RELATIONSHIPS BETWEEN *PHYTOPHTHORA RAMORUM* CANKER (SUDDEN OAK DEATH) AND FAILURE POTENTIAL IN COAST LIVE OAK

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Acknowledgements

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Summary

We catalogued failures in coast live oak (*Quercus agrifolia*) in natural stands at six locations in Marin County, California. *Phytophthora ramorum* canker (sudden oak death) was present at relatively high levels in these stands. We noted characteristics of each failure; estimated the date range in which the failure occurred; evaluated the condition of the tree with respect to *P. ramorum* infection, colonization by *Hypoxylon thouarsianum* and other decay fungi, beetle boring, and tree defects; and noted stand characteristics in the immediate vicinity of the failure. Nonfailed trees in the stand were used as a control population to which failed trees were compared. Results from natural woodlands were compared to coast live oak failures recorded in the California Tree Failure Report Program (CTFRP) database. Failures recorded in the CTFRP database date back as far as 1987 and occurred primarily in urban trees rather than in natural stands.

Stands of coast live oak that have been impacted by *P. ramorum* canker show rates of tree failure that are higher than recent historical failure rates. Among trees that failed between about July 2001 and December 2002, 83% showed symptoms of *P. ramorum* infection. Branch, scaffold, bole, and root crown failures showed a strong association with advanced symptoms of *P. ramorum* canker. By definition, advanced or late symptoms of *P. ramorum* canker include evidence of wood degradation by *H. thouarsianum* and/or various wood boring beetles. Early *P. ramorum* canker symptoms, in which the only sign of infection is bleeding cankers, were not associated with an increased likelihood of failure.

Bole failures were the most common type of failure in these *P. ramorum*-affected woodlands. For the years 1992 through 1996, we estimated that bole failures occurred in about 0.5% of the trees each year. The incidence of bole failures increased to 5% per year for the period from mid-2001 through the end of 2002. Among recent failures (2001-2002), 39% of the bole failures and 30% of the scaffold failures occurred in live stems. The majority of observed root and root crown failures also occurred in live trees. Root failures were only observed in 4% of the failed trees in this study. In contrast, root failures are the most common failure type reported in the CTFRP database, making up 39% of reported failures.

Wood decay was the most consistent and important factor influencing failure potential. Decay was present and rated as a contributing factor in almost all failures. Fruiting bodies of *H. thouarsianum* and other wood decay fungi, decay columns, and canker rot symptoms were significantly more common among failures than among nonfailed controls. Also, several variables related to decay were highly significant in both recursive partition and multivariate logistic regression models. Beetle boring was also significantly more common among failures than among nonfailed trees. Other factors associated with increased failure potential include overtopping of the tree canopy, local alteration of the stand canopy due to dead or failed trees, multiple trunks, multiple branches arising from the same point, and asymmetric canopy shape. Failures in live and dead trees were largely influenced by the same factors.

Based on our results, we present a set of preliminary guidelines for evaluating failure potential of coast live oak in woodlands affected by *P. ramorum*. The most important risk factors in these guidelines are factors related to the amount of decay present in the tree.

INTRODUCTION

Anecdotal reports have suggested that coast live oaks (*Quercus agrifolia*) are more likely to fail if they have been infected with *Phytophthora ramorum*. Concern over failure potential of *P. ramorum*-infected trees has led to removal of live, symptomatic trees in China Camp State Park and other areas. Better information about the relationship between *P. ramorum* canker and failure potential is needed to determine whether such actions are necessary or effective for reducing tree failure hazard.

Dead oak trees have an inherently high risk of failure. Thus, *P. ramorum* infections that result in tree mortality will, by definition, increase tree failure potential. However, for some wildland management purposes, it is useful to know whether trees killed as a result of *P. ramorum* tend to fail more rapidly or in different ways than trees that have been killed by other agents. Furthermore, coast live oaks with *P. ramorum* canker symptoms can survive for several to many years after infection (Swiecki and Bernhardt 2003). In order to decide when and if a symptomatic tree should be removed, we need to know whether live, symptomatic trees have an elevated likelihood of failure.

It appears unlikely that the presence of *P. ramorum* cankers alone would increase the failure potential of infected trees. *P. ramorum* cankers primarily affect the bark, cambium, and some of the outer sapwood (Rizzo et al 2002). Preliminary data released by the UC Forest Products Laboratory (Shelly 2002) indicate that *P. ramorum* does not directly cause significant losses in wood density. However, wood decay fungi that are associated with *P. ramorum* cankers, such as *Hypoxylon thouarsianum,* do significantly reduce wood density and strength and may increase the likelihood of failure. Although beetles, especially ambrosia beetles, are often associated with decay in declining *P. ramorum*-infected trees, previous studies have not addressed whether beetle boring contributes meaningfully to failure potential.

High levels of decay associated with various native wood decay fungi exist in many coast live oak and California black oak (*Q. kelloggii*) stands (Swiecki and Bernhardt 2001a). Such stands may have relatively high failure rates in the absence of *P. ramorum* cankers. In these stands, *P. ramorum* and associated wood decay fungi such as *H. thouarsianum* could interact synergistically with existing wood decay, giving rise to elevated rates of tree failure or different patterns of tree failure. Hence, failure potential in oak stands affected by *P. ramorum* may vary between sites as a function of the complex of wood decay fungi present.

This report presents the results of a retrospective study on tree failure in coast live oak woodlands affected by *P. ramorum*. (i.e., this study looks at failures which occurred before the study was initiated). Our objectives were to quantify levels of failure in these stands and determine how various tree and stand factors are related to failure potential. Factors under study included *P. ramorum* cankers, colonization by *H. thouarsianum* and other decay fungi, beetle boring, tree defects, and stand characteristics. Failure data collected on wildland trees in this study were compared with failure records in the California Tree Failure Report Program (CTFRP) database. Failures recorded in the CTFRP database date back as far as 1987 and occurred primarily in urban trees rather than in natural stands. In addition, decay fungi in wood samples collected from failed trees in this study are being identified via molecular techniques as part of a related study conducted by Matteo Garbelotto and his associates at U. C. Berkeley.

METHODS

Study site selection

To obtain an adequate sample size for this study, we needed to locate areas where both *P. ramorum* infection and failures of coast live oak (*Quercus agrifolia*) were common. We were able to accomplish this by surveying the area around permanent survey plots that we had established in September 2000 as part of a related study (Swiecki and Bernhardt 2001b, 2002a,b). We have visited these areas annually beginning in September 2000 and already had observations on overall disease levels and the age of some recent failures in the areas. We selected six of these locations (Table 1) for study, all of which are located in Marin County, California. Location numbers used in this study are nonsequential because they are the same as those used in our other study (Swiecki and Bernhardt 2001b, 2002a,b).

Table 1. Locations of study areas.

Location number	Location	Approximate latitude and longitude
2	Marin Municipal Water District lands - Pumpkin Ridge south	37.9527 N 122.5949 W
3	Marin Municipal Water District lands - Pumpkin Ridge north	37.9599 N 122.5989 W
5	China Camp SP - Miwok Meadows area	38.0044 N 122.4848 W
6	China Camp SP - SE Buckeye Point area	38.0044 N 122.4768W
8	Lucas Valley (Private land)	38.0432 N 122.5996 W
11	Marin County Open Space land, Novato	38.0988 N 122.6273 W

Survey design

At each location we surveyed a wide area around the pre-existing plots and catalogued all failures of coast live oak and California black oak that appeared to have occurred within the past 10 years. Field data were collected over a period of about six weeks between late October and early December 2002, with final observations made at all locations in December 2002. Although we noted the presence of failures greater than 10 cm in diameter, we established a minimum size of 20 cm diameter for branch and scaffold failures and 15 cm DBH for bole, root crown, and root failures for detailed data collection and analysis. After cataloging all failures, we made a complete count of all coast live oak and California black oak trees with DBH of 10 cm or more within each study area. Boundaries of the surveyed areas were determined from GPS readings and aerial imagery of the sites. We used ArcView® GIS software to construct polygons of the study sites for calculating area and to plot the location of failures.

Variables assessed

We collected data on all coast live oak and California black oak trees within the study areas, but the level of detail and number of variables measured varied between subsets of the trees (Table 2). At each location, we first scored a basic set of information on all observed failures. We recorded GPS coordinates of observed failures using a Garmin GPS76 receiver equipped with an external antenna mounted on a telescoping pole. Where satellite coverage was available, coordinates were corrected using real-time WAAS differential correction (nominal 1-3 m positional error). GPS coordinates were used to help relocate trees that were selected for more detailed data collection for the case-control portion of the study.

Cases were 106 coast live oak trees with recent failures (occurring within about 1.5 years of the survey date) that exceeded the minimum size thresholds noted above. Due to time constraints, not all recent failures at all locations could be rated as cases. The number of cases rated per location ranged from 11 to 25. We attempted to ensure that cases were spatially distributed throughout the study areas to the degree possible and that most of the variables of interest (Table 2) could actually be observed. Other than these two considerations, cases were selected without bias from candidate failures. Secondary failures (failures caused by the impact of the failure of an adjacent tree) were not selected as cases.

Controls were 170 nonfailed coast live oaks within the sampled stands where the failures were located. The number of controls rated per location ranged from 22 to 37. We sampled both near controls, i.e., the nonfailed tree closest to a given failure, and far controls (nonfailed trees located away from failures). Overall, 103 controls were located within 10 m of a failed tree and 71 were more than 10 m from a failure. Far controls were included to ensure that variation in site factors (e.g., slope, aspect) was not constrained, since such factors tend to be similar among trees that are near to each other. Both types of controls were sampled without bias and were not matched to cases with respect to tree form or other characteristics. This allowed us to investigate a wide variety of tree and site factors as potential explanatory variables in the statistical models. Data collected on controls are described in Table 2. GPS positions were also recorded for controls.

For 154 other failures within the study areas that had occurred within the past 10 years and exceeded the minimum size thresholds, we evaluated a subset of the case data variables (Table 2). These failures included 141 coast live oaks and 13 California black oaks. For a small number of trees with failures (24 coast live oaks and 5 California black oaks) only a few variables were scored (species, stem count, failure type, failure date, failure size class) and coordinates were not recorded. These 29 trees are either older (>1.5 years) and/or relatively small-diameter failures that were located during the complete count of trees within the study locations.

We estimated failure dates for failures scored in the study area using a variety of indicators including the amount of oxidation and weathering of the broken wood surface, the condition of foliage, if any, degradation and loss of fine twigs, the amount and type of debris that had accumulated on exposed surfaces, and knowledge of recent failure dates based on previous visits to the sites. In addition, for relatively recent failures, we chipped into the bark of the failed part to qualitatively assess the amount of moisture remaining in the wood.

For all recent failures and some older ones, we evaluated whether the failed part was live or dead at the time of failure. This was generally obvious for trees that had failed within the prior 1 to 2 months. For somewhat older failures (up to about 2 years old), we inferred the status at the time of failure from factors such as the degree of leaf retention and orientation of dead leaves, evidence of post-failure wilting of leaves and stems, sunburning of large stems (which commonly occurs after failures of live stems), moisture level in the wood, and the pattern of breakage on impact. In the case of some older root failures, trees had remained live after failure, so the status at the time of failure was not in question.

Factors related to failure, including decay and beetle boring, were rated by close inspection of exposed wood surfaces at the point of failure. For controls, we estimated amounts of beetle boring and decay and the extent of cavities based on symptoms and signs that were visible from the outside of the tree. Consequently, ratings for decay, beetle boring, and cavities in controls may underestimate actual levels of these factors, especially in trees which lacked external evidence of these factors.

We noted the presence of various defects associated with failure potential in both control and failed trees (Table 2). The list of defects is based on that used in the CTFRP tree failure report form

(Edberg et al 1993). For case trees, we also noted whether any given defect appeared to be a contributing factor to the observed failure.

Table 2. Variables rated for trees in the study. Cases are trees with recent failures (previous 1.5 years) that exceed size thresholds (20 cm for branch/scaffold failures, 15 cm DBH for all other failures). Controls are nonfailed trees. Tree denoted "others" are additional observed failures for which a reduced set of variables were recorded.

Variable	Definition and notes	Rated for:	Levels
Site / stand variables			
Ground slope	Slope (percent) in vicinity of tree measured with a clinometer	cases controls	Continuous
Ground aspect	Slope direction (degrees), measured with a compass	cases controls	Continuous, 0-359º; the cosine of the angle in radians was used for analysis
Exposure to wind	Percent of tree canopy edge exposed to wind through an unobstructed gap of at least 10 m	cases controls	(0) No significant exposure (1) Up to 25% (2) 26-50% (3) 51-75% (4) >75%
Maximum length of wind run	Estimate of the maximum length of unobstructed wind run leading to exposed canopy side(s)	cases controls	(1) 10-50 m (2) >50 m
Wind exposure direction	Direction to major wind exposure, measured with a compass	cases controls	45º compass directions (N, NW, W, SW, etc.)
Tree height in canopy	Height of tree relative to surrounding trees in immediate neighborhood	cases controls	(1) Above: taller than surrounding trees (2) Average: similar to surrounding trees (3) Below: shorter than surrounding trees
Sky-exposed canopy	Percent of canopy projection area with unobstructed access to direct overhead sunlight.	cases controls	pretransformed 0-6 scale[a]
Altered neighborhood	Portion of stand immediately adjacent to tree (within about 2-3 canopy widths) has been altered within the past 5 years due to mortality and/or tree failure.	cases controls	(0) no (1) yes
Neighborhood alteration type	For trees in altered neighborhoods, we noted the type and position of trees contributing to the alteration	cases controls	Noted whether a single tree or multiple trees in each of the following categories were present. (1) Adjacent failure(s) (2) Close, nonadjacent failure(s) (3) Adjacent standing dead defoliated tree(s) (4) Close, nonadjacent standing dead defoliated tree(s)
General tree variables			
Species	Only failures of two oak species were counted	cases controls others	(1) *Q. agrifolia* (2) *Q. kelloggii*
Number of stems	Stems originating within 30 cm of the soil grade were counted as separate stems.	cases controls others	Count
DBH	Diameter (cm) at 137 cm height, measured for all stems over 3 cm diameter. For multistemmed trees, effective diameter is calculated as $(\Sigma \text{ cross sectional areas}/\pi)^{1/2}$	cases controls	Continuous

Table 2. (continued)

Variable	Definition and notes	Rated for:	Levels
Failure descriptors			
Failure type	Site of primary failure on tree	cases others	(1) Root (2) Root crown (lower edge of fracture is near soil surface) (3) Bole (main stem) (4) Scaffold (lowest first order branches arising from bole) (5) Branch (all other branches)
Estimated failure date	Failure date was estimated from multiple factors, including amount of weathering of failed surface, degradation of failed part, and previous observations. The 3 most recent time intervals (July 2001-Dec 2002) were combined for analyses.	cases others	(1) July to Dec 2002 (within past 6 months). (2) January to June 2002 (6 to 12 months ago) (3) July to Dec 2001 (12 to 18 months ago) (4) 1997 to July 2001 (1.5 to 5 years ago) (5) 1992 to 1997 (5-10 years ago)
Diameter at failure	Average diameter measured at midpoint of fracture.	cases others	Exact measurement for trees used as cases. For other failures estimated size classes: (1) <20 cm diameter (2) 20-25 cm diameter (3) diameter measured if greater than 25 cm
Foliation when failed	Condition of foliage at time of failure, based on interpretation of condition of twigs and foliage.	cases	(1) Green (2) Brown (3) Uncertain, with brown attached foliage (4) Defoliated
Failure direction	Direction of main failure was measured with compass	cases	45º compass directions (N, NW, W, SW, etc.)
Height of failure above ground	For failure types other than root failures, the height to the midpoint of the fracture was measured.	cases	Continuous
Thickness of failed wood	Measurement of the maximum thickness of wood that failed along the shortest available path. For a solid stem with a circular cross section, this is the under-bark diameter. For trees with cavities, this is typically the greatest distance between the interior of the cavity and the bark along a radius from the tree center.	cases	Continuous
Associated with previous failure	If failure is associated with a previous failure of the same tree, the type of failure was noted and the distance (m) to the previous failure was measured.	cases	(0) No association (1) Previous branch failure (2) Previous partial bole failure (3) Previous bole failure of a multistem tree
Main causes of failure	Failed area was inspected and factors that appear to contribute to the failure were noted.	cases others	(1) Decay (2) Cavity (3) Beetle boring (4) Structural defects (5) Mechanical wound (type of wound noted) (6) Impacted by other failure (i.e., secondary failure)
Secondary failures induced	Number of failures induced in adjacent trees as a result of the impact of the failing part.	cases	Count

Table 2. (continued)

Variable	Definition and notes	Rated for:	Levels
Failure descriptors			
Distance from attachment	For branch and scaffold failures, the distance (m) between the failure and point of branch attachment was measured.	cases	Continuous
Branch order	For branch and scaffold failures, the branch order was noted. By definition, scaffolds have a branch order of 1.	cases	Integer
Branch angle from vertical at break	For branch and scaffold failures, the angle of the branch from vertical (degrees, 0=vertical) was estimated with a clinometer.	cases	Continuous
Tree condition variables			
Tree condition at time of failure	Based on interpretation of condition of twigs and foliage, primarily determined for recent failures.	cases others	(1) Live (2) Dead (3) Uncertain
P. ramorum-related symptoms	For failures, status at time of failure was estimated from previous observations and by interpreting stem symptoms. Status was estimated primarily for recent failures. For controls, symptoms were rated as of the time of the survey.	cases controls others	(0) No symptoms (1) Early - bleeding cankers only (2) Late - cankers plus beetles and/or *H. thouarsianum* (3) Dead as result of *P. ramorum* infection; evidence of bark cankers present -If the status is uncertain, the most likely status is noted and a questionable code ("?") is added.
Recent bleeding from *P. ramorum* cankers	The presence of relatively recent bleeding (within current growing season) from cankers was noted.	cases controls	(0) absent (1) present
Tree decline or death due to agents other than *P. ramorum*	Decline was noted if condition was poor enough that the tree appeared likely to die within 10 years. Trees were scored as dead if all main stems are dead, even if small live basal sprouts were present. Canker rots and other decay fungi are typically the cause of such decline and mortality. For cases, status is rated for the time of failure. For controls, status is rated as of the time of the survey.	cases controls others	(0) No symptoms (1) Other decline (2) Other dead -If the status is uncertain, the most likely status is noted and a questionable code ("?") is added.

Table 2. (continued)

Variable	Definition and notes	Rated for:	Levels
Tree condition variables			
Defects present	Presence of each of the defects was noted. For failed trees (cases) , an additional notation was made to indicate whether the defect contributed to the failure.	cases controls	(1) Dead branch or branch stubs (2) Multiple trunks/ codominant stems (3) Hollow branch stubs (4) Dense crown (5) Heavy lateral limbs/ excessive branch end weight (6) Uneven branch distribution: one sided (7) Uneven branch distribution: top heavy (8) Multiple branches from same point (9) Embedded bark in crotch (10) Crook or sweep (11) Leaning trunk (12) Cracks or splits (13) Kinked or girdling roots (14) Cavity (15) Decay column
Beetle boring	Evidence of wood- boring beetle activity in the lower 2 m of the main stem(s) was assessed.	cases controls	(0) None seen (1) Present (2) Abundant
Beetle boring depth	Maximum depth (cm) of boring into the wood was measured on the fracture.	cases	Continuous
Beetle boring % of circumference	For cases, beetle boring was scored in the area of the fracture and within 0.5 m on either side of failure. For controls, the lower 2 m of the main stem(s) was assessed.	cases controls	0-6 scale[a]
Beetle boring density class	For cases, we evaluated the density of tunnels on the exposed fracture and estimated the number of tunnels in an 5 × 5 cm area with average density. For controls, only qualitative density ratings were made based on the number of exit holes and frass on the bole.	cases controls	(0) not observed (1) low: about 1-3 tunnels/25 cm^2 (2) medium: about 4-6 tunnels/25 cm^2 (3) high: about 7 to 10 tunnels/25 cm^2 (4) very high: >10 tunnels/25 cm^2 Level 4 was only recorded for cases. It was combined with level 3 for analyses including both cases and controls.
Beetles present	Type of beetles present were inferred from the size, shape, and location of tunnels and exit holes.	cases controls	(1) Ambrosia (*Monarthrum* spp.) (2) Bark (*Pseudopityophthorus* spp.) (3) Roundheaded (Cerambycidae) (4) Flatheaded (Buprestidae) (5) Other/undetermined
Hypoxylon thouarsianum Percent of stem circumference affected	Visual estimate of the percent of circumference with stromata (fruiting bodies) as if stromata at all levels on bole were viewed in same cross section. Areas between fruiting bodies are assumed to be affected if distances are less than about 10 - 15 cm.	cases controls	pretransformed 0-6 scale[a]

Table 2. (continued)

Variable	Definition and notes	Rated for:	Levels
Tree condition variables			
Hypoxylon thouarsianum maximum stromatal density	Count the number of stromatal centers in a 1 m by 0.1 m vertical strip visualized over the densest patch of stromata. For failed stems, estimate is centered around the fracture, i.e., within about 0.5 m above and below the fracture.	cases controls	Continuous. Stromatal centers (individual hemispherical protrusions) were counted rather than stromatal clusters (fused or compound groups of stromata) to partially account for size differences between masses of stromata.
Cavity rating	Percent of stem cross sectional area affected. Estimated for controls based on external symptoms.	cases controls	(0) None (1) Up to 25% (2) 26-50% (3) 51-75% (4) >75%
Decay rating	Percent of stem cross sectional area affected. Estimated for controls based on external symptoms.	cases controls	(0) None (1) Up to 25% (2) 26-50% (3) 51-75% (4) >75%
Type of decay	All decay types present are noted.	cases controls	(0) None (1) White rot (2) Brown rot
Decay location	All locations of decay are noted.	cases	(1) Sapwood (2) Heartwood
Other decay category	Other specific categories of decay were noted if present	cases controls	(1) Canker rot (2) Root rot (3) Sprout rot - decay in root crown area of sprout-origin trees (4) Pocket rot
Fungal fruiting bodies	Fruiting bodies on trees were identified to genus and, if possible, to species.	cases controls others	

[a]The 0-6 scale is based on the following arcsine-transformed percentage scale:

0: Symptom not seen	3: 20% to < 50%	6: 97.5% to 100%
1:< 2.5%	4: 50% to < 80%	
2: 2.5% to <20%	5: 80% to < 97.5%	

Sampling decay fungi

We collected samples of wood with evidence of decay from a subset of the recent tree failures. Samples were placed in paper envelopes and held in a desiccator at -19 C for up to several months. Samples were subsequently transferred to Dr. Matteo Garbelotto's lab at UC Berkeley for processing and identification of decay fungi from extracted DNA. Results of that study will be reported elsewhere.

Statistical analyses

We used JMP® statistical software (SAS® Inc., Cary NC) for data analysis. Unless otherwise indicated, effects or differences are referred to as significant if $P \leq 0.05$.

We used the likelihood ratio chi square test to test for independence of variables in 2×2 or larger contingency tables.

We used the recursive partitioning platform in JMP® to develop models relating various predictor variables to the case (failure) outcome. The platform recursively partitions data in a dichotomous fashion according to a relationship between the predictor and outcome values, creating a tree of partitions. Each partition is chosen to maximize the difference in the responses between the two branches of the split. For continuous predictor variables, the partitions are created by a cutting value which divides the sample into values below and above the cutting value. For categorical predictors, the sample is divided into two groups of levels. For the binary categorical outcome case/control, the estimated probability for each response level is the fitted value, and the most significant split is determined by the largest likelihood-ratio chi-square statistic. Splitting was done interactively and was stopped when an endpoint had fewer than 5 trees in it or consisted of all failures or controls. After splitting, models were pruned upward to minimize the misclassification rate. We also calculated and compared k-fold crossvalidated G^2 statistics ($k = 5$) for candidate models to assess relative improvement in fit when building models. Unless they were associated with a large change in the crossvalidated G^2, we also pruned splits in which both sides of the split had a majority of the same outcome (cases or controls).

For logistic regression models of the case (failed) versus control (not failed) outcomes, the likelihood ratio chi square was used to test the significance of each effect in the model. Likelihood ratio chi square tests are calculated as twice the difference of the log likelihood between the full model and the model constrained by the hypothesis to be tested, i.e., the model without the effect (SAS Institute 2000). The reported significance level of each factor in a multivariate model is therefore dependent upon the other factors which are included in the model. Hence, the significance level of each factor reported in the models should be interpreted as if it were the last factor added to the model. We also calculated Akaike's information criterion (AIC) to compare the fit of alternative models. For models constructed for a given data set, smaller AIC values indicate better model fit.

Only one failure per tree was used for all statistical model building. For the few case trees in which more than one failure was scored, one failure was randomly selected to be included in the recursive partition and logistic regression analyses.

RESULTS

Overall failure rates

Within the six study areas, we recorded data on 1540 coast live oak (*Quercus agrifolia*) and California black oak (*Q. kelloggii*) trees (Table 3). We catalogued 308 failures that were within the age range (past 10 years) and size classes (at least 20 cm diameter for branch or scaffold failures, at least 15 cm diameter for bole or root failures) that were used as cutoffs for the study. The catalogued failures occurred in 297 trees, some of which had multiple large failures. Seven of the failures (2.3%) were secondary failures, i.e., failures that occurred because the trees were hit by material from an adjacent tree failure.

Table 3 shows failure rates for the different locations for failures above the size thresholds and within the target date range. The proportion of failed trees differed significantly between locations (likelihood ratio test $p<0.0001$). The relative prevalence of bole, branch, and root failures also varied significantly by location overall (likelihood ratio test $p=0.0001$). The majority of the failures within the target size and age ranges were bole failures (Table 3).

California black oak was a minor component of the woodlands in the study, comprising only 5% of the oak trees included in the sample. Of all trees with failures, 6.8% were California black oak. Overall failure rates for coast live oak and California black oak were 19.1% and 23.7%, respectively, which are not significantly different.

In addition to the failures listed in Table 3, we noted 105 failures within the study areas that were below the size thresholds. With one exception (a bole failure <15 cm diameter), these were branches and scaffolds that were between 10 and 20 cm in diameter. Trees with these smaller failures are not included in the analyses of failures discussed below.

Table 3. Percent of coast live oak and California black oak trees experiencing a major failure during the last 10 years and distribution of failures by type for the six study locations. Includes branch/scaffold failures >20 cm, and bole, root, and root crown failures of stems > 15 cm DBH. Areas are based on projected GIS polygons and underestimate actual area due to significant ground slopes at many sites.

Location	Area (ha)	Total trees surveyed	Failures	Bole	Branch and scaffold	Root and root crown
			% of all trees	% of failures		
2	1.984	489	8%	70.5%	25.0%	4.5%
3	1.494	286	20%	62.5%	28.6%	8.9%
5	2.077	204	23%	37.2%	51.0%	11.8%
6	1.471	186	31%	67.3%	22.4%	10.3%
8	1.668	163	33%	35.8%	49.1%	15.1%
11	0.949	212	20%	41.3%	56.5%	2.2%
Totals	9.644	1540	19%	52.6%	38.3%	9.1%

Overall characteristics of failures

DATE OF FAILURE

We estimated failure dates using various indicators noted in the methods. Our estimates of the most recent failure dates (within the past 18 months) are the most reliable. Estimates of failure dates for failures more than a few years old are more subject to error, so broad time intervals were used for estimating failure dates older than about 1.5 years (i.e., failures occurring before July

2001). Evidence of old failures can be lost over time due to loss or degradation of downed wood. However, the study areas have not burned for well over a decade and are subject to only limited clearing activities near roads and trails. Consequently, downed wood is fairly persistent within the study areas. We believe that we were able to detect evidence of almost all of the large failures that occurred in the 10 years or so before our survey.

Several types of failures were much more common in the 1.5 years before our survey than in the previous decade (Figure 1). The rate of bole failures shows the greatest increase overall, but the rate of scaffold and branch failures also changed significantly over the time intervals (likelihood ratio test $p<0.0001$). Root and root crown failure rates did not differ significantly over the three time intervals.

Although recent failures (within 1.5 years of the survey) constituted the majority of failures at all locations, the proportion of failures in the three age classes varied significantly among locations (likelihood ratio test $p<0.0138$). For example, the proportion of recorded failures that had occurred in the most recent interval (previous 1.5 years) ranged from 45% (20/42) at location 2 to 74% (46/62) at location 11.

Although we do not know the precise timing of the observed failures, estimates of failure dates from recent failures suggests that failures occurred throughout the year. About one third of the failures that occurred in 2002 were rated as having occurred in the first half of the year. Of 112 recent failures we catalogued, 27 still had green leaves and moist wood, indicating that these failures had occurred within the preceding month or so. We observed at least six trees that failed between successive visits to a site, so their failure dates can be pinpointed to a span of several weeks during autumn 2002.

In addition, we heard 6 tree failures while we were in the field at the various study sites between September and December 2002. We estimate that each of these failures occurred within about 300 m of our position. All of these failures occurred during relatively calm conditions. Most occurred on warm afternoons with little or no wind. Although extreme weather conditions, such as rainstorms or high winds are known to induce failures, our observations indicate that many of the failures in the study areas occurred in the absence of severe weather.

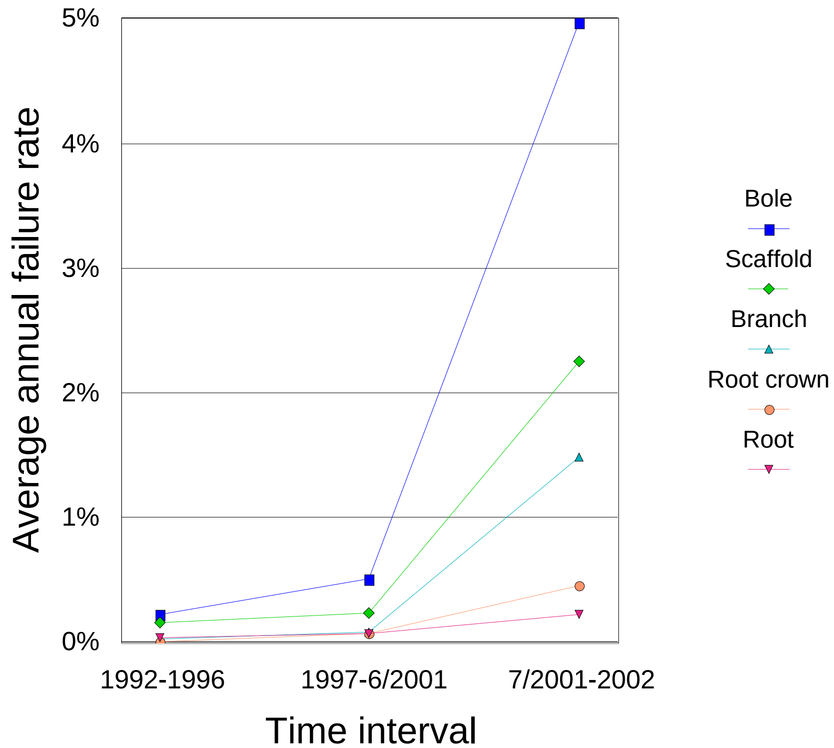

Figure 1. Estimated annual failure rates by failure type for the standing tree population (coast live oak and California black oak) within the study areas over three time intervals. The tree population size was adjusted downward for each interval by subtracting trees with bole, root crown, and root failures that occurred in the previous interval(s) (n=1540, 1521, and 1476 for the three intervals in the order shown on the graph).

DISEASE STATUS OF FAILED TREES

P. ramorum **canker**

Each failed tree was rated for the presence of symptoms of *P. ramorum* canker and related secondary organisms (*H. thouarsianum* and wood-boring beetles) and decline due to other agents, such as canker rot fungi or root pathogens. In general, disease status at the time of failure could be rated with some confidence only for trees that had failed in the previous 1.5 years, so the analysis in this section is restricted to that group of trees (Figure 2). Trees for which disease status was unclear were coded as questionable, but the most likely disease status was also noted if possible. Trees of questionable disease status are excluded from Figure 2, although the overall trends do not change if the questionable trees are included with their most likely disease categories. Trees with symptoms of *P. ramorum* canker constitute about 31% of the nonfailed controls compared with 83% of the trees with failures (likelihood ratio test $p<0.0001$). *P. ramorum*-infected trees fail much more frequently than do asymptomatic trees, although some asymptomatic trees did fail.

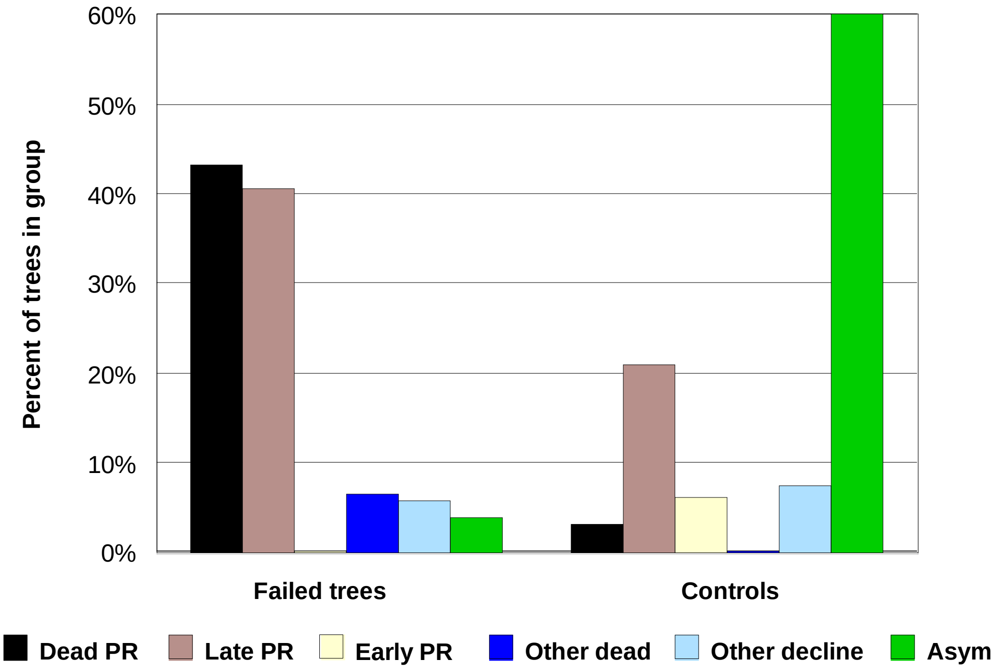

Figure 2. Disease status for coast live oaks with recent failures compared to nonfailed control coast live oak. Failures and controls with uncertain *P. ramorum* disease status are excluded. Recent failures were estimated to have occurred within 1.5 years of the survey (late 2001 through 2002). Controls are trees without failures that were sampled for the case-control portion of the study. **Dead PR**= tree dead as a result of *P. ramorum;* **Late PR**= live trees with *P. ramorum* cankers plus beetle boring and /or *H. thouarsianum* fruiting bodies; **Early PR**= live trees with *P. ramorum* cankers only; **Other dead**= tree dead due to agents other than *P. ramorum;* **Other decline**=tree in severe decline due to agents other than *P. ramorum;* **Asym**= no evident symptoms of *P. ramorum* infection or decline due to other agents. Missing columns indicate 0%. n=155 failures and 162 controls.

The overwhelming majority of recent failures occurred in trees that were either dead as a consequence of *P. ramorum* infection or were in the late stages of disease with beetle boring and/or *H. thouarsianum* fruiting bodies present (Figure 2). None of the recorded recent failures occurred in trees displaying only early symptoms of *P. ramorum* infection, i.e., bleeding cankers only (Figure 2). Increased risk of failure is associated with degradation of wood by decay fungi and/or beetles following *P. ramorum* infection, and not with *P. ramorum* infection itself.

None of the control trees had been killed by causes other than *P. ramorum* (Figure 2). Severe infections by wood decay fungi are the most common cause of tree mortality among trees without *P. ramorum* symptoms. Trees killed by these fungi usually experience multiple failures before they die.

Figure 3 shows disease status with respect to *P. ramorum* canker for recent failures by failure type. Trees with uncertain disease status designations are shown in the graph; similar overall trends are observed if the uncertain trees are omitted. The majority of all failure types other than root failures occurred in trees that were dead as a result of *P. ramorum* canker or were in late stages of disease and were colonized by wood-boring beetles and /or *H. thouarsianum* (Figure 3). As noted above, no failures were observed among trees with only early symptoms of *P. ramorum* canker.

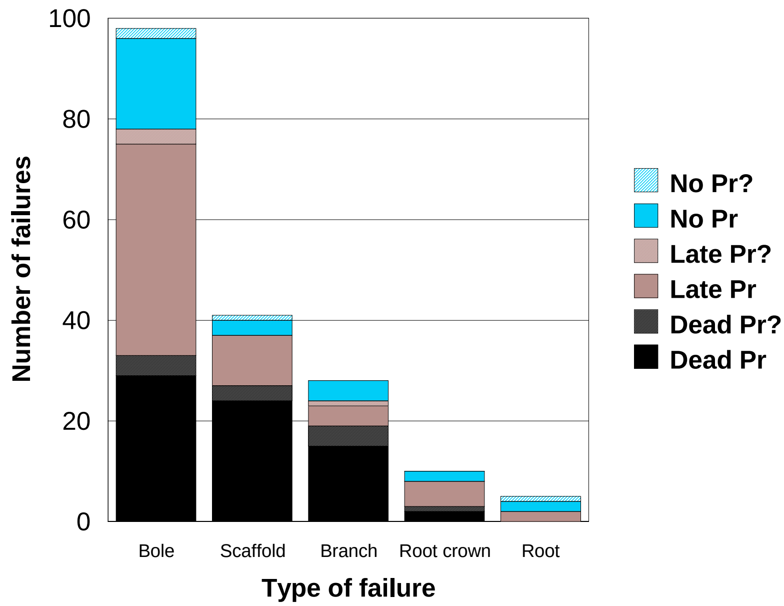

Figure 3. Disease status of trees by failure type for failures that occurred within 1.5 years of the survey (late 2001 through 2002). Includes both California black oak and coast live oak. **No Pr**=no evidence of infection by *P. ramorum*, **Late Pr**= late symptoms of *P. ramorum* infection (bleeding cankers plus beetle boring and /or *H. thouarsianum* fruiting bodies), **Dead Pr**= dead as a result of *P. ramorum* infection. Question marks denote trees with uncertain disease designations. n=186 coast live oaks and 5 California black oaks.

As noted above, bole failures were the most common failure type overall (Table 3, Figure 3). Bole failures also showed the largest increase in frequency in the most recent time interval (Figure 1). Figure 4 shows the distributions of stem diameters at the point of failure for trees with bole failures with or without *P. ramorum* symptoms. The distributions are left-censored at 15 cm because this is the minimum bole failure diameter that was included in the data set. Bole failures in trees with *P. ramorum* symptoms occur across the full range of size classes represented, with the majority of bole failures occurring in trees between 20 and 60 cm at the point of failure (mean diameter at failure 38.7 cm, standard deviation [sd] 16.7). In contrast, most bole failures in trees lacking *P. ramorum* symptoms (Figure 4, bottom) occurred in smaller diameter stems (mean diameter at failure 28.4 cm, sd 14.7). Small diameter trees with bole failures are typically suppressed understory trees that are colonized by wood decay fungi.

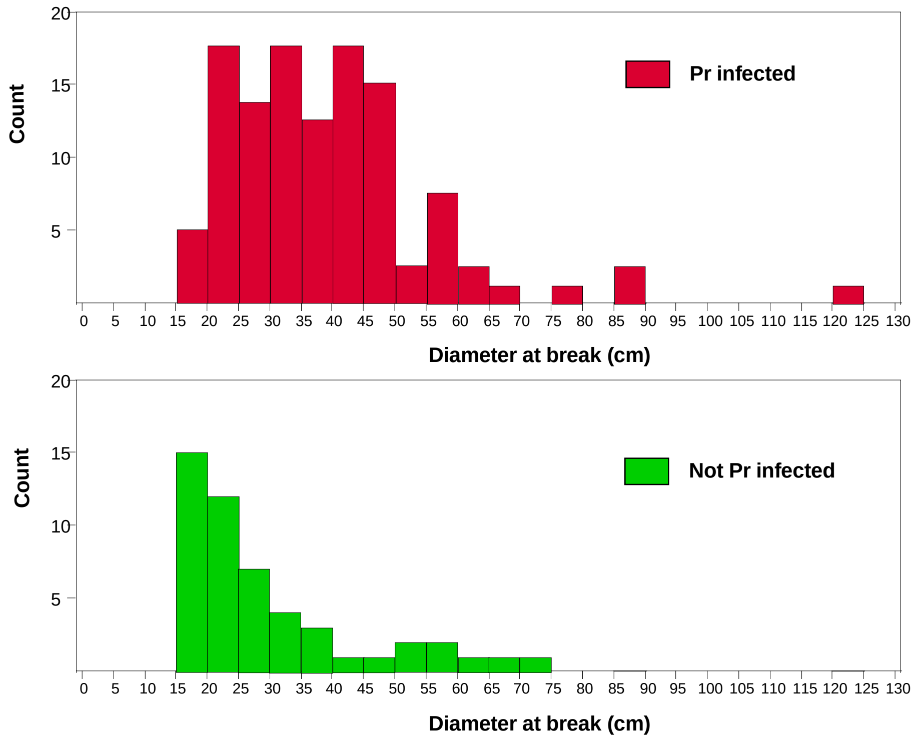

Figure 4. Histograms of diameter at the point of failure (cm) and *P. ramorum* infection among all bole failures rated as occurring within the past 10 years. Trees with uncertain disease status designations are included with the most likely corresponding disease categories. n=141 coast live oaks and 3 California black oaks.

Decline and mortality due to other agents

Most of the recently failed trees that lacked *P. ramorum* canker symptoms were either dead or in decline due to other causes (Figure 2), most commonly due to attack by canker rots or other wood decay fungi. Only a small percentage of apparently healthy live trees exhibited recent failures above the size thresholds. Excluding trees with *P. ramorum* symptoms, the proportion of dead and declining trees is significantly greater among failures (cases) than among controls (likelihood ratio test $P<0.0001$).

Twenty-nine recently failed trees had no *P. ramorum* canker symptoms. Of these, 41% were in decline and 34% were dead. In comparison, 113 nonfailed controls had no *P. ramorum* symptoms; of these 11% were in decline and none were dead.

Live and dead stems

For most trees that experienced a failure, the part that failed was already dead (Figure 5). However, we found that a substantial number of live stems also failed. Among those trees where the status at failure could be determined (primarily failures occurring within the past 1.5 years), 39% of the bole failures and 30% of the scaffold failures occurred in live stems. Root and root crown failures also occurred predominantly in live trees.

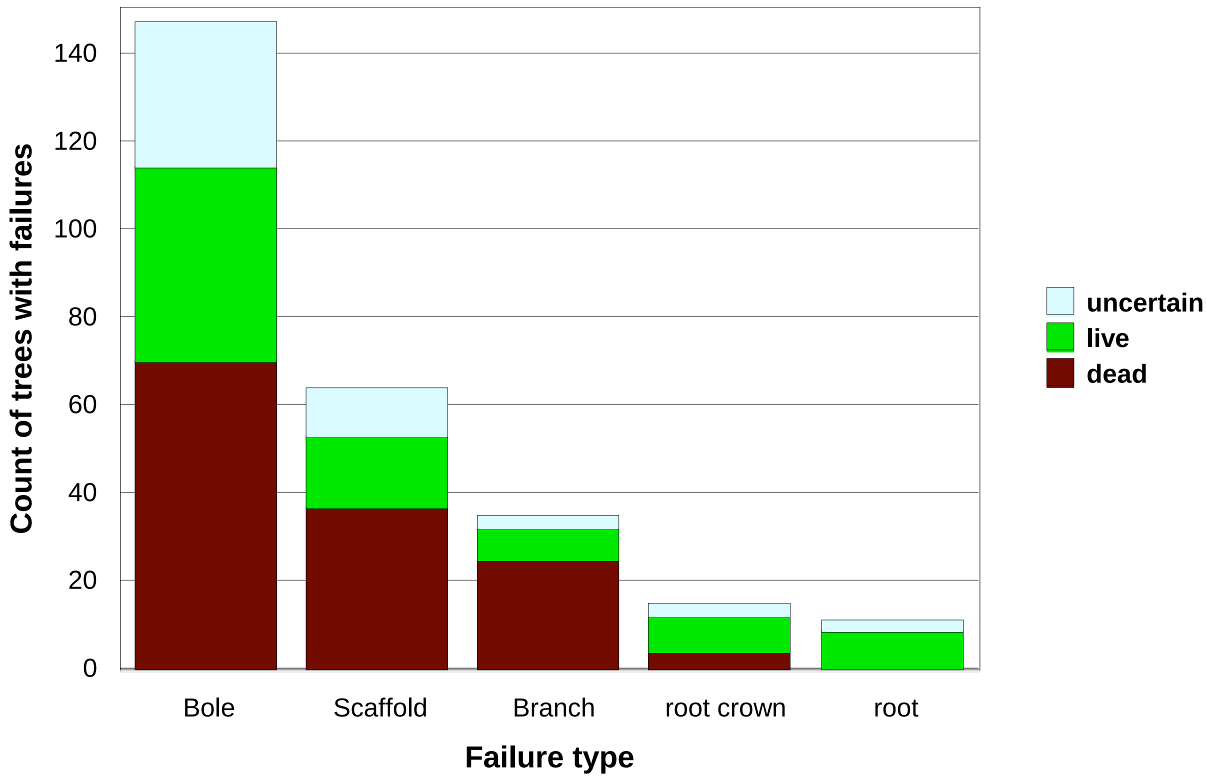

Figure 5. Frequencies of failures estimated to have occurred in the last 10 years by type and status (live or dead) of the failed part at the time of failure. Failures which could not be assigned with certainty to either dead or live category, mostly older failures, are shown in the uncertain category. n = 283 coast live oak failures and 18 California black oak failures.

Dead trees are generally considered to have a high failure potential. Within the study areas, 75% (131/174) of the dead trees had failures above the threshold size. Nonetheless, standing dead trees that had not yet failed were present at each of the locations. Trees that died as a result of *P. ramorum* canker (75% of all dead trees) failed at the same rate overall as trees that died from other causes.

SPATIAL DISTRIBUTION OF FAILURES WITHIN STUDY AREAS

The spatial distributions of failures at the study locations are illustrated in Figures 6 through 12. Various patterns are evident when the data are plotted spatially. For location 3, five different tree data layers have been plotted in Figures 6 (failure type, secondary failures), 7 (*P. ramorum* status), and 8 (failure date, status of failed part). Location 3 has a preponderance of bole failures (Figure 6), most of which were recent (Figure 8) and occurred in *P. ramorum*-infected trees that had late disease symptoms or were dead (Figure 7). Location 2, located about 0.8 Km south of location 3, also shows a preponderance of bole failures (Figure 9). However, location 2 has a higher proportion of older failures (Figure 9) and failures associated with *P. ramorum* are in smaller clusters compared with location 3 (Figure 7).

Failures at the remaining locations also show varying levels of spatial clustering. Most of this clustering is associated with the occurrence of *P. ramorum* symptoms. In most locations, root failures also tend to be clustered (Figures 6, 11, 12), although this uncommon type of failure is not strongly associated with *P. ramorum* canker (Figure 3). The spatial clustering of root failures may be due to local distributions of root pathogens and/or soil characteristics that predispose trees to root failure.

One interesting paradox that is especially evident when data are plotted spatially is the relative lack of large secondary failures. For example, despite the nearly complete canopy cover and large number of bole failures at location 3, only two secondary failures larger than the size threshold were observed (Figure 6). Of the 112 failures for which we collected the most detailed information, only 5 induced secondary failures. Due to both stand density and tree structure, many large tree failures in these stands did not contact other trees. Also, when failing trees hit sound trees, typically only smaller-diameter branches (less than 20 cm diameter) are broken off. Thus, at least at these locations, *P. ramorum*-related tree failures have had only minimal effects on adjacent asymptomatic trees.

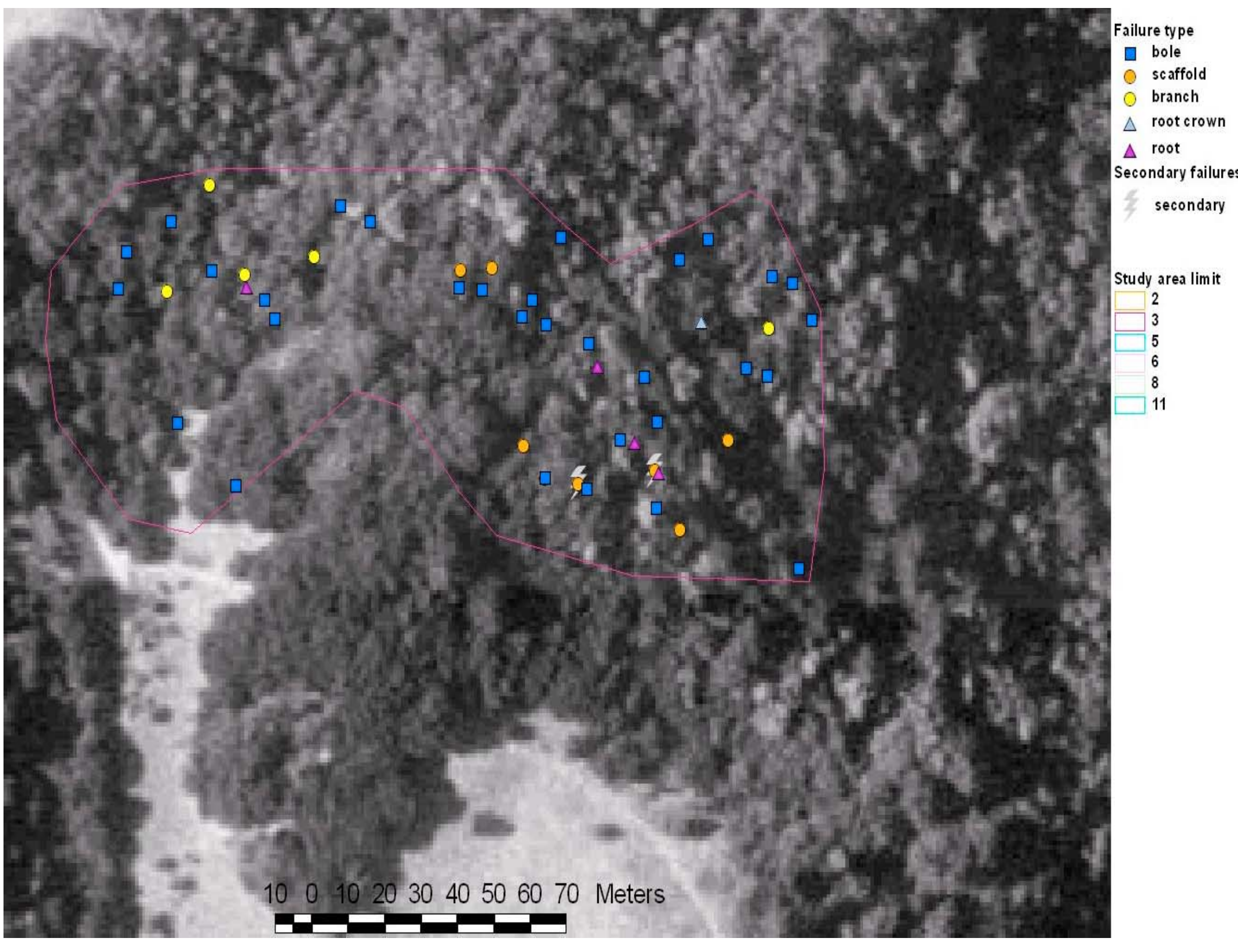

Figure 6. Spatial distribution of failures at study location 3 by failure type, with secondary failures noted.

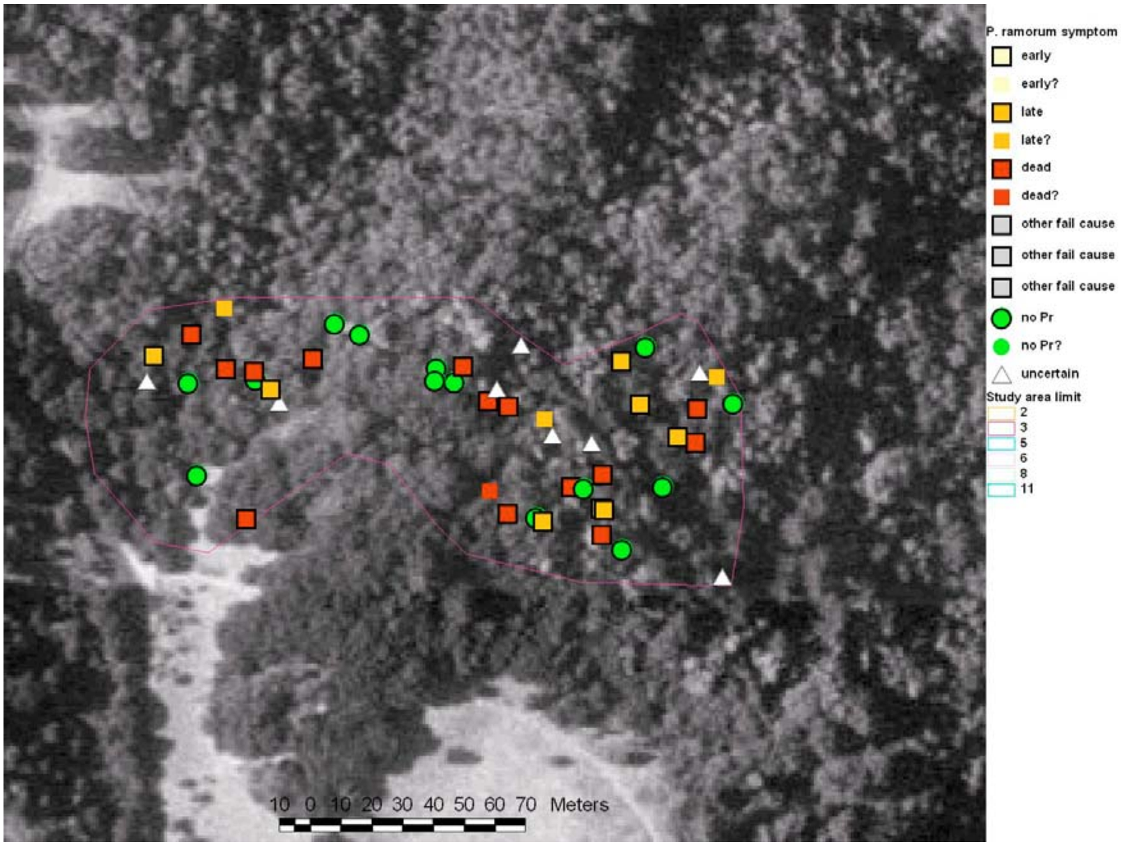

Figure 7. Spatial distribution of failures at study location 3 showing *P. ramorum* canker disease status. Symptom classes (early, late, etc.) are described in the text. Gray squares (other failure causes) denote trees with *P. ramorum* symptoms that have failed due to causes unrelated to *P. ramorum*.

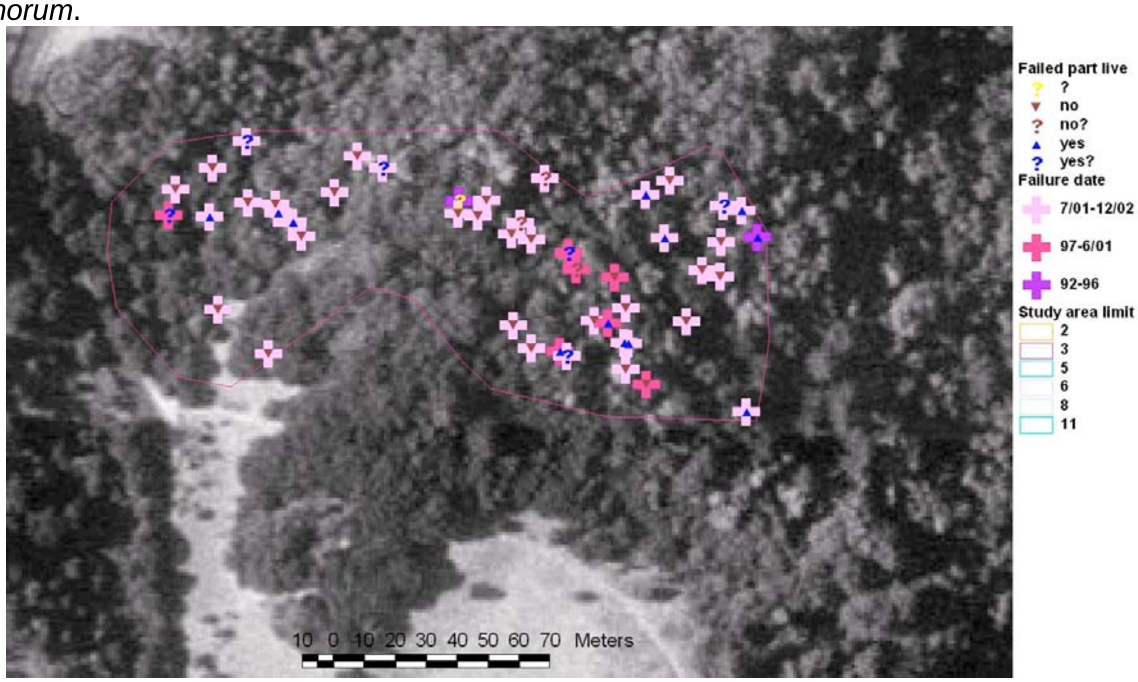

Figure 8. Spatial distribution of failures at study location 3 by failure date (crosses). Status of failed part (live or dead at time of failure) is superimposed.

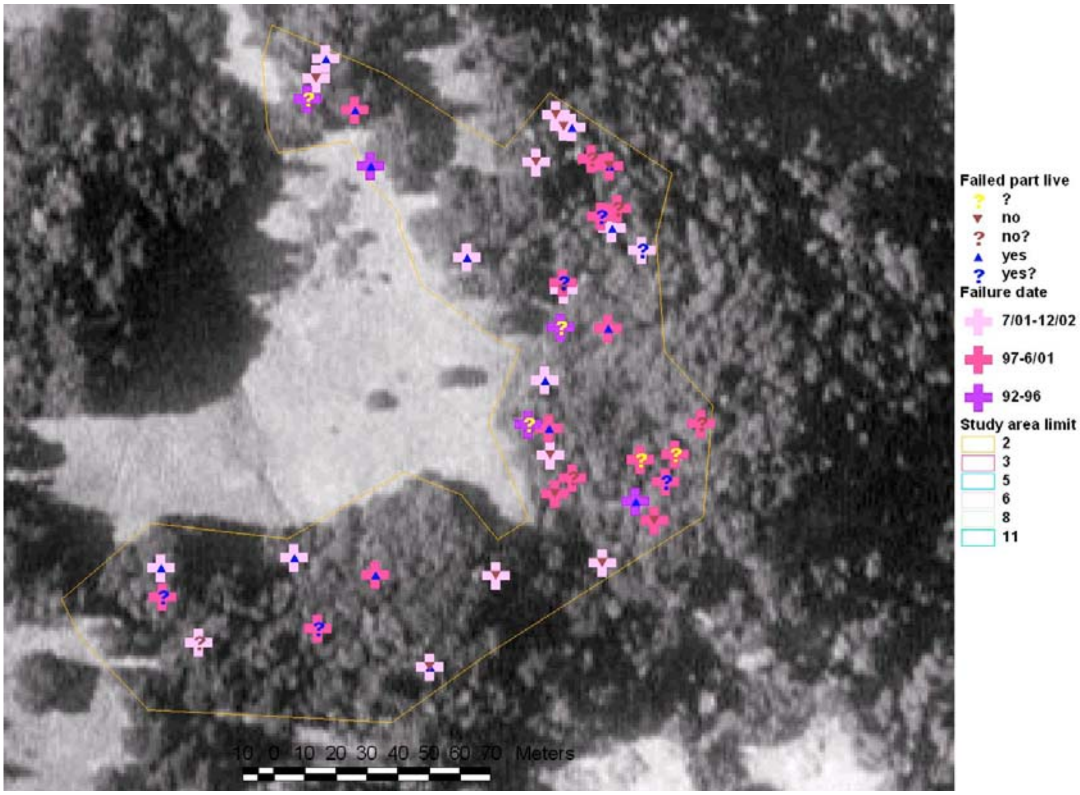

Figure 9. Spatial distribution of failures at study location 2 by failure date (crosses). Status of failed part (live or dead at time of failure) is superimposed.

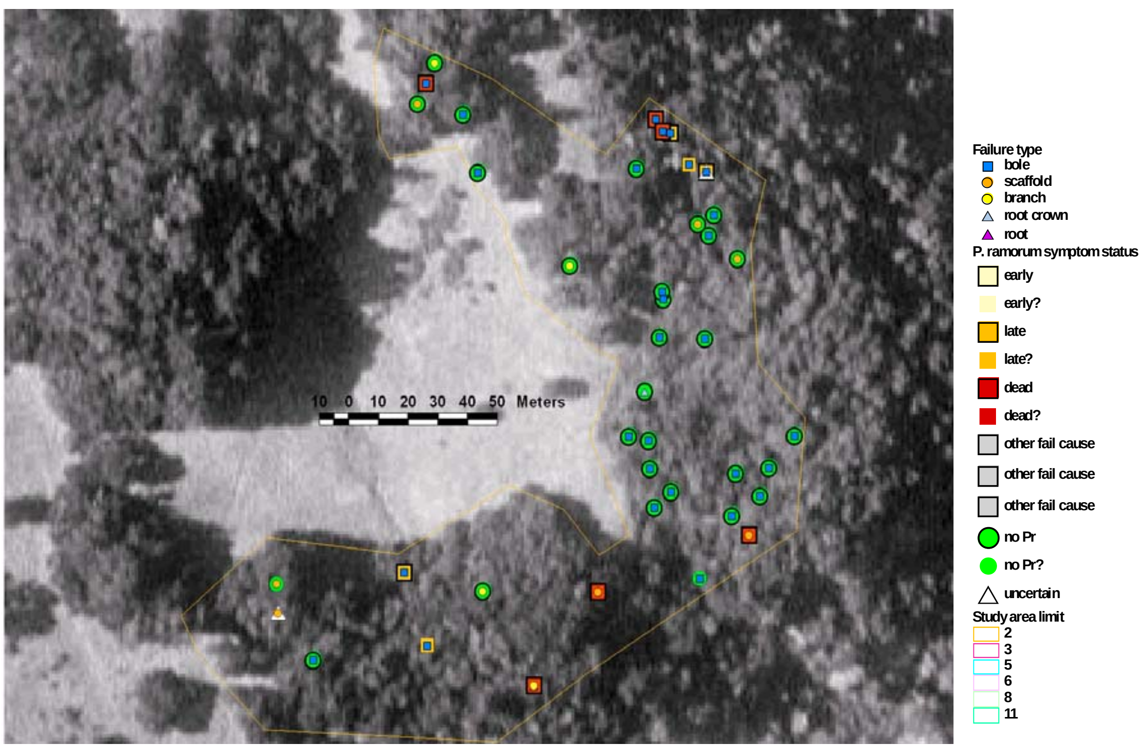

Figure 10. Spatial distribution of failures at study location 2 showing failure type and *P. ramorum* canker disease status. Symptom classes (early, late, etc.) are described in the text.

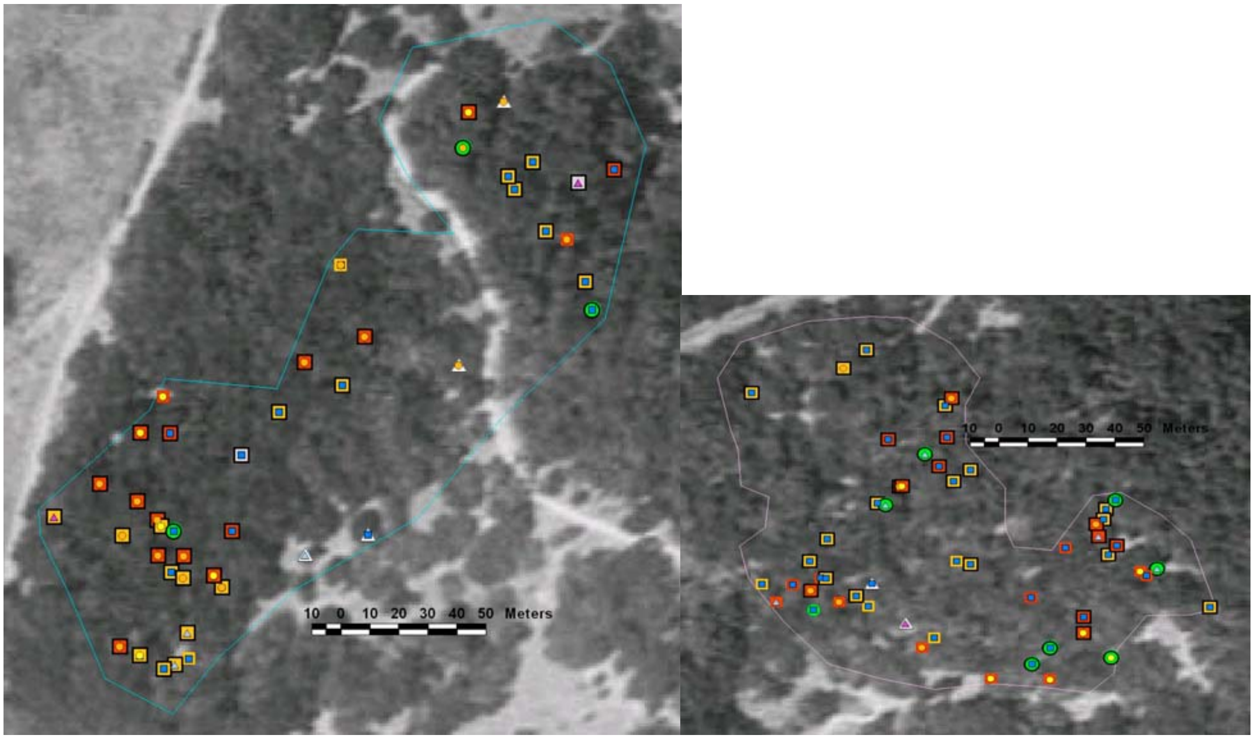

Figure 11. Spatial distribution of failures at study locations 5 (left) and 6 (right) showing failure type and *P. ramorum* canker disease status (see Figure 10 legend).

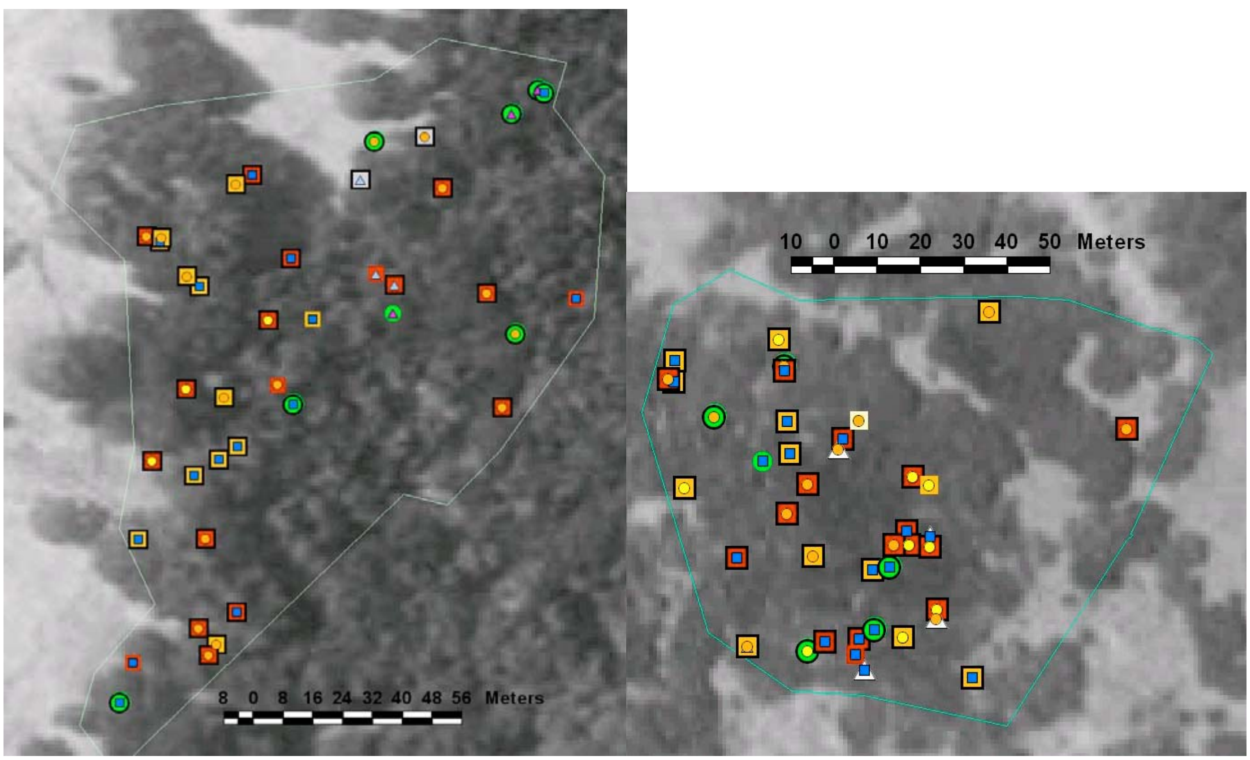

Figure 12. Spatial distribution of failures at study locations 8 (left) and 11 (right) showing failure type and *P. ramorum* canker disease status (see Figure 10 legend).

Case-control study on coast live oak trees

For the case-control portion of the study, we examined case (failed) and control (nonfailed) trees in detail in order to assess whether various tree and stand factors were related to failure potential. Only coast live oak trees that were estimated to have failed within 1.5 years prior to the survey date were included among the cases. We collected data on 112 failures in 106 case trees and 170 nonfailed control trees. The distribution of failure types among cases is shown in Table 4.

Table 4. Location of break for failures scored in case trees.

Location of main failure	Number scored	Percent of failures
bole	68	61%
root crown	8	7%
root	4	4%
scaffold	19	17%
branch	13	12%

Overall, the distributions of bole diameter (DBH) for case and control trees were similar, but there were more large diameter trees among the cases than among the controls (Figure 13). The average effective DBH (Table 2) of case trees is 48.5 cm compared to 42.8 cm for control trees, a significant difference (unequal variance t test P=0.0285).

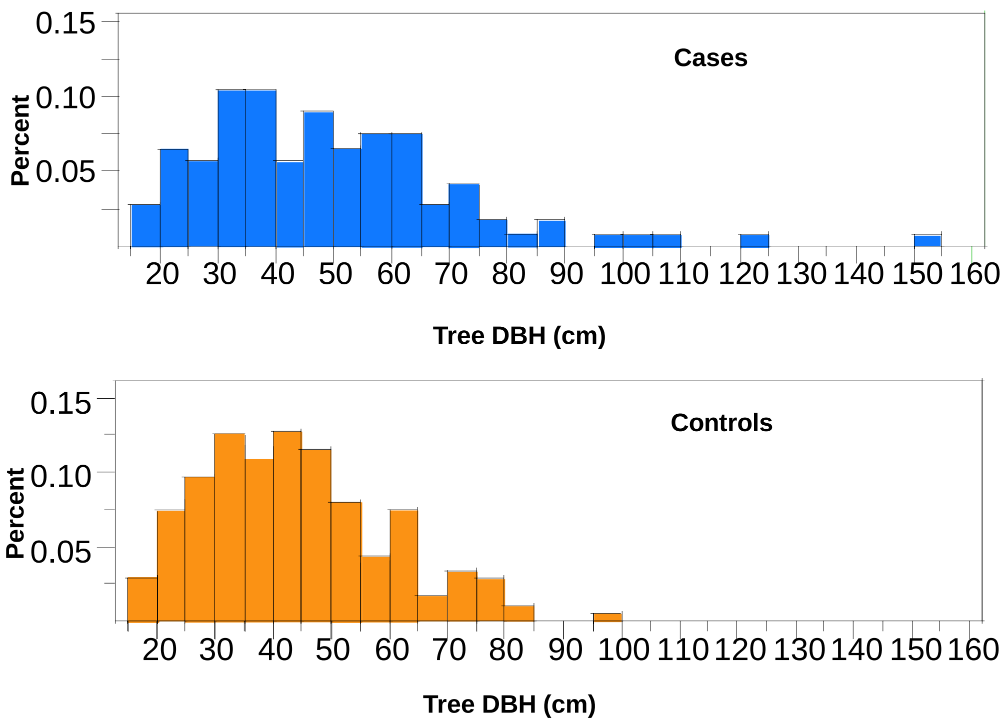

Figure 13. Histograms of effective DBH for coast live oak cases and controls. For multistemmed trees the effective DBH is calculated as described in Table 2. n=106 cases, 170 controls.

SIZE OF FAILURES AND HEIGHT ABOVE GROUND

Even though the largest failed stem was nearly 1.4 m in diameter, the greatest thickness of failed wood we observed was about 0.5 m (Figure 14). Although the majority of failures involved failure of wood across the entire stem cross section, this was less commonly the case for larger stems. Often, these larger stems had substantial cavities or involved codominant stems that split apart. In these situations, the maximum thickness of failed wood can be much less than the stem diameter at the point of failure.

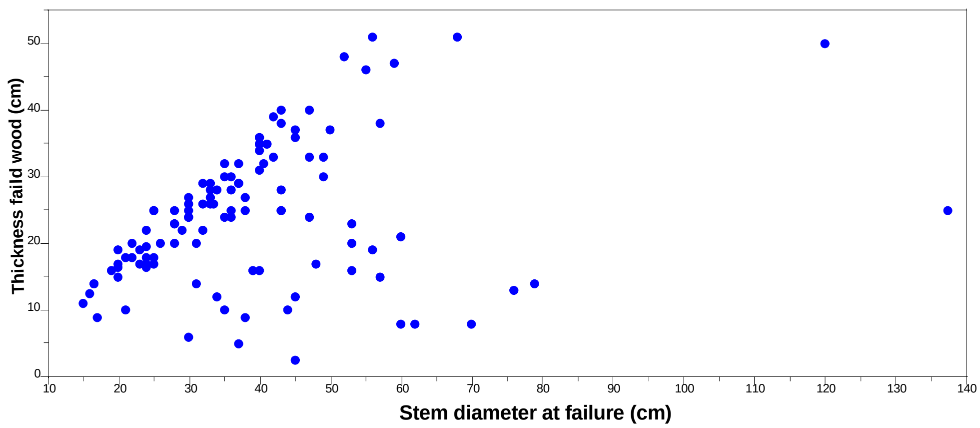

Figure 14. Thickness of failed wood as a function of stem diameter of the failure at the break for failures scored in coast live oak case trees. Stem diameter measurements include bark thickness but failed wood thickness measurements do not.

Most bole and root crown failures occurred within 1.5 m of the ground, but a few bole failures occurred at heights up to 6 m above the ground (Figure 15). All failures scored as root crown failures occurred within 0.35 m of the ground. Failures of branches and scaffolds (20 cm diameter of more) originated at heights ranging from 0.5 to 9 m above the ground.

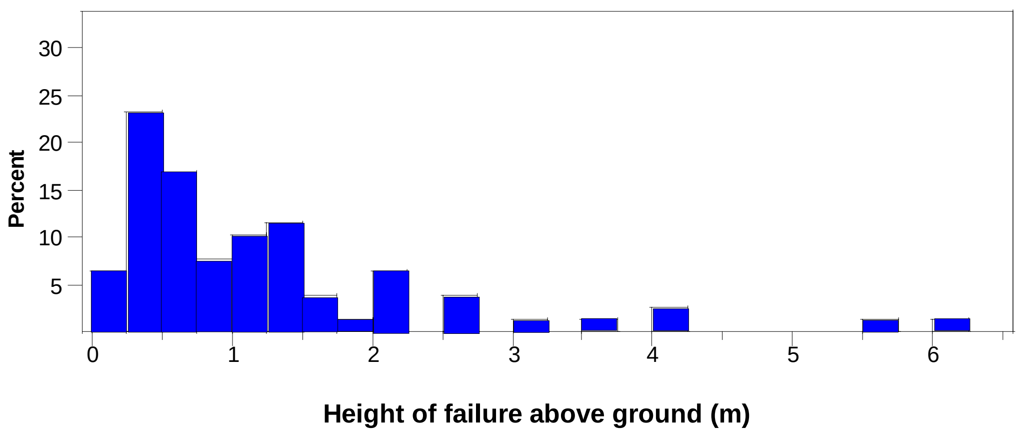

Figure 15. Height above the ground of bole and root crown failures scored in coast live oak case trees. For angled breaks, height is measured midway between the highest and lowest points of the failure. n=112 failures in 106 cases.

FAILURE DIRECTION

Hazards associated with tree failure are often directly related to the direction that the failed part falls. For all cases, we recorded the direction in which the failed part fell. For both cases and controls, we also assessed various characteristics of the site (aspect, slope, directions that tree the tree was exposed to the wind, degree of exposure) that might influence the direction of failure. As illustrated in Figures 16 and 17, failures occurred in all directions. Many failures occurred generally in the downslope direction (Figure 17), but cross-slope and upslope failures were also common.

Failure direction was not correlated with the prevailing wind direction, which is generally from the west-southwest for all locations. Furthermore, many of the trees that failed were only minimally exposed to wind: 44% of these failures had no appreciable wind exposure to the sides of the canopy and only 10% had as much as 25 to 50% exposure.

In general, the weight distribution of the failed part overwhelmingly influenced the direction of failure in these trees. Defects related to canopy imbalance (one-sided canopy, lean, crook/sweep, and/or heavy lateral limb) were scored as contributing to failure in 79% of the cases. Given that a preponderance of failures fell toward the south and southwest (Figure 16), it is likely that many of the trees with failures were leaning or otherwise weighted in those directions. Most of these stands are quite dense and competition for light has caused many trees to develop highly asymmetric and often contorted canopies. High average light intensities toward the south and southwest could result in many trees with canopies unbalanced toward those directions, leading to a preponderance of failures in those directions.

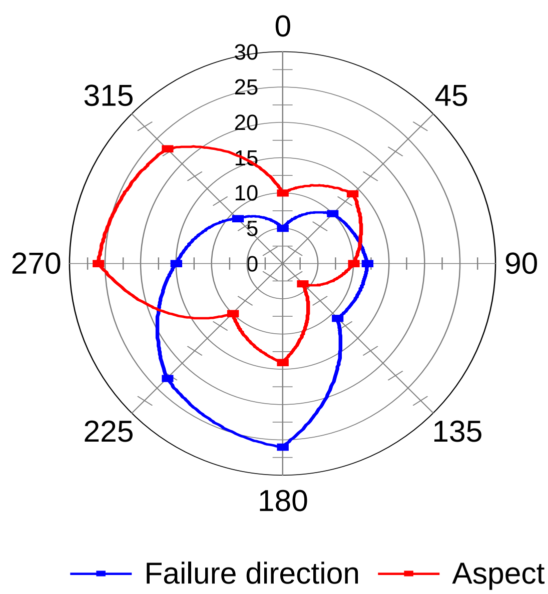

Figure 16. Frequency distributions of failure directions (blue) and ground aspect (red) for failures in coast live oak cases at all study locations. Direction (degrees) is plotted around the circumference and frequency (number of trees) is plotted as the distance from the center of the graph.

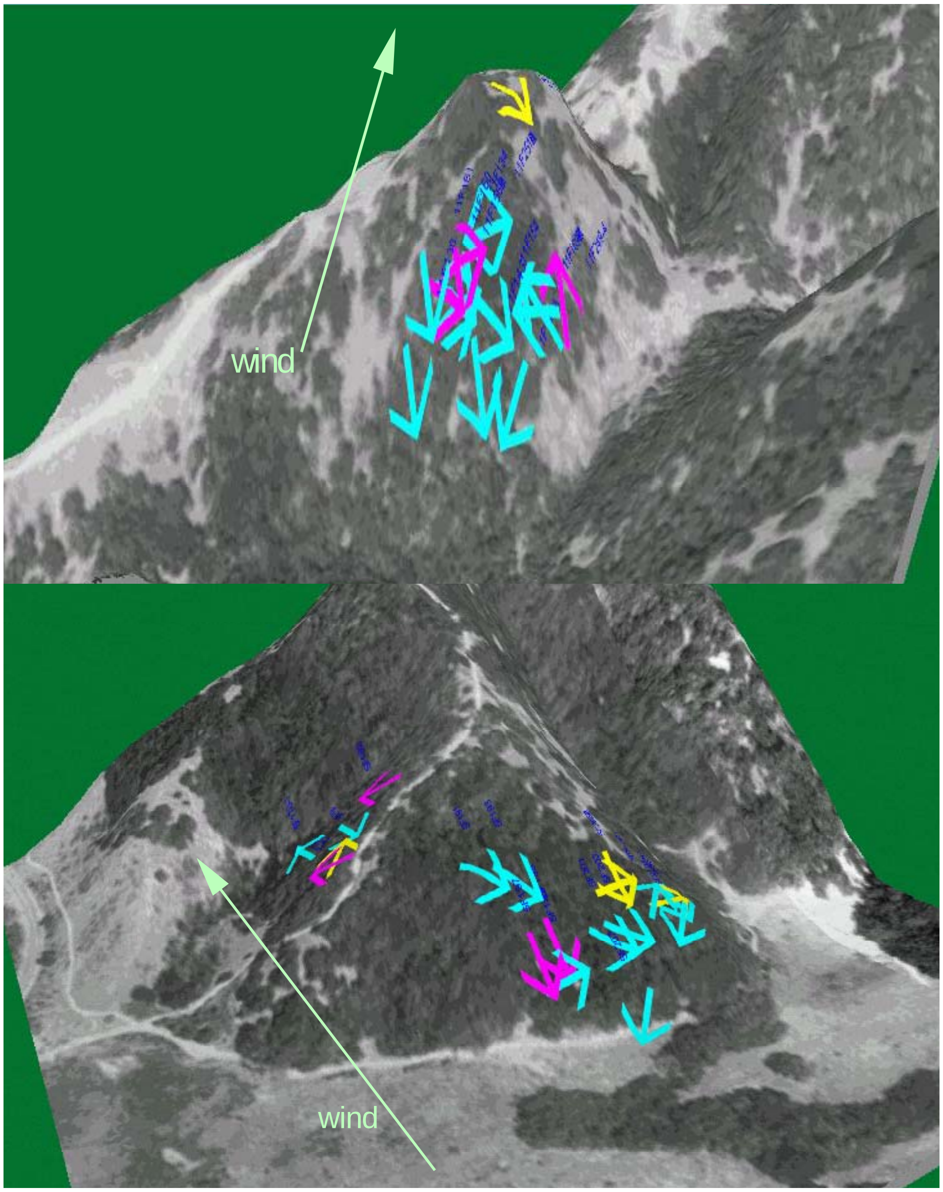

Figure 17. Failure directions of recent coast live oak failures (in previous 1.5 years) at study locations 11 (top) and 5 (bottom) plotted on three-dimensional images of the landscape (vertical exaggeration 3:1 to emphasize slope directions). Short arrows point in failure direction; arrow color indicates percent wind exposure of the tree canopy prior to failure (magenta = no significant exposure; aqua = up to 25%; yellow = 25-50%). Long green arrow indicates prevailing wind direction (west-southwest).

FACTORS CONTRIBUTING TO FAILURE

For all failures (cases plus additional failures not used as cases), we noted the major factors that appeared to have contributed to failure (Figure 18). Factors had to be present at levels high enough to feasibly affect failure potential in order to be scored as a contributing factor. Wood decay was evident in almost every failure and was judged to be a major factor contributing to failure in over 96% of the observed failures (Figure 18). Cavities, beetle boring, and structural problems also contributed to failure in a sizeable number of trees, but in all of these trees, decay was also scored as a contributing factor. Wounds contributed to failure in only a single tree. In addition to these general ratings, we made detailed observations on decay, cavities, beetle boring, structural defects, and other factors that might be related to failure potential in case and control trees. Summaries and analyses involving of these variables are presented in the remainder of this section.

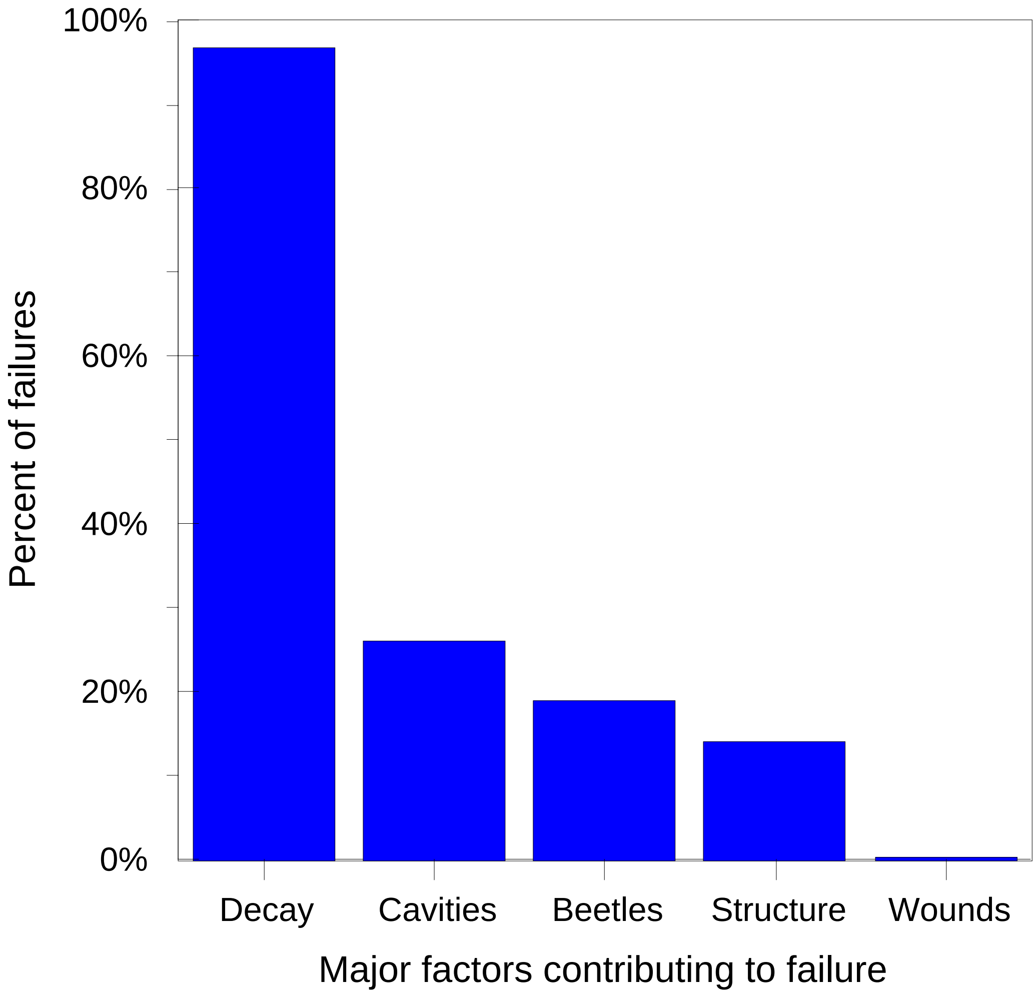

Figure 18. Major factors contributing to all failures (cases+other recorded failures) observed during the study. Multiple contributing factors were scored on many trees. Factors present at low levels that would not have affected failure potential (e.g., minor beetle boring) are not included in these totals. n = 259 coast live oak failures and 13 California black oak failures. Older failures for which contributing factors could not be assigned are excluded from these figures.

Decay and cavities

White rot was the predominant decay type among failures in coast live oak cases. Two failures had brown rot in addition to white rot. We also observed one California black oak bole failure that was associated with extensive brown rot only. This California black oak had *Laetiporus* *sulphureus* fruiting bodies present on the lower bole. Decay was present in both the heartwood and sapwood at the point of failure in most of these trees (Table 5).

Table 5. Decay location scored at the break for failures in coast live oak cases (n=108 failures, excludes root failures).

Decay location	Percent of failures
Heartwood only	3%
Sapwood only	16%
Heartwood and sapwood	81%

In all cases, we estimated the percent of the stem cross-sectional area at the point of failure that was affected by decay or cavities. Most failed stems showed high levels of decay (Figure 19). Cavities were present in only 27% of the failures, and only 9% had cavities affecting more than half of the cross sectional area (Figure 19).

Estimates of decay in the nonfailed control trees were based on external symptoms only. Decay estimates in controls are not completely comparable to decay estimates in trees with failures because they will likely underestimate the amount of decay present. Our evaluations indicate that 58% of the controls had no obvious decay and only 1% of the controls had more than 50% cross-sectional decay. Even if we assume that these ratings underestimate decay somewhat, it is likely that severe wood decay is much less common in nonfailed trees than in failed trees, as we would expect.

Exposed cavities in nonfailed trees were probed to gauge their extent, so cavity ratings of controls are more reliable than decay ratings and are more directly comparable to cavity ratings in cases. Cavity ratings in controls will still underestimate actual levels in situations where the cavity is completely internal. Even so, the distribution of cavity ratings (recoded to 3 levels for contingency table analysis) did not differ significantly between cases and controls (likelihood ratio test $p=0.129$). Given that most observed cavities were small, this suggests that the presence of relatively small cavities does not necessarily render coast live oaks more prone to failure.

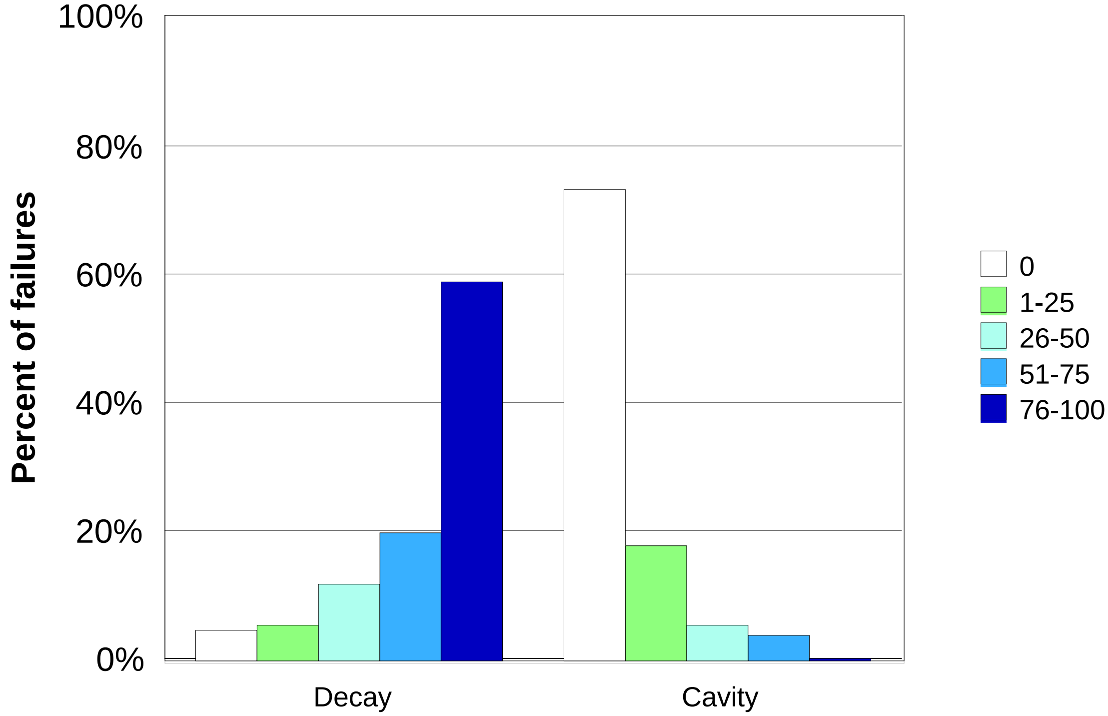

Figure 19. Percent of cross-sectional area at the point of failure affected by decay and cavities among failures scored in coast live oak cases.

Cavities and related defects, such as wounds from previous failures and decayed branch stubs, were not always present directly at the point of failure. However, such defects were commonly located near the point of failure as shown in Figure 20. Over half of the recorded failures were near previous branch or stem failures (Figure 21). The distance from such a defect to the point of failure ranged from 0 to 2 meters, and the average distance was 0.42 meters. When such defects occur at or very near to the point of failure, they commonly represent a point of structural weakness that contributes to failure potential. In other situations, especially where the defects are further from the point of failure, they may represent points where decay organisms gained entry into the tree. Alternatively, these defects may be associated with the same decay columns that contributed to both recent and earlier failures on the same stem.

Figure 20. Failure of a living coast live oak scaffold with green foliage occurring adjacent to an old branch failure scar (bottom center) and its associated decay column. The open canker on bottom of the failed branch is a typical canker rot symptom. Also note the substantial lean of the bole.

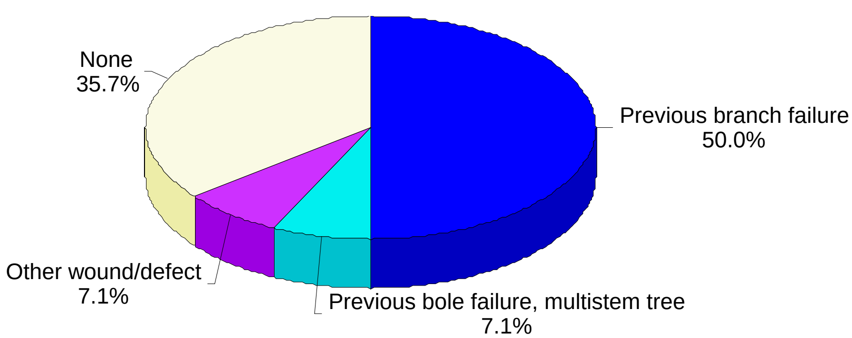

Figure 21. Percent of failures (n=112 failures in 106 trees) in coast live oak cases that were closely associated with defects. The other wound/defect category includes fire scars, cavities, and branch stubs not related to previous failures.

Decay fungi associated with failure

Trees affected by *P ramorum* canker commonly show fruiting of the wood decay fungus *H. thouarsianum* (Figure 22). *H. thouarsianum* was significantly more common in failed case trees than in nonfailed control trees (Figure 23). *H. thouarsianum* fruiting was present on 91% of the cases that had *P. ramorum* canker symptoms, but on only 39% of cases without *P ramorum* symptoms.

Figure 22. *Hypoxylon thouarsianum* fruiting associated with bole failure of a live coast live oak.

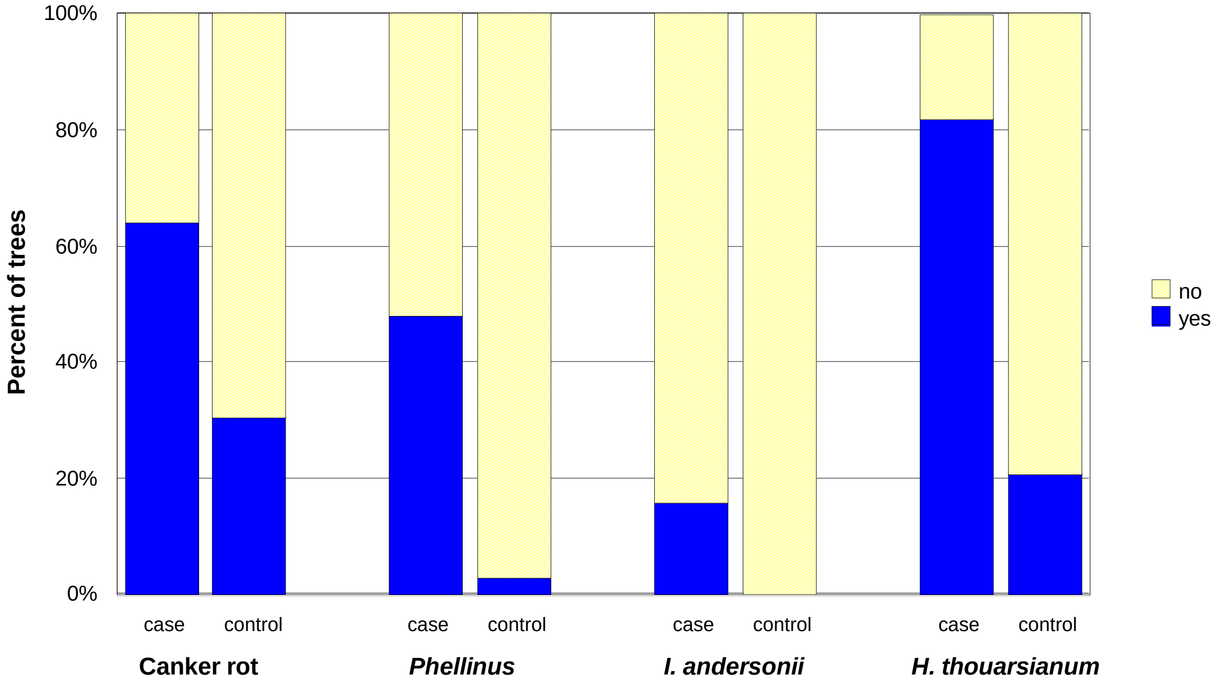

Figure 23. Percent of cases (coast live oak tree with failures occurring between June 2001 and Dec 2002) and controls (nonfailed coast live oak trees) with canker rot or fruiting bodies of *Phellinus* spp., *I. andersonii*, or *H. thouarsianum.* All differences between cases and controls are highly significant according to contingency table analysis (likelihood ratio test $p<0.0001$).

Wood decay caused by *H. thouarsianum* is often quite extensive, and is therefore likely to contribute to the failure potential of trees infected by *P ramorum*. In cases and controls, we attempted to quantify *H. thouarsianum* infections on the basis of stromatal (fruiting body) density and distribution to determine whether such variables could be used to estimate failure potential.

We used the six-level pretransformed scale (Table 2) to estimate the amount of the circumference at the break that was affected by *H. thouarsianum,* based on the presence of stromata. Ratings for controls were based on the distribution of stromata around intact stems. The average rating for the percent of stem circumference affected by *H. thouarsianum* was significantly higher in cases than controls (t-test $p<0.0001$). The distribution of *H. thouarsianum* ratings for cases and controls is shown in Figure 24. The percentage of affected stem circumference is a significant predictor of failure, even if trees without *H. thouarsianum* are excluded from the analysis (likelihood ratio test $p=0.001$ for 128 trees where *H. thouarsianum* is present). The likelihood of failure generally increases as the percent of the circumference with *H. thouarsianum* stromata increases. Controls with high *H. thouarsianum* distribution ratings (Figure 24) presumably represent trees at high risk of failure that had not yet failed by the time of the survey.

We also attempted to quantify the maximum density of *H. thouarsianum* stromata on stems (Table 2) to determine whether this variable was associated with failure risk. Maximum stromatal density counts did not differ significantly between failed and nonfailed trees (8.8 vs 9.7 respectively). Also, the overall range in the measured density of stromata (1 to 28) was identical for cases and controls. Hence, the maximum density of stromata does not appear to be a useful indicator of failure potential in coast live oak.

We also did not observe a strong correlation between the density of stromata and the amount of associated internal decay in our inspection of failed stems. The density of stromata is often highly variable on affected trees and older stromata can degrade or fall off, especially when trees fail. Reliably measuring the density and/or total biomass of stromata is also difficult. Based on our current findings, we believe that the distribution of stromata around the stem is a better indicator for assessing the contribution of *H. thouarsianum* to failure potential than is the density of stromata.

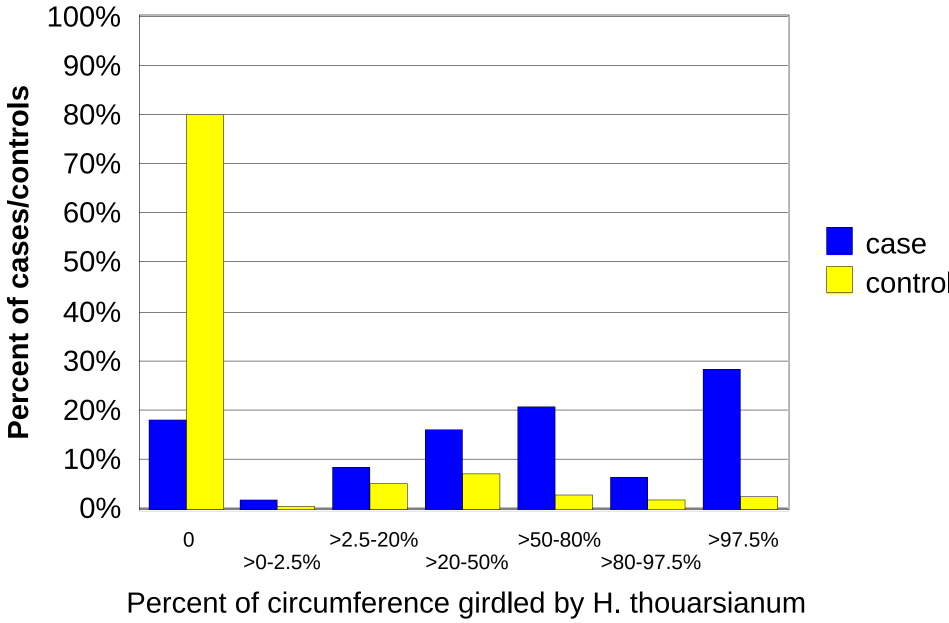

Figure 24. Comparison of amount of circumference affected by *H. thouarsianum* in coast live oak cases and controls (nonfailed coast live oak trees).

Several different wood decay fungi that can kill cambial tissue cause diseases known as canker rots. Symptoms of canker rot are relatively common in many coast live oak stands. Canker rot symptoms in coast live oak may include:

- decay columns associated with old branch stubs, cavities, or wounds;
- elongate cankers (e.g. Figure 20), some of which bleed a dark exudate, that are associated with underlying wood decay;
- fruiting bodies of canker rot fungi such as *Inonotus* and *Phellinus* spp. (Figures 25-27);
- a general slow decline of the top or a portion of the top.

Likely canker rot symptoms were noted in 57% of the 270 failures for which this factor was rated. The incidence of canker rot was higher among cases than controls (Figure 23) and the presence of canker rot symptoms was a highly significant predictor of failure (likelihood ratio test $p<0.0001$). Fruiting bodies of *Phellinus* spp. (Figures 26 and 27) and *I. andersonii* (Figure 25) were also significantly more common among cases than controls. Fruiting bodies of the canker rot fungus *I. andersonii* were found only on failed trees, typically in close association with the failure. *Phellinus* spp. (most commonly *P. gilvus*) were also very common on failed trees. *P. gilvus* often seemed to fill a niche similar to that of *H. thouarsianum* as an opportunistic but somewhat aggressive colonizer of stem areas affected by *P. ramorum* canker. Fruiting of *H. thouarsianum* and/or *Phellinus* spp. was present on 82% of all cases but only 21% of the controls.

Figure 25. Close-up of *Inonotus andersonii* fruiting on underside of a failed dead coast live oak bole.

Figure 26. *Phellinus gilvus* and *Hypoxylon thouarsianum* fruiting on failed coast live oak.

Figure 27. *Phellinus robustus* fruiting at the break of a live coast live oak scaffold failure.

Beetle boring

Boring by beetles, particularly ambrosia beetles, was significantly more common in cases than controls. Beetle boring was noted in 54% of the 260 trees (includes 13 California black oaks) with failures for which this factor was scored. Among the most recent failures that were used as cases, the incidence of beetle boring was 86% (Figure 28). In comparison, beetle boring was noted on the lower 2 m of the main stem(s) in 30% of the 170 controls. Trees with failures were significantly more likely to have beetle boring than nonfailed trees (likelihood ratio test $p<0.0001$).

For the cases and controls, beetle galleries, exit holes, and boring dust were examined to generally classify the types of beetles present. Based on these features, ambrosia beetles (*Monarthrum* spp.) were the most common beetles associated with failures. Ambrosia beetles were associated with 79% of the failures in case trees. Ambrosia beetle boring was also closely associated with advanced cases of *P. ramorum* infection. Obvious *P. ramorum* canker symptoms were present in 88.5% of the 122 trees (cases+controls) that had evidence of ambrosia beetle boring. Only four trees with ambrosia beetles were rated as free of *P. ramorum* symptoms; the remaining ten were of uncertain disease status. As shown in Figure 28, overall beetle boring and ambrosia beetle boring specifically were significantly more common in cases than in controls (likelihood ratio test $p<0.0001$). Beetle boring may be underestimated in control trees because rough bark or heavy moss cover can make holes difficult to detect, and boring dust can be washed or blown away over time. Underdetection is most likely to occur when infestation levels are low.

Boring of other types of beetles, including bark beetles (*Pseudopityophthorus* spp.), flatheaded borers (Buprestidae), and roundheaded borers (Cerambycidae), were commonly observed in trees that had ambrosia beetles. Flatheaded borers were the most common of these other beetles, especially on relatively small-diameter branches where they were often a major factor contributing to failure (Figure 29).

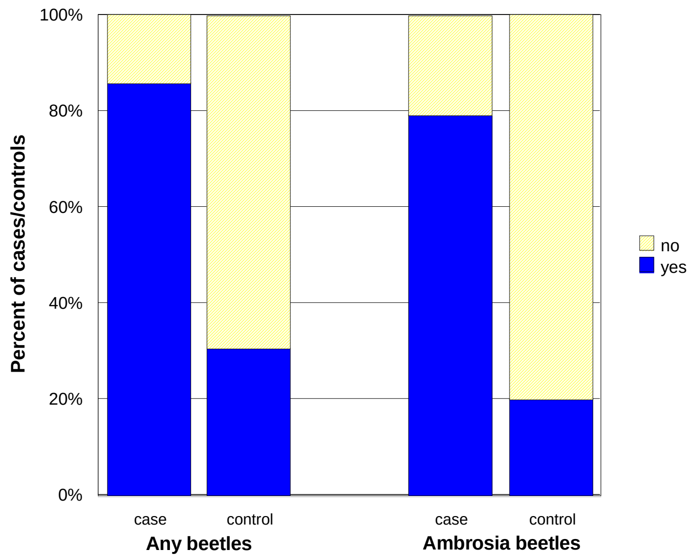

Figure 28. Percent of cases (coast live oak trees with failures occurring between June 2001 and Dec 2002) and controls (nonfailed coast live oak trees) with evidence of any wood-boring beetles or only ambrosia beetles (*Monarthrum* spp.). Differences between cases and controls are highly significant according to contingency table analysis (likelihood ratio test p<0.0001).

Figure 29. Failed branch showing ambrosia beetle and flatheaded borer tunnels.

In failed trees, ambrosia beetle boring was almost exclusively limited to portions of the wood that showed incipient to advanced decay (Figure 30). All of the cases that had beetle boring present also had wood decay present. In contrast, of the failures that had wood decay, 17.8% had no ambrosia beetles and 11.6% had no evident beetle boring of any type.

Figure 30. Failed coast live oak bole with white rot in the heartwood and sapwood and especially dense ambrosia beetle boring. Only 4% of failures had a similar density of tunneling. Rating for percent of circumference with beetle boring and with *H. thouarsianum* fruiting was >95% for this tree, which was dead prior to failure. Percent of cross-sectional area decayed scored as 50 to 75%. Average diameter at break = 33.5 cm.

We measured the maximum depth to which beetle tunnels extended into the wood on 92 failed stems. The maximum observed depth was 15 cm from the cambium. Thus, beetle boring can reach the center of stems with a below-bark diameter of 30 cm or less. The mean depth of boring was 7.3 cm; 90% of all tunnels extended 10 cm or less into the wood (Figure 31). Depth of boring was not significantly correlated with stem diameter (Figure 31), so as the diameter of the failed wood increases, the proportion of the cross section mined by beetles decreases. Consequently, beetle boring is less likely to contribute substantially to failure potential in large diameter stems than in small diameter stems.

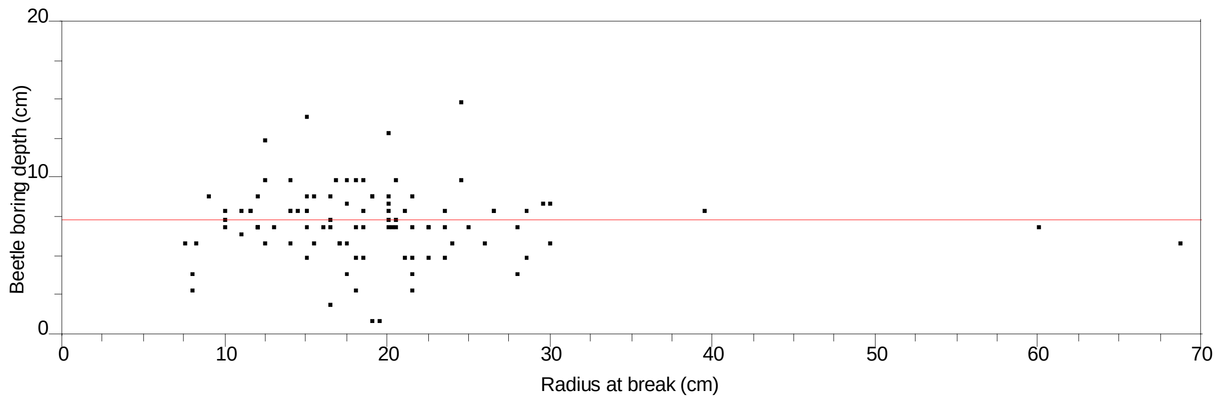

Figure 31. Ambrosia beetle boring depth into wood (excluding bark) plotted against stem radius (bark included) measured at the failure point for coast live oak. Red line represents the average boring depth measured from the cambium.

We visually estimated the extent of beetle boring on the bole of both cases and controls using the six-level pretransformed scale (Table 2), similar to the rating used for *H. thouarsianum*. For intact trees, ratings were made with the assumption that galleries fan out from observed holes, in order to reflect the likely lateral spread of boring and not simply the surface distribution of entry and exit holes. The average extent of beetle boring around the bole circumference was greater overall in cases than controls (Figure 32). Considering only the 148 cases and controls with evidence of beetle boring, the extent of beetle boring is significantly correlated with the failure outcome (likelihood ratio test $p = 0.0002$).

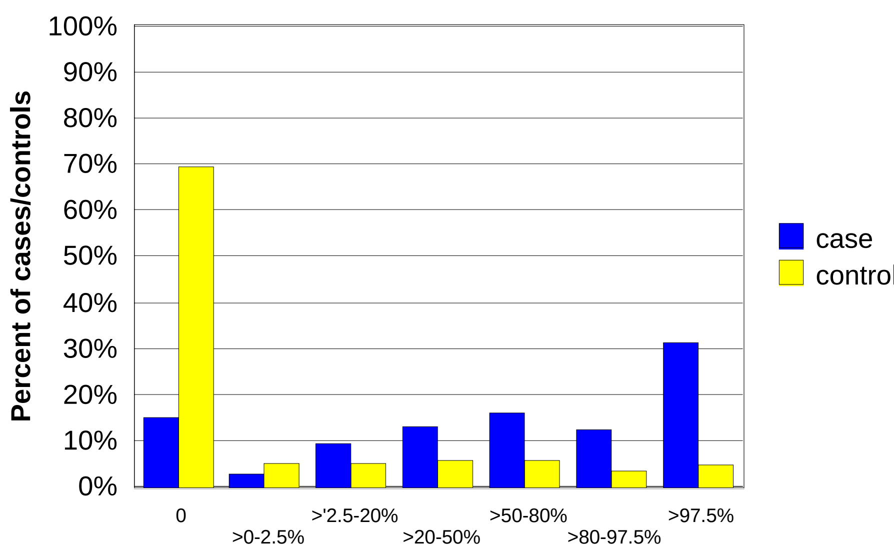

Figure 32. Percent of circumference of coast live oak cases and controls showing beetle exit holes.

To estimate beetle boring intensity in intact trees, we ranked the density (high, medium, low, none) of boring holes per unit area of the stem surface. For failed trees, we made similar ratings, but ratings were based on the density of tunnels visible on an average 25 cm^2 section of the failed surface (Table 2). We attempted to calibrate the two rating scales so that the rankings were roughly equivalent, except that an extra level (very high) was used in ratings of failed stems (Figure 30). This extra level was recoded to high for analyses comparing cases and controls.

The beetle boring intensity rating is only a significant predictor of failure (likelihood ratio test $p<0.0001$) if the zero level (no beetles) is included in the analysis. Among the 148 cases and controls with beetle boring, the boring intensity rating was not a significant predictor of the case (failure) outcome (likelihood ratio test $p=0.123$).

As noted above, estimates of beetle boring intensity in controls are probably less accurate than in cases. Estimates of the extent of boring around the tree's circumference may be more accurate than intensity measurements. Our results indicate that the extent of beetle boring is a better indicator of failure potential than beetle boring intensity, similar to the situation involving *H. thouarsianum* sporulation discussed above.

Defects

We scored all cases and controls for the presence of the defects noted on the CTFRP form (Edberg et al 1993) and several additional defects that were common in the trees we surveyed (Table 2, Figure 33). For failed trees, we also noted whether the defect was likely to have contributed to the failure. Overall, many defects were equally common in cases and controls. Multiple trunks/codominant stems, multiple branches at one point, embedded bark, heavy lateral limbs, and decayed or hollow branch stubs occurred at similar frequencies in cases and controls. Decay columns, cavities, one sidedness, and cracks or splits were noted more frequently in trees with failures than in nonfailed trees (Figure 33).

Only one defect, tree lean, was present at significantly higher incidence in controls than in cases. However, this may be an artifact associated with rating failed trees. Particularly for bole and root crown failures, it can be difficult to estimate the pre-failure amount of lean after failure has occurred.

As shown in Figure 18, tree structure was scored as a main causative factor in only 20% of failures although structural defects were commonly scored as playing a contributing role in failures (Figure 33). For instance, as noted earlier, many failures occur in close proximity to defects such as cavities and decayed branch stubs. In such situations, these defects may be scored as contributing factors even though they were not the primary cause of failure. In general, structural defects did not substantially increase failure potential in trees that have little or no decay. In trees with high levels of decay, failures were more apt to occur in stems that are compromised by structural defects.

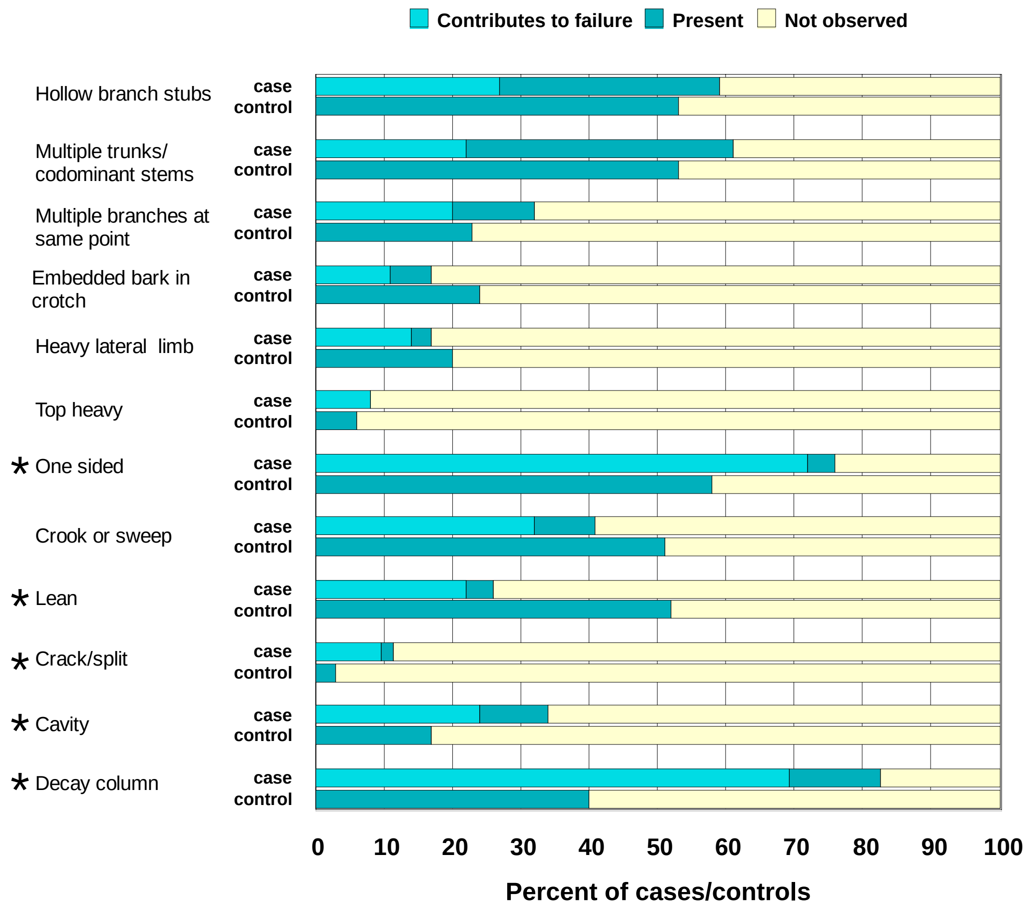

Figure 33. Defects scored in coast live oak trees with (cases) and without (controls) failures. For cases, the light colored portion of the bar represents defects that were rated as having contributed directly or indirectly to failure. Defects marked with an asterisk occur at significantly different frequencies in cases and controls (likelihood ratio test $p<0.05$).

Multiple stems

We coded multiple trunks and codominant stems as a single defect type to maintain consistency with the CTFRP reporting form (Edberg et al 1993). As shown in Figure 33, the incidence of this combined defect category did not differ significantly between cases and controls. Stem count data show that 44% of trees in this category have a single bole but codominant leaders. If trees with multiple stems are considered separately, the percentage of multistemmed trees was significantly greater among cases (41%) than controls (28%) (likelihood ratio test $p=0.035$).

Because we recorded the number of stems for almost all trees within the study areas during the tree count, the multiple stem variable can be analyzed over a much larger data set of failed and nonfailed trees. For coast live oak ($n=1431$, excludes secondary failures), failures were significantly more common among trees with multiple stems than in trees with single stems (Figure 34). For California black oak, which is represented by a much smaller sample ($n=76$), the failure rate did not differ between single and multiple-stemmed trees. Multiple-stemmed trees were significantly more common among coast live oaks (25%) than among California black oaks (12%) (likelihood ratio test $p=0.0061$).

In coast live oak, only bole and root crown failures were significantly more likely to occur in multistemmed trees than in single stemmed trees (Figure 34, likelihood ratio test $p<0.0001$ and p = 0.0002, respectively). Multistemmed trees are often the result of coppice sprouting and such trees frequently have unbalanced canopies and defects at the base of the tree, such as cavities and decay. These factors presumably contribute to the greater likelihood of bole and root crown failure in multistemmed trees.

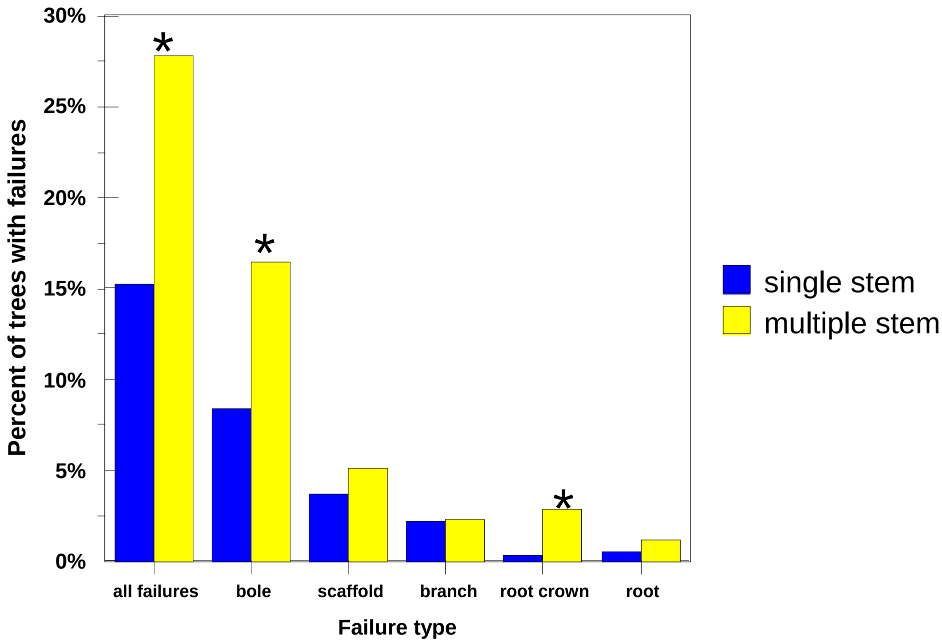

Figure 34. Failure rates among coast live oaks with single or multiple stems. For columns marked by asterisks, the proportion of failures among multistemmed trees is significantly greater than among single stem trees (likelihood ratio test $p<0.001$). Single stem n=1078 trees, multistemmed n=353 trees.

MULTIVARIATE MODELS OF FACTORS ASSOCIATED WITH FAILURE

We developed two types of multivariate models, recursive partition and logistic regression models, to identify factors associated with failure. Both types of models can be used to identify variables that predict an outcome, e.g., the case outcome in our case-control study. The two types of models are constructed in different ways and can therefore produce somewhat different sets of significant factors. Recursive partition models (other names for the overall technique include decision trees, CART™, CHAID™, C4.5, C5) are developed in a sequential, dichotomous fashion. At each step in the analysis, the procedure selects the explanatory factor that maximizes the difference in the responses between the two branches of the split. Subsequent splitting of the partitions is made in the same fashion. In recursive partition models, the algorithm accounts for the possibility that a predictor variable may affect the outcome differently in the presence or absence of another factor, or that the effects of one predictor variable depend on the levels of another. In logistic regression models, such relationships need to be modeled using interactions.

Given the wide variety of variables measured, and the fact that some of these variables are highly correlated with each other, the data can be fitted to a number of alternative models. Our objective in constructing models was to explore the relationships between explanatory variables and determine which variables or sets of related variables could be used to identify trees that are most likely to fail.

Recursive partition models

We constructed the recursive partition model for the case outcome (all failure types) starting with 43 possible predictor variables. Candidate predictor variables included defect types, indicators of disease status, variables describing the distribution and intensity of beetle boring and *H. thouarsianum* sporulation, and variables related to the site and the tree's position within the stand.

The recursive partition model for all failure types is summarized in Figure 35. The presence of *H. thouarsianum* fruiting bodies provided the best first split of the data. Trees with *H. thouarsianum* were predominantly (82%) cases, whereas the group lacking *H. thouarsianum* were mostly (80%) controls. The second split for both halves of the partition tree was based on the presence of *Phellinus* fruiting bodies. Cases were more likely than controls to have *Phellinus* fruiting whether or not they also had *H. thouarsianum* sporulation. Further splits were made on the basis of sky exposed canopy (higher percentage of cases where exposure < 50%), the presence of *I. andersonii* fruiting bodies (only present in failed trees), the distribution of *H. thouarsianum* stromata around the stem (cases more likely to have stromata around at least 50% of the stem circumference) and the presence of multiple branches arising from a single point, often as codominant stems (this defect was more common in cases).

Figure 35. Summary of results of recursive partitioning model of all failures and controls. n=106 cases (recent failures) and 170 controls (trees without large failures in the last 10 years). Blue shading indicates which of two partition branches has the greater probability of the control outcome.

This model indicates that the presence of *H. thouarsianum* and *Phellinus* fruiting bodies were the best overall predictors of failure among all trees. Other factors in the model tend to help predict failure potential when these two species are absent or present at low levels (e.g., *H. thouarsianum* stromata around less than 50% of the stem circumference).

Recursive partition models for bole/root crown failures and branch/scaffold failures are shown in Figures 36 and 37. Because the number of cases in each of these subgroups is smaller, fewer meaningful partitions can be made. The model for bole/root crown failures (Figure 36) includes several of the same variables as the model for all failures. Because few bole failures lacked *H. thouarsianum* fruiting bodies, only one split (based on sky exposed canopy) was made for trees lacking *H. thouarsianum*. Several variables not included in the model for all failures were predictors of bole failure among trees lacking both *H. thouarsianum* and *Phellinus*. In this group, increased likelihood of failure was associated with one-sided (i.e., unbalanced) tree canopy, dead trees, and multistemmed trees.

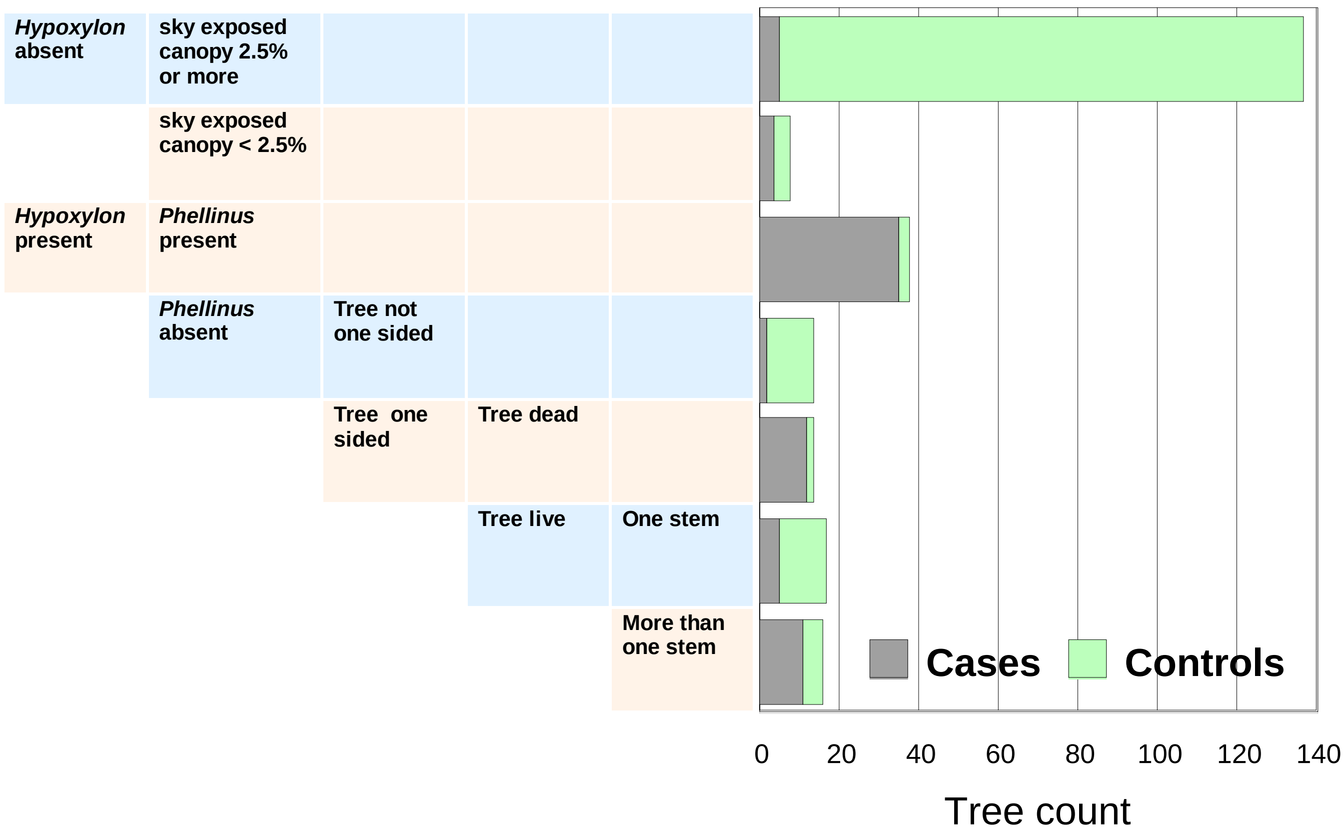

Figure 36. Summary of results of recursive partitioning model of bole/root crown failures and controls. n=74 cases (recent bole/root crown failures) and 170 controls (trees without large failures in the last 10 years). Blue shading indicates which of two partition branches has the greater probability of the control outcome.

The recursive partition model for branch/scaffold failures (Figure 37) is based on a small number of cases (n = 28). Most branch and scaffold failures occurred in dead trees (54%), whereas almost no controls were dead (3%). Among live trees, more branch failures occurred in trees with *Phellinus* conks. In dead trees, branch and scaffold failures more commonly occurred in trees with multiple trunks or codominant stems.

None of the partition models used variables describing *P. ramorum* infection as a splitting factor. This indicates that the factors that were associated with failure were similar in infected and noninfected trees. However, because we observed relatively few failures that were not infected with *P. ramorum*, it is possible that differences could exist but were not detected in this study due to a lack of statistical power.

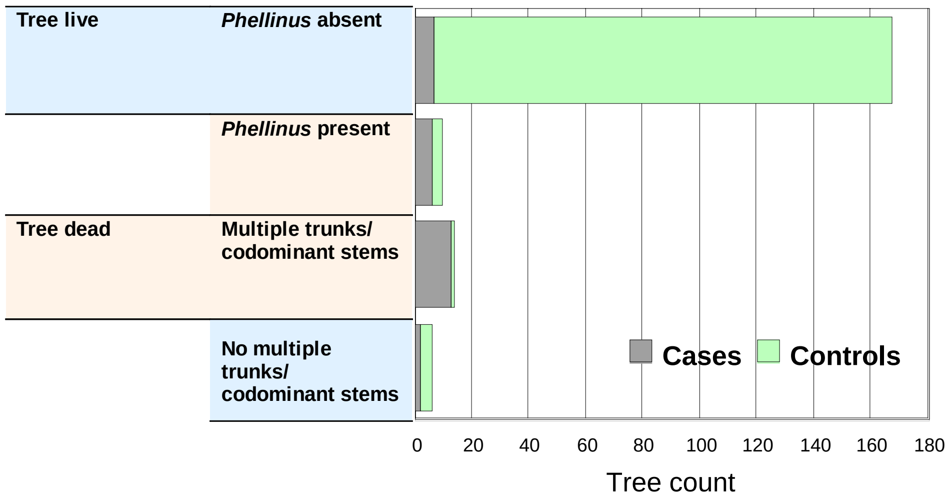

Figure 37. Summary of results of recursive partitioning model of branch/scaffold failures and controls. n=28 cases (recent branch/scaffold failures) and 170 controls (trees without large failures in the last 10 years). Blue shading indicates which of two partition branches has the greater probability of the control outcome.

Logistic regression models

Some of the explanatory variables that we recorded are highly correlated with each other. In constructing logistic regression models, highly correlated explanatory variables can often be substituted for each other with relatively little change in overall model fit. We used the Akaike Information Criterion (AIC) to help compare overall fit of related models.

One of the most highly correlated clusters of variables are those related to the presence and abundance of beetle boring, *H. thouarsianum* sporulation, and the late or dead *P. ramorum* canker status. Variables describing these three factors usually cannot be included in the same model, but they can be substituted for each other in the model without greatly affecting model fit.

The best fitting models do not necessarily constitute the best models from the standpoint of predicting failure. Some variables are more readily detected or more precisely rated in failed trees than in intact trees, or vice versa. For instance, although both internal decay and ambrosia beetle boring are strongly associated with failures, they are also more clearly evident on failed wood surfaces than in intact trees. While these factors can be fitted into multivariate models, they may not be as useful for predicting failure in intact trees. We avoided using variables in the final models that were likely to be biased due to differences in ratings of the factors in intact and failed trees.

Two models for all failures with nearly identical AIC values are shown in Table 6. In model 1, the overall *P. ramorum* disease status is included as a variable. Compared with asymptomatic trees or trees with only bleeding cankers (early *P. ramorum* symptoms), trees with more advanced disease symptoms are much more likely to fail. In model 2, the presence of beetle boring and greater distribution of *H. thouarsianum* sporulation around the stem are both positively associated with failure. By definition, one or both of these agents are present in all trees with late *P. ramorum* symptoms. The other six variables that these two models have in common have nearly identical significance levels and odds ratios in the two models. Failure was more likely to occur in dead trees, trees that have *Phellinus* sporulation or canker rot symptoms, and trees in tree neighborhoods altered by adjacent or nearby failures or mortality. Failure potential also increased with the number of stems, but decreased with increasing levels of canopy exposure to the sky (i.e., increased dominance).

Table 6. Parameters and significance levels for multivariate logistic regression models for cases (106 trees with failures) and controls (170 nonfailed trees).

Model	**Model 1**		**Model 2**	
AIC	171.3		174.29	
Overall model significance[a]	<0.0001		<0.0001	
Predictor variables	**P level[a]**	**Odds ratio (CI)[b]**	**P level[1]**	**Odds ratio (CI)[b]**
P ramorum symptoms late or dead (vs. early or none)[c]	<0.0001	13.5 (5.28-39.1)	--	--
Beetle boring present	--	--	0.0030	5.99 (1.84-20.48)
Rating of percent stem circumference with *Hypoxylon* sporulation	--	--	0.0441	4.64 (1.04-23.2)
Number of stems from ground	0.0029	50.5 (3.64-787)	0.0038	42.5 (3.21-656)
Phellinus present	<0.0001	15.5 (5.17-56-2)	<0.0001	16.03 (5.21-59.5)
Canker rot present	<0.0001	5.35 (2.36-13.03)	0.0001	4.85 (2.12-11.8)
Tree dead	<0.0001	17.1 (5.39-65.8)	0.0001	13.5 (3.58-58.5)
Sky exposed canopy rating	<0.0001	0.0181 (0.00235-0.115)	<0.0001	0.018 (0.00232-0.117)
Altered neighborhood	0.0139	4.19 (1.32-14.9)	0.0032	5.80 (1.76-21.9)

[a] Likelihood ratio test significance level

[b] Odds ratios and 95% confidence intervals. Odds ratios greater than 1 indicate that a factor is positively associated with the case (failure) outcome.

[c] Early symptoms = bleeding cankers only; late symptoms = cankers plus *H. thouarsianum* and/or beetles present

No other predictors were consistently fitted into the best overall models for all failures. However, the presence of a cavity was a significant predictor of failure in some models, for instance if the *Phellinus* present variable is excluded from the model. The AIC of that model and related models were substantially higher than that of the models reported in Table 6, indicating poorer fit.

The estimates of failure probability (i.e., the case outcome) for the modeled data set calculated from logistic regression model 2 are summarized in Figure 38. Among cases, only root failures were poorly predicted by the model. This is likely due to the low representation of root failures (n = 4) in the data set. Furthermore, root failures are likely to be associated with factors such as soil conditions and root disease centers which may not influence other types of failures.

To test the all failures model, we predicted the failure probabilities for a set of trees that were not used to develop the model. From our other study (Swiecki and Bernhardt 2001b, 2002a,b) we have sufficient data on coast live oaks in plots at four locations (location numbers 1, 4, 7, and 10) not included in this study to calculate failure probabilities using model 2. Three of the locations are in Marin County, within the overall geographic area of the six locations in this study, and one is in Napa County, well beyond the other locations. For 265 coast live oaks at these four locations, we had scored all of the factors included in model 2 with the exception of the altered neighborhood variable. However, we were able to estimate the value of the altered neighborhood variable from data on the presence of other dead and failed trees within the plot. Few failed trees were present in these plots. The failure probabilities predicted by model 2 for these trees are summarized in Figure 39. The distribution of failure probabilities for the nonfailed trees at these four locations is similar to that seen in the modeled data set. Although only 10 failures were present in the test data set, 9 of these would have been predicted using model 2 if 0.5 is used as the threshold for predicting failure (Figure 39).

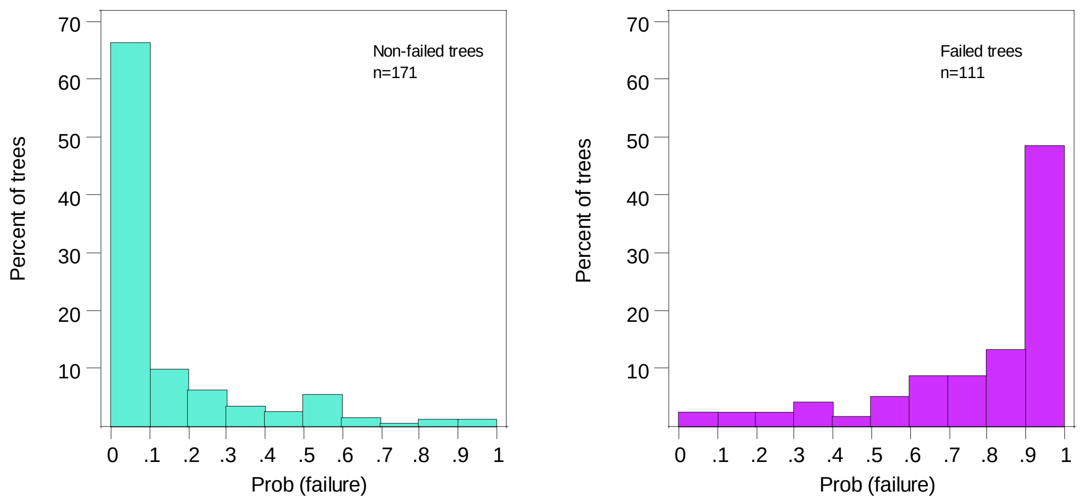

Figure 38. Frequency distributions of the probability of failure (case outcome) calculated from logistic regression model 2 (Table 6) for controls (left) and cases (right) used to develop the model.

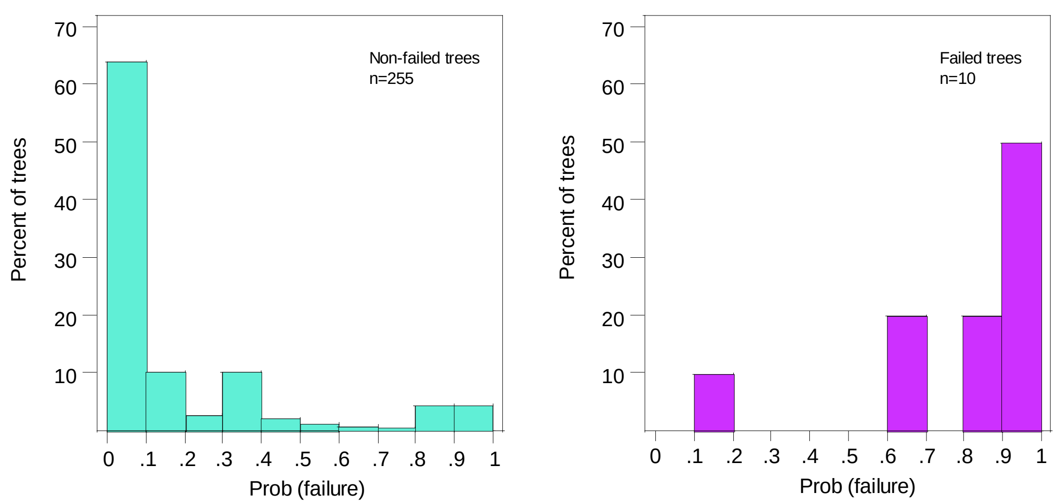

Figure 39. Frequency distributions of the probability of failure (case outcome) calculated from logistic regression model 2 (Table 6) for nonfailed (left) and failed (right) trees from four locations not used to develop the model.

Using the models, a high probability of failure is calculated only if a number of factors are simultaneously present at levels that favor failure. This is consistent with field observations. We observed that even dead trees, which have an intuitively high failure potential, generally did not have large-diameter failures unless they exhibited other symptoms associated with decay and degradation (e.g., beetle boring, *H. thouarsianum* or *Phellinus* sporulation) or poor structural characteristics (e.g., multiple stems).

Other models of interest are those that include only live trees (52 cases, 169 controls). For this subset of the data, variables related to *H. thouarsianum* and beetles can be substituted for each other, but unlike model 2 (Table 6), only the beetle variable is significant if both are included in the same model. By definition, the tree dead variable does not appear in these models and the number of stems is also nonsignificant in these models. Other variables are the same in the live failures model as in the all failures model. The overall similarity between models for only live trees and models for all failures suggests that many of the factors related to failure potential apply to either live or dead trees.

Comparison with failure reports in the CTFRP database

Larry Costello and Katherine Jones of UC Cooperative Extension provided us with an extract of coast live oak failure records from the California Tree Failure Report Program (CTFRP) database. We compared this data, which is primarily drawn from urban tree failures from throughout the state, with failure data from our field study. After excluding trees that had bole diameters of less than 15 cm DBH and branch failures less than 20 cm diameter, the CTFRP extract contained 341 failure records with failure dates ranging from 1987 to 2003.

Failed trees from the CTFRP extract had an average DBH of 84 cm, which is significantly larger than the average 48.5 cm DBH observed among failed trees in this study (t test $p<0.0001$). Among bole and root crown failures, the average diameter at the break recorded in CTFRP is 64 cm, significantly larger than the 41 cm average in our study. Differences in tree size between the two populations may be due to reporting bias in the CTFRP database, which is composed of voluntarily submitted cooperator reports. Many cooperators may be more likely to take the time and effort to file reports only for especially large and/or destructive failures. It is also possible that the underlying size distribution in the stands we studied differs from that of the largely urban tree population represented in the CTFRP. Large trees are commonly preserved during urban development in preference to smaller trees, possibly leading to a preponderance of large-diameter coast live oaks in urban areas.

The distribution of failure types also differs markedly between the two databases (Table 7). In particular, the CTFRP data contains a much higher incidence of root and root crown failures and a much lower incidence of bole and branch failures than observed in this study. The proportions of failures in each of the failure types differs significantly between the two data sets (likelihood ratio test $p<0.0001$ for all failure types). Even among failures in CTFRP which reportedly occurred in undisturbed locations ($n=57$), 33% were root failures.

Table 7. Comparison of failure type frequencies for coast live oaks in CTFRP database extract (n=340) and this study (n=271, excludes secondary failures).

Failure location	CTFRP (% of total)	This study (% of total)
Bole	24%	55%
Branch/scaffold	22%	36%
Root crown	16%	5%
Root	39%	4%

Most of the failures recorded in this study occurred in parts of the tree that were already dead (Figure 5). In contrast, the CTFRP failures were predominantly failures of live parts. For 15% of the bole failures, 5% of the branch failures, and 20% of the root failures in the CTFRP extract, the failed part was reported to be dead. The predominance of live tree failures in the CTFRP is likely due in part to reporting bias (failure of a dead tree or branch is less noteworthy than a live failure) and in part to the more intensive management of urban trees (dead trees are not typically left standing in urban areas where high value targets are common).

Whereas decay was associated with almost every failure occurring in the *P. ramorum*-affected stands we examined, decay was reported for only 75% of the failures in the CTFRP extract (Table 8). Sapwood decay was much less prevalent among failures in the CTFRP extract (Table 8) than among failures in the *P. ramorum* affected stands that we surveyed (Table 5). Sapwood and heartwood decay were present in 81% of the failed trees in our study whereas only 15% of the CTFRP extract failures were reported as having both types of decay. Furthermore, among trees where decay was noted, the extent of decay was typically greater in this study than in the CTFRP extract. The highest level of decay (>75% of the cross-sectional area at the point of failure) was scored for 61% of the failures with decay in this study but only in 25% of the CTFRP failures with decay.

Fungal conks or other fruiting bodies were reported for 20% of the failures in the CTFRP extract. In contrast, 87% of recent failures in this study exhibited sporulation of various wood decay fungi, including *H. thouarsianum*. Beetle boring was also noted far more commonly in this study (87% of recent failures) than in the CTFRP extract (7% scored as having insect injury near the break). Decay levels, fungal fruiting bodies, and beetle boring may be higher in our study trees in part because of higher frequency of dead trees in our tree population compared with the CTFRP extract population. However, most of the failures in our study also had late symptoms of *P. ramorum* canker, which include beetle boring and/or *H. thouarsianum* sporulation. Few if any of records in the CTFRP extract involve trees infected by *P. ramorum*. This suggests that characteristics of failures in trees with *P. ramorum* canker may be markedly different from those that have been commonly seen in urban coast live oaks.

Table 8. Decay location reported in coast live oaks from the CTFRP failure database extract.

Decay location	% of failures
root rot	29%
heartwood	25%
sapwood	6%
heartwood and sapwood	15%
none	25%

The most common structural defects in the CTFRP extract and their percent incidence, in decreasing order of frequency were: multiple trunks/codominant stems (30%), heavy lateral limbs (27%), leaning trunk (24%), one sided canopy (22%), and dense crown (22%). By comparing these percentages with the defects scored in both cases and controls in our study (Figure 33), it is obvious that several defects, including one sided canopy, multiple trunks/codominant stems, crook or sweep, and multiple branches at one point, were much more commonly scored as present in this study. A few defects, such as dense crown, were much more common in the CTFRP data than in our data (0.3% of the trees in this study were rated as having dense crowns).

DISCUSSION

In the *P. ramorum*-affected coast live oak woodlands we studied, failure rates have increased markedly over the last five years (Figure 1). Most of the recent failures have occurred in trees that have been killed by, or have late symptoms of, *P. ramorum* canker. Our data show that failure risk in *P. ramorum*-infected trees is increased only if the trees have been attacked by secondary organisms, including *H. thouarsianum* and wood-boring beetles. These data support anecdotal reports that *P. ramorum*-infected trees are failing at higher rates than trees that have not been infected by *P. ramorum*.

Increased failure rates are mostly due to a sharp increase in the prevalence of failures in boles and major scaffolds (Figure 1). The relative frequencies of bole and scaffold failures of trees in this study are much greater than those reported in CTFRP's mostly urban coast live oak population, where root failures predominate. Tree characteristics and pattern of failure seen in the *P. ramorum*-infected trees in this study differ substantially from what is reported in the CTFRP database.

Several lines of evidence implicate wood decay as the primary factor influencing failure potential in the stands we studied. Decay was present and rated as a contributing factor in almost all failures. Fruiting bodies of various wood decay organisms, decay columns, and canker rot symptoms were significantly more common among cases than controls. Also, variables related to decay were highly significant in both recursive partition and multivariate logistic regression models. The reduction in wood strength due to decay is a fundamental cause of almost all of the failures we observed. Similarly, in a study of oaks with stem failures conducted in the aftermath of Hurricane Hugo, 96% of failed (not windthrown) trees had internal decay (Smiley and Fraedrich (1992). Decay has also been implicated in failures among natural conifer stands (Coates 1997, Ruel 2000, Dunster 1996), but not among planted Monterey pine in a park setting (Edberg et al 1994).

Wood degradation by wood boring beetles may also contribute to failure risk, but because beetle damage is so highly correlated with the presence of decay, we were not able to completely distinguish between the effects of decay and beetle boring. For practical purposes, such a distinction may be unnecessary. The presence of extensive beetle activity serves as an indicator of increased failure potential, whether the effect is due to beetle tunneling itself or beetles are primarily an indicator of associated decay. The lack of significant beetle activity in many failed trees suggests that beetle boring is not usually the primary factor influencing failure potential. This also suggests that measures targeted at reducing or preventing beetle attack may not substantially reduce the risk of failure.

Relatively few structural defects were strongly associated with failure potential of trees in this study. Multiple stems (Table 6), multiple branches at one point (Figure 35), and one-sided crown (Figure 36) were associated with increased failure potential in various models, but none of these appears consistently in different types of models as is seen with decay-related factors. Structural defects such as multiple branching at one point, one-sided canopy distribution, and cavities either create a point of structural weakness or lead to uneven distribution of stress in the bole or branches. In coast live oak, it appears that sound wood is typically strong enough to prevent failure in the presence of these defects. However, when wood strength is lost due to decay, these same defects can help precipitate failure.

Of the defects that were associated with failure in this study, multiple trunks/codominant stems and one sided canopy were also commonly rated as contributing to failures in the CTFRP data extract. In a prospective study of failure in tropical trees, trees with asymmetric (i.e., one-sided) crowns were more likely to fail over a period of 6 years than trees with symmetrical crowns and failure tended to occur in the direction of excess canopy mass (Young and Perkocha 1994). We also observed that failure direction was primarily influenced by the direction of excess canopy mass rather than factors such as wind direction and ground aspect.

Two factors related to local stand structure are also significant in various failure models. The first, sky-exposed canopy, measures the degree of overtopping or dominance within the canopy. In all models, lower levels of sky exposed canopy (i.e., greater amounts of overtopping) were associated with a higher risk of failure. Some of this effect is related to the presence of substantial amounts of wood decay in many highly suppressed understory trees. Cooler, moister conditions in the understory may also increase the rate at which wood decay proceeds.

The second variable related to stand structure in the models is the altered neighborhood variable. The significance of this factor indicates that failures in these stands tend to occur near other dead and/or failed trees. We have previously shown (Swiecki and Bernhardt 2001b, 2002a,b) that *P. ramorum*-infected trees in these stands are clustered on a very local scale (i.e., within 8 m radius plots). Hence, spatial clustering of failures seen in this study is probably due in large part to the underlying spatial clustering of *P. ramorum* canker. However, increased wind exposure may also contribute to elevated failure potential in tree neighborhoods that have been altered by mortality and failure.

Although many of the observed failures have occurred in trees that were already dead, failures in live trees were also common. Tree mortality is clearly a major risk factor for tree failure, but other factors may be equally important. Many of the other factors related to failure potential in our statistical models influence the failure potential of both live and dead trees. In our other ongoing study in these locations (Swiecki and Bernhardt 2001b, 2002a,b, 2003), we have observed that some trees that were dead in 2000 had not experienced a failure above the threshold size by late 2002 whereas large failures had occurred in live trees during the same period. Hence, although dead trees and stems have a high failure potential, the time that elapses between mortality and failure may vary widely between trees, largely as a function of the amount and location of wood decay within the stems.

We can draw several conclusions from the recursive partitioning and logistic regression models. First, multiple factors contribute significantly to the chance that a given tree will fail. No single variable serves as a satisfactory predictor of failure. A high failure potential typically exists when multiple factors are at levels that favor failure. The logistic models also provide an idea of the relative magnitude of the effects of each factor. Even though the confidence limits for the odds ratios for each factor are relatively wide (Table 6), we can see that tree death or the presence of *Phellinus* sporulation have a bigger impact on failure potential than the presence of beetle boring, canker rot symptoms, or altered neighborhoods. Among factors modeled as continuous variables, sky exposed canopy ratings have the greatest overall impact on calculated failure probabilities, followed by the number of stems and *H. thouarsianum* girdling. The range of observable values must be considered when interpreting the odds ratios for factors modeled as continuous variables.

Although we were able to evaluate many characteristics of failed trees, some factors are clearly assessed with less accuracy on fallen trees than standing ones, e.g., lean and some canopy distribution characteristics. In addition, most trees were evaluated many months after failure had occurred. Levels of some factors, such as the presence of fruiting bodies, may have been different at the time of observation than at the time of failure. If this is so, even if a factor (e.g., decay caused by *Phellinus*) is related to failure, the rated variable (e.g., *Phellinus* sporulation) may be less useful as a predictor than is implied by the models.

These limitations can be overcome by conducting a prospective evaluation of trees that may fail. Because annual failure rates are typically low, to observe sufficient numbers of failures and the factors associated with them, prospective studies generally require very large sample sizes and frequent observations over an extended time period. In our related study (Swiecki and Bernhardt 2001b, 2002a,b, 2003), we are conducting a prospective evaluation of tree failure in *P. ramorum*-affected stands. Nonetheless, the retrospective design used in the study reported herein has allowed us to evaluate a large number of failures over a short time period and develop models that can be further refined using the results of the long-term prospective study.

Conclusion: Guidelines for assessing failure potential

Based on the results of this study, we propose the following preliminary guidelines for assessing failure potential in coast live oak stands affected by *P. ramorum* canker (Table 9). The guidelines represent a combination of results from the models and analyses as well as qualitative field observations that may not have been captured in the ratings. It should be noted that our data have been collected within a limited geographic area and a limited range of stand types. Further observations will be needed to determine if additional factors are important in some stands or if the relative importance of factors vary geographically.

Table 9. Guidelines for assessing failure potential in wildland coast live oaks in areas impacted by *P. ramorum* canker (sudden oak death)

Risk factor	Factor level	Contribution to failure potential	Additional considerations and interactions
P. ramorum symptoms	late symptoms (cankers plus beetle boring and/or *H. thouarsianum* sporulation)	moderate to high	failure potential increases as the degree of colonization by secondary organisms increases, and is also influenced by the presence of other types of decay and defects present
	early symptoms (bleeding cankers only	low	trees should be monitored over time for invasion by secondary organisms
Tree or part dead	present	high	small-diameter stems tend to fail earlier than larger stems; levels of decay and other factors influence how quickly failure occurs
Decay and related factors			
Decay	more than 50% of the stem cross section affected	high	failure potential increases with increasing decay; decay in critical areas could result in higher failure potential; decay assessment methods (drilling, etc) are needed to assess amounts of decay in standing trees; in absence of direct decay assessments, use other indicators of decay noted below (fruiting bodies, canker rot symptoms, decline symptoms, beetles)
	25-50% of the stem cross section affected	moderate	
	<25% of the stem cross section affected	low	
Fruiting of *Hypoxylon thouarsianum*	50% or more of stem circumference with visible sporulation	high	failure potential increases as percent of circumference affected increases; interacts in an additive fashion with other decay columns present in tree; risk decreases somewhat for very large stem diameters (>60 cm) unless other types of decay are also present
	2.5% to 50% of stem circumference with visible sporulation	moderate	
Fruiting of other wood decay fungi	presence of fruiting bodies of *Inonotus* spp., *Phellinus* spp., *Laetiporus sulphureus* and other primary decay fungi	high	failure potential varies somewhat between fungal species so identification is important. In absence of positive ID, consider any fruiting body emerging from or through bark to be important; interacts in an additive fashion with decay caused by *H. thouarsianum*
Beetle boring	50% or more of stem circumference with exit holes	high	failure potential increases as percent of circumference affected increases; risk is increased for small diameter stems (especially <30 cm) and may be increased if intense boring is present in a structurally critical area; beetle boring activity is commonly associated with decay, especially in larger stems
	2.5% to 50% of stem circumference with exit holes	moderate	
Cavities	>50% of stem cross sectional area affected	moderate to high	risk increases as the percent of cross sectional area affected increases; increases failure potential primarily if decay and other factors are also present
Canker rot	presence of symptoms, but no fruiting bodies	moderate	in absence of fruiting bodies, canker rot symptoms provide an indication that decay columns are present; interacts in an additive fashion with decay caused by *H. thouarsianum*
Decline due to other agents	presence of severe decline, but no fruiting bodies	moderate	in absence of fruiting bodies, severe decline symptoms may provide an indication that decay columns or root disease are present
Old failures, large decayed stubs	present	low to moderate	can serve as point of weakness where failure is likely to occur; may serve as indicators of internal decay

Table 9. (Continued.)

Risk factor	Factor level	Contribution to failure potential	Additional considerations and interactions
Tree structure factors			
Number of stems from ground	multiple stems from ground	low to moderate	mainly increases failure potential in trees with dead stems, decay and other substantial risk factors
Multiple branches from one point	present (especially if crowded)	low	mainly increases branch failure potential in trees with dead stems, decay and other substantial risk factors
One sided canopy	present	low	mainly increases bole failure potential in trees with dead stems, decay and other substantial risk factors
Stand factors			
Sky exposed canopy rating	<50% of canopy exposed to overhead sunlight	low	mainly increases failure potential in trees with dead stems, decay and other substantial risk factors; failure potential increases as sky exposure decreases (i.e., as degree of overtopping increases)
Tree neighborhood altered	other dead or failed trees present within 2-3 canopy widths of tree	low	may primarily serve as an indicator of a *P. ramorum* disease cluster; increased exposure to wind possibly increases failure risk in trees with dead stems, decay and other substantial risk factors

Given the limitations of our data set, we have not attempted to produce a strict quantitative estimator of failure potential. Rather, we present a set of guidelines that may be used to adjust existing failure rating systems to account for failure risk factors identified in this study. These guidelines apply to failures in coast live oak exceeding 20 cm branch diameter or 15 cm bole diameter. They are also limited to factors influencing failure potential in relatively undisturbed stands. Other risk factors may be important for trees in urban areas that are subjected to root disturbances, altered moisture regimes, and similar impacts.

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