Annosus Root Disease in True Firs in Northern and Central California National Forests[1]

G. W. Slaughter   J. R. Parmeter, Jr.[2]

Abstract: True fir stands in California (3.5 million acres) were surveyed during 1979-1980 to estimate the prevalence of infection by Heterobasidion annosum, and to determine stand and tree characteristics associated with the occurrence of annosus root disease. Approximately 4 percent (1.46 billion board-feet) of the live true firs were estimated to be infected by H. annosum; dead firs associated with the fungus were estimated to be 25 percent (68 million board-feet) of the total dead firs during a 1.5-year period. Annosus root disease was estimated to infest 18 percent of the surveyed area (632,000 acres), indicating a high prevalence in fir stands. The fungus occurred most often in pure fir stands, red fir stands, in stands where the basal area of live true fir exceeded 20 m^2 per hectare, and in stands having patterns of chronic mortality. Larger, older trees, near stumps, had high rates of infection.

Annosus root disease, caused by Heterobasidion annosum (Fr.) Bref. (Fomes annosus [Fr.] Karst.), causes root decay and mortality in conifers throughout California (Bega and Smith 1966). In red fir (Abies magnifica A. Murr.) and white fir (Abies concolor [Gord. & Clend.] Lindl.), root decay often leads to bark beetle attack (Cobb and others 1974) or to windthrow (Smith 1978). Forest productivity can be seriously reduced by such losses.

The presence of annosus root disease in California forests has been known for decades, but an objective estimate of its prevalence is lacking. Statewide estimates of the prevalence of annosus root disease in true fir forests, the amount of tree mortality associated with infection by the fungus, and the stand and tree characteristics related to its occurrence should be useful for the evaluation of the impact of this root pathogen upon forest productivity.

In the past, root disease surveys generally focused on sites of tree mortality, rather than on entire forests. Surveys incorporating aerial photography (Hanson and Lautz 1971, Johnson and Wear 1975, Williams and Leaphart 1978, Byler and others 1979, James and others 1984) detected standing dead trees and stand openings suggestive of mortality centers. Surveys of states and regions have often incorporated data from several sources collected by different methods and with various levels of precision (Smith 1984). Ground surveys generally have involved transects through forest stands (Bloomberg and others 1980, Filip and Goheen 1984), studies of tree mortality in plantations (Hadfield 1970, Filip 1979), or scouting surveys near roads (Bega and others 1966). Hamilton (1984) discussed the need to sample both live trees and dead trees to estimate mortality rates.

The survey reported here had two objectives: to estimate the prevalence (the proportion of trees infected out of the population of both live and dead trees, at a given time) of annosus root disease in true firs on the National Forests of northern California, and to describe stand, site, and tree characteristics associated with the occurrence of annosus root disease in stands with true firs. Estimates were, therefore, necessary both for stands having evidence of root disease and also for apparently healthy stands showing no tree mortality on aerial photographs.

The methods discussed below are a compromise among the needs to survey the forest as a whole, without reference to tree mortality, to sample a sufficient number of recently dead fir trees to allow a useful count of fir mortality, and to provide sufficient opportunities to collect data at locations where annosus root disease occurs.

METHODS

Plot Selection

The Forest Pest Management staff of the U.S. Department of Agriculture, Forest Service, Region 5, conducted surveys in California during

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[2] Staff Research Associate IV and Professor, respectively, Department of Plant Pathology, University of California, Berkeley, California.

1977-1979 to evaluate conifer mortality on National Forests following a major drought. Plots (each approximately 284 acres) were selected from each of five forest types: mixed conifer, red fir, ponderosa pine, eastside pine, and Douglas-fir (Smith and others 1983). This process provided 168 plots in the 12 National Forests of northern and central California (Mendocino, Six Rivers, Klamath, Shasta-Trinity, Modoc, Lassen, Plumas, Tahoe, El Dorado, Stanislaus, Sierra, and Sequoia). These plots were at least 50 percent under Forest Service control and were capable of producing commercial yields of timber and wood products on at least 50 percent of this area. The studies reported here were based on these plots. The four National Forests in southern California were omitted from this survey, since only negligible numbers of true firs are harvested there.

Normal-color, aerial photographic transparencies (high-speed Kodak Ektachrome S0-397; approximately 1:10,000 scale) were taken of each of the 168 plots in June 1979. Boundaries delineating a one-square-kilometer plot (247 acres) were drawn on the aerial photo best showing the plot. The photos were inspected stereoscopically for true firs by using characteristics similar to those discussed by Croft and others (1982) to identify tree species. Stands were designated (by photo delineation) mixed fir (10-80 percent true firs) or pure fir (more than 80 percent true firs).

For our survey, only plots with at least 20 hectares of contiguous mixed fir or pure fir stands or both within the square kilometer were considered for further study. Ninety plots had sufficient true fir to qualify, but five plots were omitted because they were in wilderness areas or other preserved areas where no timber management is contemplated. The remaining 85 plots provided the base sample universe.

Photo Interpretation and Cell Selection

The aerial photographs of each plot were interpreted for recently dead true fir trees, using methods developed for sequential imagery by Wear (1960) and Caylor and Thorley (1970). Recently dead firs (firs that were green on 1977 photos and discolored [faded] on 1979 photos) were circled, numbered, and the number of dead trees at that location (spot) were recorded.

Two separate samples from the 85-plot base were selected for ground checking, one representing all fir stands (green plots) and one representing fir stands with photo-detectable, recent fir mortality (mortality plots). The following selections were made with probability-proportional-to-size (PPS), with replacement (Cochran 1963). a. Green plots: forty green plots were selected PPS of the area within each plot supporting true fir stands (mixed + pure); several plots were picked more than once. A grid of potential cells (each representing 625 m^2 = 1/16 hectare) was overlaid upon that portion of the plot containing fir stands. Ten square cells were selected within the delineated fir stand boundaries on each of the 40 green plots. Plots and cells were randomly selected by using a PISYS desk-top calculator/plotter (DeMars 1980). PISYS produces transparent overlays that fit directly on the aerial photographs and that show the exact location of each cell. b. Tree mortality plots: thirty tree mortality plots were selected with PPS of the number of recently dead fir trees detected within the delineated fir-type boundaries on the plots. This number varied considerably, so some plots were selected several times, while some had no probability of selection (no tree mortality on the plot). Ten tree mortality spots were chosen with PPS of the number of dead trees per spot on each of the selected tree mortality plots. When less than 10 tree mortality spots occurred on a plot, all spots were visited.

Data Collection on Cells

Both green and tree mortality cells were located on the ground by examining photographs with a field stereo viewer (sun-illuminated), then walking to the correct location by using the photos as a map. A square 1/16 hectare cell (25 m by 25 m) was established at each green cell location or tree mortality spot; boundaries were marked with string. After a green cell was located, additional data were collected if at least one live cuttable fir (10-54 cm diameter at breast height [dbh]) was present. Forest Service policy did not permit the cutting of any green trees with a dbh larger than 54 cm. If there were no cuttable fir trees, the cell was recorded as zero. A tree mortality cell was acceptable if the dead tree(s) were true fir, had died within 2 years of the ground check, and were dbh 10 cm or larger. Although a tree mortality cell did not require the presence of a cuttable live fir tree, in all but two cells there was at least one cuttable live fir tree. Tree mortality cell locations were adjusted slightly on the ground so that recent tree mortality occurred in the center of the cell.

One live true fir tree on each cell was sampled by selecting at random a tree of cuttable size from all cuttable fir trees within the cell boundaries. Recently dead firs were also sampled at random. Standard sampling procedure for both green and dead trees involved felling trees with a chain saw, making a single horizontal cut across the stump top approximately 30 cm above ground, then cutting a full disk (1-2 cm thick) from the stump. The only exception to this procedure was for dead trees larger than 54 cm dbh. For these, a portion of a disk (approximately 1/4 pie-cut-shaped) was cut from the base of the standing tree. The disk (or portion) was sealed in a polyethylene bag containing a moist paper towel for 7 days, then inspected with a

Figure 1--"Laminated" decay in true fir stump, typical of annosus root disease. If such a stump occurred on a survey cell, the cell would be rated FA3, to indicate highly probable but not positively confirmed annosus root disease.

dissecting microscope (60X) for the conidial state of H. annosum. A positive reading required that the same colony appear on both sides of the disk or portion.

Data describing stand and site characteristics within cell boundaries were collected from the aerial photos or maps (geographic region in California, forest type, and stand species composition), and in the field (annosus root disease condition [fig. 1], basal area, tree mortality center pattern, slope, aspect, brush history, site potential, other tree species dying). Individual tree characteristics recorded to describe those live and dead trees felled for sampling included annosus root disease rating (+ or -, based on inspection of the cultured disk sample), species, total age, dbh, total height, crown class, crown ratio, radial growth, terminal growth, stumps within five meters, woodpecker injury, wetwood, insects, symptoms or signs of other diseases, and basal scars.

Estimation and Analysis

Relationships of annosus root disease presence to the above stand, site, and tree characteristics were evaluated by chi-square analysis. The prevalence of annosus root disease in true fir trees over the entire study area was estimated for northern and central California U.S. Department of Agriculture Forest Service land by expanding data collected during this survey. The general form of the estimation equation for numbers and volumes of live or dead fir trees with annosus root disease was derived from Cochran (1963), and is given in Smith and others (1983). The green and tree mortality plot survey data yielded two different kinds of estimates for the same variable: a green plot estimate and a mortality estimate. The green plot survey is considered to give a more accurate and useful estimation of losses, and it is the source for the following disease prevalence estimates because it:

a. accounts for tree mortality that is not detected on aerial photos (omission errors);
b. indicates the circumstances under which damage or tree mortality is rare or absent; c. indicates the distribution of disease as well as the distribution of tree mortality.

The tree mortality plot survey provided vital additional data (regarding dead fir trees) which was necessary for the chi-square analyses.

RESULTS AND DISCUSSION

During the survey, 47 square-kilometer plots were ground-checked. On these plots, 473 ground-sample cells were visited: 320 green cells and 153 tree mortality cells. A total of 694 true firs (449 live, 245 dead) was sampled on these cells.

Estimation of Annosus Root Disease Prevalence

Estimates of disease prevalence and associated losses are listed in tables 1 and 2. These estimates from the green plot survey apply to commercial forest land in the 12 National Forests of northern and central California. Numbers reported in the text are rounded to the nearest thousand.

Fir tree mortality associated with annosus root disease and occurring between fall 1977 and summer 1979 (table 1) was estimated to be 634,000 trees (25 percent of the total dead fir trees), having a volume of 319,000 m^3 (68 million board-feet). These estimates must be modified somewhat (as discussed below) to allow comparison with available (annual) statistics for California.

Most infected firs were attacked by the fir engraver beetle, Scolytus ventralis LeConte, which generally has a single, summer flight

Table 1--Numbers and timber volumes of two sizes of dead and annosus root diseased true fir trees estimated by green plot survey in National Forests in northern and central California

Tree status and size		Study period[1]				Annual losses[2]	
Status	Size(dbh)	No. trees	Std. Error	Volume[3]	Std. Error	No. trees	Volume[3]
Dead	> 9 cm	2,486,273	662,342	2,910,003	1,422,184	1,657,515	1,940,002
Diseased	> 9 cm	633,756	213,927	318,886	199,646	422,504	212,591
Dead	> 30 cm	780,007	259,377	2,653,238	1,428,346	520,005	1,768,825
Diseased	> 30 cm	97,501	68,054	213,971	196,386	65,001	142,647

[1] Study period was from late fall 1977 to spring 1979 or approximately 1.5 years.

[2] Study period loss estimates divided by 1.5 years, to give approximate annual losses.

[3] Individual tree volumes in cubic meters, derived from Wensel (1977), tables A.4, A.5. To convert cubic meters to board-feet, multiply by 211.9.

period in the survey area (Struble 1937). Trees attacked early in the 1977 season could have faded before fall 1977 photos were taken, and thus would not have been counted as part of this survey. Trees attacked late in the 1978 season might not have faded by the photo date in June 1979. Checking the 1979 survey photos against those from 1977 provided a discrete set of firs--those that died and faded during November and December 1977, all of 1978, and the winter or early spring of 1979. Since the percentages of trees fading during the seasons following attack are unknown, the estimate represents between 1 and 2 years of tree mortality. If figures in table 1 are considered to represent about 1.5 years, estimated annual losses become 1,658,000 dead fir trees, including 423,000 dead fir trees (volume 213,000 m^3) with annosus root disease. The estimates for trees over 30 cm dbh give some indication of annual losses of merchantable timber associated with annosus root disease: 13 percent of the dead trees (65,000/520,000) and 8 percent of the volume (143,000/1,769,000 m^3). We believe these percentages to be low, because the green plot survey was not designed to detect fir tree mortality specifically, but only incidentally.

The magnitude of these numbers is emphasized by comparison with the average annual harvest of true fir trees from Forest Service lands in California: approximately 4.7 million m^3 (one billion board-feet). Net annual growth of true fir growing stock on the National Forests in California was 4.1 million m^3 (876 million board-feet) for the year 1975 (Bolsinger 1980). By admittedly low green plot estimates, volume losses associated with annosus root disease were equal to about 4.5 percent of the annual cut and about 5.2 percent of the annual growth. This loss is similar to that estimated by Filip and Goheen (1984) for three root rots of fir (6 percent of annual growth) in Oregon and Washington. The annual fir tree mortality rate (total annual dead firs from table 1, divided by total live fir trees >9 cm dbh in table 2) would be 0.46 percent; for dead fir trees with annosus root disease the mortality rate would be 0.12 percent. Hamilton (1984) lists average annual tree mortality rates ranging from 0.289 percent for grand fir to 1.610 percent for western white pine in a mixed conifer forest.

Approximately 12.3 million live true fir trees were estimated to be infected with annosus root disease (3.8 percent of total, table 2). The estimated total volume of these trees was 6.9 million m^3 (1.46 billion board-feet), or nearly 150 percent of the annual harvest of true fir in California. We do not know the rate at which these infected live trees will die, how many will survive until harvest, or the extent of the yield reduction.

Problems with the Expression of Root Disease Prevalence

The total area of Forest Service lands in the study area supporting 10 percent or more true fir was estimated to be 1,427,000 hectares (3,527,000 acres). If each cell with annosus root disease is considered an infested 1/16 ha, then 18 percent (256,000 hectares; 632,000 acres) of the study area was infested.

Table 2--Numbers and volumes of live true fir trees and amount of annosus root disease infection estimated by green plot survey in National Forests in northern and central California.

Tree classes according to dbh (cm)	No. of trees	Std. Error	Volume[1]	Std. Error
Total true fir trees				
9<dbh<55	326,286,762	30,138,168	NA[2]	NA[2]
dbh>9	357,389,549	32,008,118	NA[2]	NA[2]
Diseased				
9<dbh<55	12,333,863	4,833,539	6,895,367	2,593,732

[1] Individual tree volumes in cubic meters, derived from Wensel (1977), tables A.4, A.5. To convert cubic meters to board-feet, multiply by 211.9.

[2] Not applicable - live trees were counted on each cell, but only felled live trees were measured: an insufficient sample to calculate total live true fir tree volumes.

Standardized methods to describe root disease prevalence are not available. With bark beetles, as little as 0.5 dead or dying tree per acre of timber type (1.2 trees/hectare) has been considered to be an infestation (Ciesla and Yasinski 1980). We found 0.2 dead trees per acre (0.5 trees/hectare) and 3.5 live trees per acre (8.5 trees/hectare) infected with annosus root disease. A combination of these two gives almost 4 infected trees per acre (9 trees/hectare). Thus, by the standards of Ciesla and Yasinski (1980), we could estimate that the entire survey area is one large annosus root disease infestation of about 3.5 million acres (1.4 million hectares). Viewed another way, if each 1/6-acre cell (1/16 hectare) in which annosus root disease was discovered represents a 1/6-acre infestation, there are 632,500 acres (256,000 hectares) of fir stands affected by the disease; or, if one of each six 1/6-acre cells has annosus root disease, then every acre is infested. Given this wide variation in possible infestation area estimates, we believe none of these statistics adequately describes the prevalence of annosus root disease.

Stand, Site, and Tree Factors

Chi-square analyses of data from all 473 cells (320 green and 153 tree mortality cells) were made to determine possible relationships between stand, site, or tree factors and the occurrence of annosus root disease. For all but one of the relationships listed below, the probability of the null hypothesis (no relationship) being true is $\underline{P}<0.01$.

Annosus root disease occurred more often than would be expected by chance in the following circumstances:

a. On cells with stumps, and in trees within 5 m of stumps
b. In red fir stands
c. In stands with > 80 percent fir
d. In stands where the basal area of live fir exceeded 20 m^2/hectare (87 ft^2/acre) and where the basal area for all live species exceeded 35-40 m^2 /hectare (150-175 ft^2/acre) ($\underline{P}$ < 0.05)
e. In firs older than 120 years
f. In firs larger than 30 cm dbh and 16 m tall
g. In codominant and intermediate firs
h. In the dry northeast region
i. In stands having centers with patterns of chronic mortality
j. In firs showing decreased terminal growth but increased radial growth for the last 20 years
k. In trees with wetwood at stump height.

Annosus root disease occurred less often than expected in stands where brush was, or had been present (live and/or dead brush).

There were either no significant relationships, or insufficient data, to analyze site potential, mortality of other species, dwarf mistletoe infestation and other diseases, crown ratio, or basal scars. Over 90 percent of all dead firs, in the same proportion whether infected with annosus root disease or not, were associated with damage caused by bark beetles and woodpeckers.

A few additional comments regarding these relationships:

Stumps

This is the single most important factor associated with annosus root disease in fir stands. The presence of stumps means a high likelihood of annosus root disease.

Age/Size

The chances of a stand or tree being infected with annosus root disease are cumulative over time; thus, younger trees have had less time to become infected, and smaller trees have a correspondingly smaller root system with less chance to become infected through root contact. Old-growth stands of true fir in California have generally been found to be heavily infested with annosus root disease. As these stands are converted to young growth through more intensive forest management, the importance of this size and age information may decrease from the timber management perspective, but it may increase from the management perspective for parks and preserved stands.

Tree Growth

Mean radial growth for firs with annosus root disease was 2.18 mm/year, while that for disease-free firs averaged 1.55 mm/year (significantly different $P < 0.001$). It was thought that annosus root disease incidence would be associated with a decreasing growth rate in the individual tree (Ferrell and Smith 1976). This was confirmed by the terminal growth data but contradicted by the radial data. The tendency for increasing radial growth rates over the last 20 years to be associated with *H. annosum*-infected trees is probably related to the fact that some trees are dying in annosus root disease centers, allowing more growing space for the remaining live firs. These are able to put on additional radial growth, utilizing the increased growing space, but are also more likely to be infected with *H. annosum*, because they are growing near infected trees. Studies have shown that radial growth often responds faster to thinning or release cutting than terminal height growth (Oliver 1979; Scharpf 1979). An increased rate of radial growth in root disease centers has been recorded previously (Chavez and others 1980). An increase in vigor of uninfected trees (as measured by annual basal area increment per unit of sapwood area) in a root-diseased stand where nearby trees were dying from root rot was noted by Oren and others (1985).

Brush

The presence of brush on a site now occupied by true fir usually indicates open and sunny stand conditions that allowed brush establishment sometime in the last 25 to 75 years. These conditions are normally related to some catastrophe that removes most or all of the trees from the site (fire, windstorm, logging, etc.). Presumably, during the period of brush cover, remnants of root systems from previous stands would have decayed and inoculum of *H. annosum* in the soil would have declined to the point where infection of new trees by contact with old roots would be unlikely.

Wetwood

This relationship is consistent with the hypothesis that wetwood is a host response of the tree to the occurrence of *H. annosum* in heartwood (Worrall and Parmeter 1982).

FUTURE RESEARCH

The estimates of true fir losses and chi-square relationships suggest the need for additional research to develop management guidelines to reduce the impacts of annosus root disease.

1. We have presented loss estimates, but these must be converted to impact estimates to be most useful to forest managers. Methods to accomplish this are unavailable at present; these might include consideration of the size of diseased trees in relation to stand stocking levels, contribution of trees to future stand growth and yield, salvageability, utilization standards, and the timing of future stand entries.
2. The prediction of future impacts under various stand conditions and manipulations requires data on rates at which key disease processes proceed. These include the rates at which new annosus root disease centers are established, rates at which those disease centers enlarge, and the length of time that trees survive after becoming infected.
3. A thorough evaluation of thinning in fir stands is needed because many fir stands are overstocked and thinning is increasingly being done, and because reduced basal area is associated with reduced annosus root disease. On the other hand, stumps are associated with increased annosus root disease. Thinning may be setting the stage for extensive losses in "leave" trees.

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