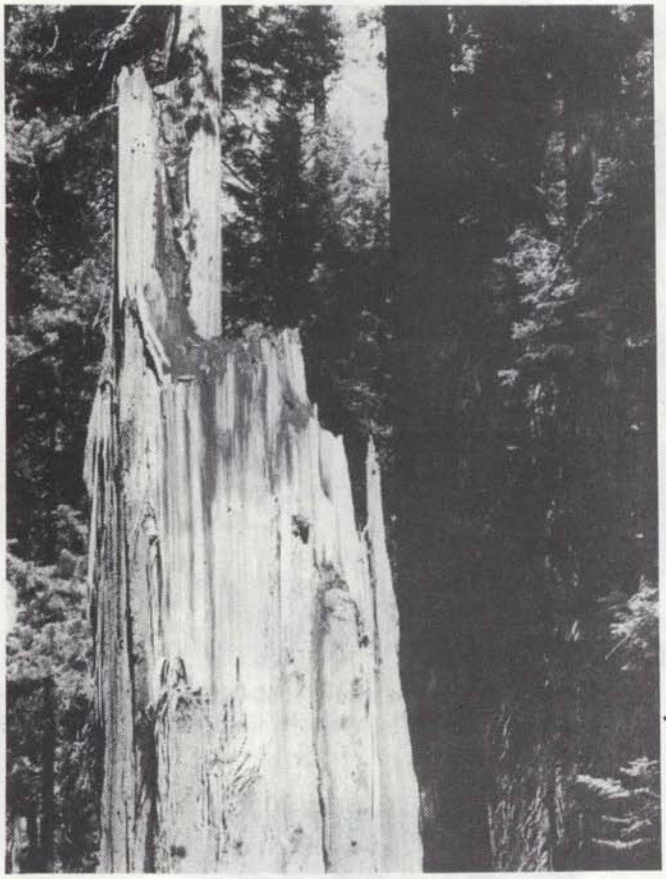

Figure 4. Stem failure (Specimen L-1) in the Lost Grove area. Carpenter ant galleries and a stringy rot were observed in the failure zone. Tree fell in early 1970s.

Figure 5. Sectional view of a root from a root failure (Specimen W-4) in Whitaker's Forest adjacent to Sequoia-Kings Canyon National Park. Note the advanced decay (stringy rot) on the left side of the root. *Poria incrassata* was isolated from the decayed wood. Extensive fire scarring also occurred on the left side of the root. Tree fell in winter 1974-1975. Approximate dimensions: Height, 2.5 feet; width, 1.5 feet.

Figure 6. Carpenter ant galleries observed in numerous locations throughout a stem failure (Specimen H-1) in the Hazelwood Grove area. Tree fell in August, 1969. Photograph shows a cross-sectional view of part of the lower stem. Approximate dimensions: Height, 2 feet; width, 3 feet.

Figure 7. Wood debris associated with fallen giant sequoia trees (Specimens R-2, R-3) in the Redwood Mountain Grove area. Tree fell in winter 1968-1969.

TABLE 2. Comparative Growth Rate Data for 10 Recently Fallen, Old-Growth Giant Sequoia Trees.

		Rings per inch									
		Time period (100-year intervals from the cambium)		Time period (25-year intervals from the cambium)							
Tree no.	Failure type*	0-100	101-200	0-25	26-50	51-75	76-100	101-125	126-150	151-175	176-200
R-1	A	72.5	62.1	83.3	75.8	67.6	64.1	61.0	58.1	61.0	71.4
R-2	B	63.7	71.9	69.4	59.5	65.8	78.1	80.6	73.5	65.8	71.4
R-3	B	37.4	45.7	52.1	39.1	33.8	32.5	41.0	46.3	55.6	42.4
R-4	A	23.9	44.8	32.0	26.3	25.8	20.7	30.1	43.9	59.5	56.8
M-1	A	52.4	43.5	56.8	61.0	52.1	42.4	56.8	43.9	33.8	45.4
Mck-1	A	38.9	27.3	53.2	49.0	35.7	29.8	31.2	19.6	33.8	29.1
MH-3	A	41.3	61.3	32.9	51.0	33.8	58.1	61.0	80.6	43.9	75.8
C-1	A	39.2	30.0	56.8	33.8	38.5	35.7	36.2	33.3	26.0	26.6
S-1	A	34.7	39.2	24.3	28.4	54.3	54.3	56.8	33.3	34.2	39.1
W-3	A	30.0	26.4	36.2	38.5	26.0	24.8	23.6	29.1	25.5	28.4

*Failure classes:
A: root failure
B: earth failure (root system covered with soil)

TABLE 3. Decay Capacity Test Data of Isolated Basidiomycete Fungi.

	Weight loss (%)*					
	Giant sequoia sapwood		Giant sequoia heartwood		Sugar pine reference blocks	
Fungus	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.
Armillaria mellea	2.03	0.55	3.92	2.32	0.58	0.21
Fomes annosus	4.41	2.82	4.16	2.23	1.84	0.37
Naematoloma capnoides	0.13	0.27	4.31	2.99	0.00	0.00
Polyporus versicolor	37.52	18.84	2.12	1.64	40.07	3.30
Poria albipellucida†						
6	14.78	1.07	6.57	3.48	26.41	1.16
26	28.01	5.13	6.37	1.29	19.31	18.27
100	17.53	3.94	5.39	2.68	16.64	3.25
Poria incrassata	44.12	4.12	8.64	3.89	58.92	0.63
Stereum hirsutum	22.90	3.99	8.49	1.64	12.41	0.43
Unknown No. 23B	0.13	0.28	4.97	1.54	0.00	0.00
Poria monticola	56.75	0.65	14.03	8.63	68.84	1.03
Control (non-inoculated)	0.90	0.45	6.40	2.92	0.22	0.38

*Where
$\bar{X}$ = mean weight loss
S.D. = standard deviation
†Three sources: Nos. 6 and 26 were isolated from two different fallen giant sequoia trees. No. 100 was isolated from discolored wood in coast redwood.

Data from the decay capacity test (Table 3) must also be carefully interpreted because some fungi do not cause appreciable decay in culture, yet in the forest they are principal wood destroyers. *Polyporus versicolor, Poria albipellucida, Stereum hirsutum*, and *Poria incrassata* were the most vigorous sapwood decomposers in a soil-block test of those fungi isolated from giant sequoia. *Stereum hirsutum* and *Poria incrassata* showed, in addition, a limited capability of decaying giant sequoia heartwood. Yet, advanced decay was observed in the field in heartwood of the roots and lower stems of almost all of the 33 study trees. Special conditions not present in laboratory tests may be required by Basidiomycetes to cause such appreciable decay. Such conditions can include: microorganism associations, leaching of extractives, changes in extractive toxicity upon removal of wood from the tree, and/or variability in heartwood decay resistance between and within giant sequoia trees.

Microscopic examination of heartwood near carpenter ant galleries

Microscopic examinations revealed bore holes, cell wall thinning, and hyphae possessing clamp connections in discolored wood associated with carpenter ant galleries. It was estimated from microscopical characteristics (Wilcox, 1968) that the discolored wood was in an early to moderate stage of decay (Figure 8), suggesting that a decrease in strength could be expected. Subsequent toughness tests, however, revealed no noticeable strength loss of discolored wood (Piirto, 1977). Microscopic examination of nondiscolored wood adjacent to carpenter ant galleries revealed no evidence of decay or stain fungi.

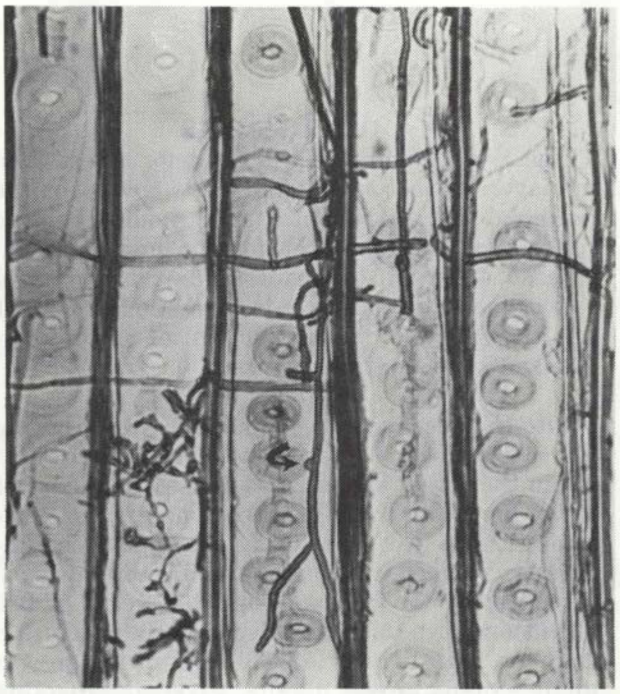

Figure 8. Early to moderate stage of decay (estimated 15 to 25 percent weight loss) in discolored giant sequoia heartwood associated with carpenter ant galleries from the failure zone of a stem failure (Specimen L-1) in the Lost Grove area. Note hyphae, one of which has a clamp connection (→). (Magnification 320 X)

Carpenter ant-fungus interaction

In **Trial A**, where isolations were attempted from carpenter ants, several nonhymenomycete fungi (e.g., *Penicillium* Link and *Paecilomyces* Bainier) were observed. However, no Basidiomycetes were isolated.

In **Trial B**, where living carpenter ants were placed on Monterey pine discs, no evidence of *Fomes annosus* developed.

Data of Trials A and B suggest that these carpenter ants did not vector wood decay fungi. It is possible, however, that formic acid and other substances secreted by the ant through handling may have affected the outcome of these two trials or, possibly, the experimental methods employed were not satisfactory. Consequently, additional studies are recommended to determine more precisely the ability of carpenter ants to vector decay fungi.

In **Trial C**, using decayed and nondecayed old-growth giant sequoia outer heartwood, successful results (evidence of excavation) were obtained in 11 of the 20 test chambers. Excavation, ranging from slight to heavy, was observed only in the decayed giant sequoia heartwood blocks. The amount of decay (weight loss) in the giant sequoia heartwood blocks, as determined from matched blocks, was 33 percent.

In **Trial D**, using decayed and nondecayed white fir sapwood, successful results (evidence of excavation) were obtained in 14 of the 20 test chambers. Excavation was observed only in the decayed white fir blocks. Excavation, as in Trial C, ranged from slight to heavy. The amount of decay (weight loss) in the white fir sapwood blocks, as determined from matched blocks, was 50 percent.

Decayed giant sequoia heartwood blocks in Trial C were generally more heavily excavated than decayed white fir sapwood blocks in Trial D, even though the former were generally less decayed. In both Trial C and Trial D, very little evidence of excavation was found on control (sound) blocks. While definite shortcomings are evident in this test method, results suggest that carpenter ants prefer to excavate decayed or softened wood rather than sound wood of the same species. This agrees with field observations of frequent association between decayed wood and carpenter ant galleries and confirms previous reports that carpenter ants prefer decayed or softened wood for nest excavation (Kangas, 1946; Hölldobler, 1962; Graham and Knight, 1965; Sanders, 1964).

Results of Trials C and D also suggest that a range in excavation activity—from none to heavy—exists among carpenter ants. Increasing the sample size and possibly increasing the test's duration might improve results. Results of Trials C and D support the hypothesis that trees containing a significant amount of decay in the roots and butt may be selected by carpenter ants for nest excavation. Additional research is required to define this relationship more carefully.

Summary

Giant sequoia trees are subject to the same natural forces as other tree species. Field studies show that many factors may be involved in tree failure, depending upon the type of failure. Advanced decay and fire scars were, however, the most frequently observed and most significant factors associated with tree failure in the study. In 21 of the 33 study trees (64 percent) and in 19 of the 22 root failure trees (86 percent), one-third or more of the failure zone was not structurally functional because of advanced decay. Of the 27 trees containing fire scars, 26 fell toward the scarred side. Nine Basidiomycetes (*Armillaria mellea, Fomes annosus, Naematoloma capnoides, Polyporus schweinitzii, Polyporus versicolor, Poria albipellucida, Poria incrassata, Stereum hirsutum* and one unknown) were isolated from decayed giant sequoia wood; several of them have the reputation or potential for being very serious forest pests.

Carpenter ant galleries were found in or near the failure zone in 16 study trees: only six of these, however, contained carpenter ant galleries in the immediate failure zone. Microscopic examination of discolored wood associated with carpenter ant galleries revealed an early to moderate stage of decay. These studies indicate that carpenter ants are not solely responsible for tree failure. Attempts to isolate decay fungi from carpenter ants were not successful and, therefore, it is not yet clear whether carpenter ants play any role in vectoring decay fungi or in facilitating their spread within wood. Exploratory tests demonstrated a preference by carpenter ants for excavating decayed wood, substantiating field observations and previous reports. A range in excavation activity was noted. Both decay and carpenter ant galleries were frequently associated with fire scars. Although such physical disturbances as roads, trails, and streams were associated with 22 study trees, their role in initiating premature failure of giant sequoia trees requires further inquiry. The fact that large portions of the root system and butt have been found to be no longer structurally functional suggests that trails, roads, and similar improvements should be kept away from giant sequoias as much as possible. Such improvements may result in damage to roots and the lower bole, allowing fungi to enter and affecting water drainage.

It was shown that measurement of changes in rate of stem growth in old-growth giant sequoia may not be appropriate for assessing the long-term effects of stress, such as attack by fungi and insects, or of physical disturbances; at least, they had no apparent relationship to tree failure.

Conclusions

These results point to the need for forest land managers to become increasingly aware of the financial and detrimental effects of pathogenic fungi and insects on the forest community. Increased attention to understanding the natural role of these organisms in the forest environment and the influence of man's activities on these organisms must continue to occur.

White fir trees have the reputation of harboring many destructive organisms. Control of fire has led to the establishment of a dense understory of white fir within these giant sequoia groves. Reintroduction of fire, alone, may not remove the understory because of the size and fire tolerance attained by these trees through 100 years of fire exclusion. These facts have led us to the conclusion that the high density of white fir in old-growth giant sequoia groves may be adversely affecting the survival of these trees. Therefore, we feel that silvicultural management and continued research on silvicultural strategies (e.g. thinning and/or direct removal of dense white fir understories, in combination with prescribed fire) may be required to sustain giant sequoia groves.

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