JARRAH DIEBACK –
A DISEASE OF THE JARRAH FOREST OF WESTERN AUSTRALIA

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SUMMARY

The jarrah (*Eucalyptus marginata* Sm.) forest of southwest Western Australia is threatened by a soil-borne fungus, *Phytophthora cinnamomi* Rands. Black-and-white aerial photographs were used to map the extent and pattern of the disease which was found to affect some 5 per cent of the 750 000 ha checked. The mapping gave evidence of a complex of factors such as proximity to roads and streams, annual rainfall, soil type and date of cutting which influenced the spread of the pathogen. Analysis by computer was used to evaluate the relative importance of these factors.

The role of motor vehicles in spreading infected root material was investigated. The potential for initiating new infections varied greatly among the units tested, although all are able to transport diseased soil for considerable distances. Washing with a high pressure hose removed the bulk of the soil from even the most awkward units.

The survival of *P. cinnamomi* was examined in relation to soil type and moisture curve, the rate of drying, and the time and season of exposure. The propagules which fall on freely drained sites or roads are unlikely to survive the harsh summer weather; on moisture-gaining sites, or where the inoculum is buried, the chances of survival are greater. The pathogen was able to survive the mild autumn irrespective of the site.

A short discussion of the management programme undertaken to minimise the impact of the disease on the forest is given.

I MAPPING DISEASED AREAS FROM AERIAL PHOTOGRAPHS

INTRODUCTION

The dedicated State Forests of Western Australia cover about 1 800 000 ha in the extreme southwestern portion of the State. Jarrah (*Eucalyptus marginata* Sm.) is the main timber species of this dry sclerophyll forest and accounts for 75 per cent of the annual cut from State Forests.

This forest is threatened by a serious disease known as dieback, caused by the soil-borne fungus *Phytophthora cinnamoni* Rands (Podger, 1972). The first sign of the disease is normally observed in the understorey strata where *Banksia grandis* Willd., *Xanthorrhoea preissii* Endl. and *Macrozamia reidleii* C. A. Gardn. yellow and die. The jarrah overstorey is affected later, often after most of the understorey has died. A typical symptom is a thinning out of the leaves leading to twig and branch dieback followed by the eventual death of the tree. Boundaries of diseased patches may be gradual or abrupt. Some tree species such as marri (*E. calophylla* R. Br. ex Lindl), blackbutt (*E. patens* Benth), bullich (*E. megacarpa* F.v.M) and wandoo (*E. wandoo* Blakely), which are of less abundance and economic value than jarrah, display considerable resistance and can recolonize diseased areas.

One of the initial requirements in the management of a forest disease situation is to determine the extent and location of the diseased areas. Various techniques including ground reconnaissance, aerial survey and photo interpretation have been used to map the extent of fungal and insect damage.

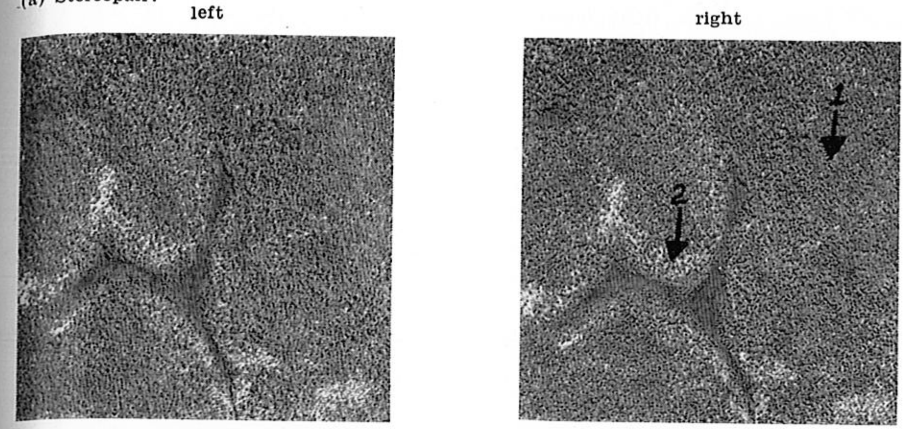
A number of attempts at mapping jarrah dieback from 1 : 15 840 black-and-white and infra-red photographs were made in the period 1956-1962. Because none of these succeeded, there were no reliable maps of the diseased areas nor estimates of their size.

During 1965, 1 : 40 000 aerial photographs of the northern jarrah forest became available. These showed distinct tonal differences within the forest area and subsequent field checks correlated areas of lighter tone with known areas of dieback. The interpretation of the diseased area from the available photographs was begun. As errors are inherent in any system of interpretation, a numerical expression of reliability of the estimates produced was needed.

METHOD

A number of diseased areas were inspected, the disease syndrome was described in detail and specimens of indicator species were collected for future reference. A number of stereograms were prepared covering the range of types to be interpreted (Figures 1 and 2) and other factors likely to cause difficulty, e.g., fire damage, logging and thinning.

(a) Stereopair:



(b) Unaffected forest, type code 1. Note dense understorey of *Banksia grandis*.

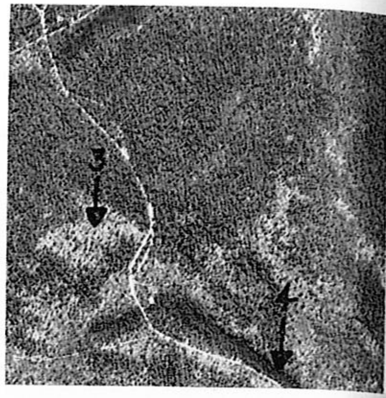
(c) Moderately affected forest type code 2. The original understorey of *B. grandis* has died and some mortality is occurring in the jarrah overstorey.

Figure 1.
STEREOGRAMS AND GROUND PHOTOGRAPHS OF UNAFFECTED AND MODERATELY AFFECTED FOREST

(a) Stereopair:

left

right



(b) Severely affected forest type code 3. Note the resistant marri (*E. calophylla*) in the foreground.

(c) Swamps and creeks, type code 4. Narrow swamps of tea-tree with *E. megacarpa* growing on the swamp edge.

Figure 2
STEREOGRAMS AND GROUND PHOTOGRAPHS OF SEVERELY AFFECTED AND SWAMP TYPES

Black-and-white aerial photographs (1 : 40 000) with the field types noted during a ground reconnaissance were used for interpretation. The minimum area outlined in the mapping was about 2 ha. Particularly doubtful areas were checked against 15.8 m/mm photographs and fire-damage plans, especially those of the 145 000 ha Dwellingup fire.

Field checks were carried out using strip lines that crosssed type boundaries. Every 20.1 m along the lines the field types were noted (Figure 3). These field types were compared with the respective photo types thus gaining estimates of reliability.

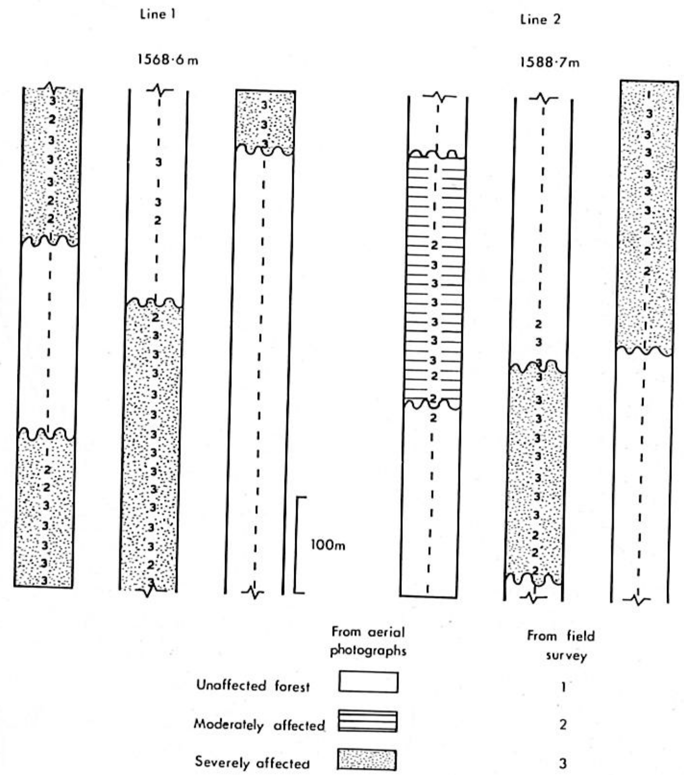


Figure 3
Field types noted from strip lines.

From the interpreted photographs, 31.7m/mm plans were prepared (Figure 4). Using these maps, check lines 402m in length were randomly selected within each type. As both methods of field checking were carried out on an area of 33 200 ha a comparison between the two can be made.

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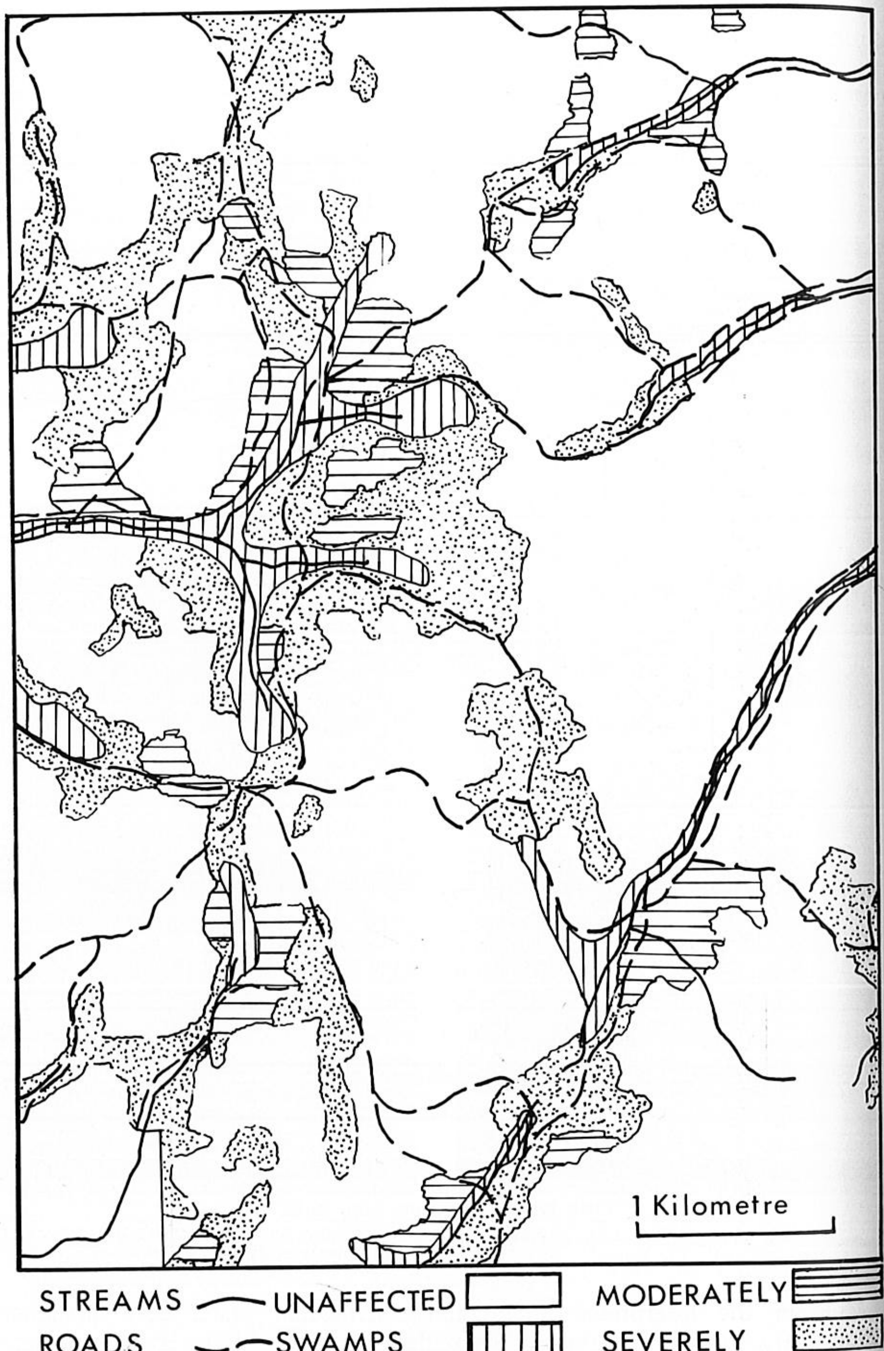

Figure 4
Plan prepared from interpreted photographs.

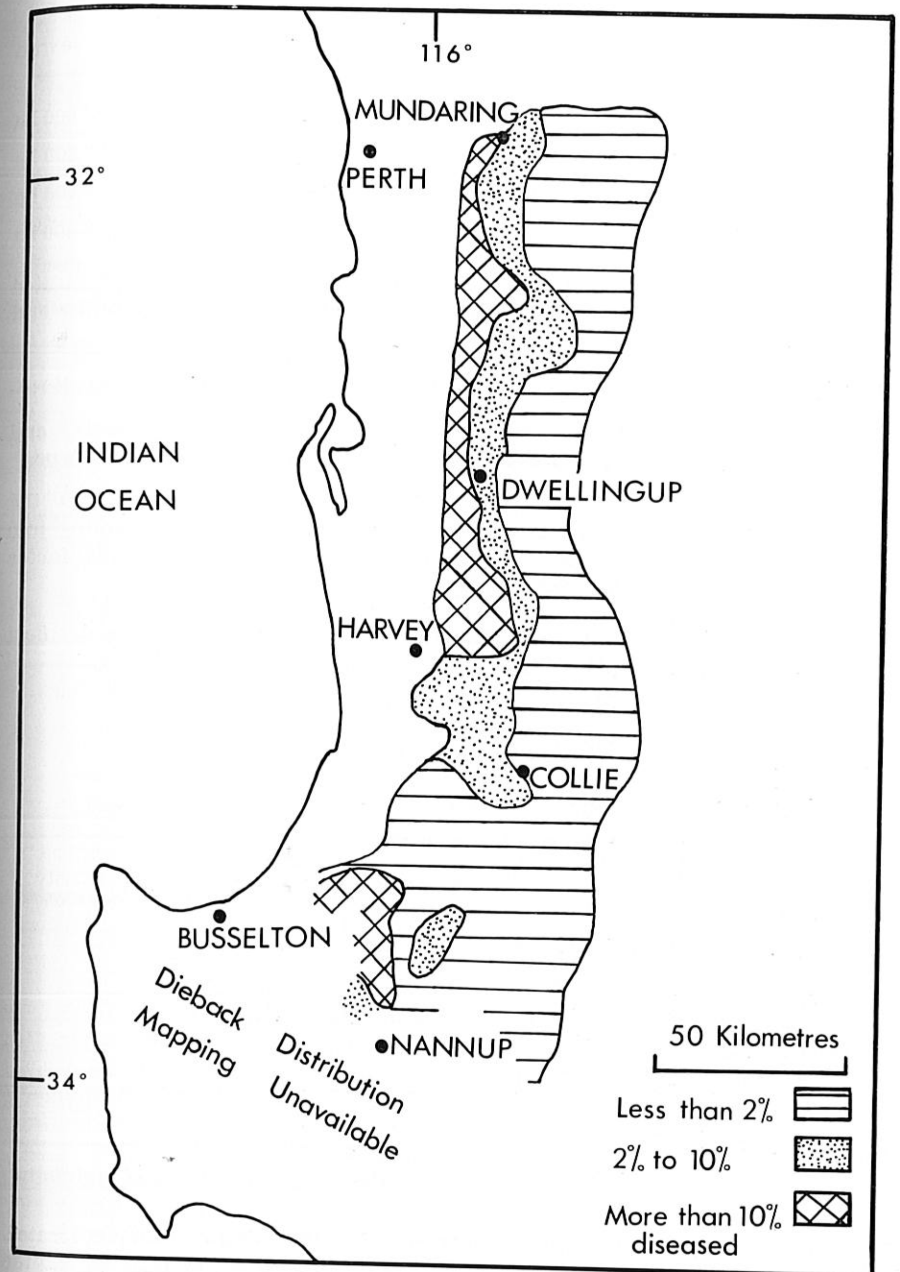

Figure 5
Distribution of Diseased Forest.

RESULTS

Some 750 000 ha of State Forest and Crown Land in the northern jarrah forest have been mapped, revealing the following situation:

Total area mapped	748 600 ha
Total area of diseased forest	37 200 ha
Area moderately affected	23 400 ha
Area severely affected	13 800 ha

The diseased forest is unevenly distributed, being strongly concentrated in the region of the Darling Scarp (Figure 5) and predominating in gullies and other water-gaining sites.

The errors were analysed in two ways, as suggested by Humphries (1961):—

(a) Errors in total area. These allow for compensating errors and may be expressed as a per cent of the total area of that type.

(b) Reliability of the map produced. This was expressed as the probability of a point randomly selected on the map, falling into the correct type when it is located in the field. This factor does not allow for compensating errors.

Errors in total area and reliability for a sample were determined by field checking an area of 251 ha with 59.6 km of strip lines (Table 1).

TABLE 1

Interpretation Accuracy from a Strip Line Check

Type	Area (ha)		Reliability per cent
	From Photos	From Striplines	
Unaffected forest	59 769	60 024	96
Affected forest	7 858	8 324	73
Swamps and Creeks	4 534	3 813	72
Water Surfaces	834	834	N.A.
Totals	72 995	72 995	86

The unaffected forest has been accurately mapped and reliably located. The affected forest has been underestimated by about 6 per cent whilst the swamp and creek type was overestimated.

A comparison between the strip line and random plot method of field checking is shown in Table 2. Area and reliability values for both the unaffected and the affected type are quite comparable.

TABLE 2

Strip Line and Random Plot Checks Compared

Type	Area (ha)			Reliability (per cent)	
	From Photos	From Strip Lines	From Random Plots	Strip Lines	Random Plots
Unaffected forest	27 952	28 084	27 682	95	96
Affected forest	4 603	4 596	4 625	69	61
Swamps and Creeks	1 797	1 672	2 045	81	96
Totals	34 352	34 352	34 352	83	84

Salable volumes of jarrah (greater than 1.5 m GBHOB) obtained by standard inventory procedures on a 33 200 ha study area are shown in Table 3. There is a marked reduction in salable volume in the affected areas and in swamps and creeks. The severely affected forest had a lower salable volume per acre and was more readily typed correctly than the moderately affected.

TABLE 3

Salable Volume by Disease Class

Type	Salable Volume m^3/ha	95 per cent Confidence Limits (per cent)
Unaffected forest	35·63	7
Affected forest	14·52	17
Moderately	22·04	15
Severely	7·31	53
Swamps and Creeks	2·76	N.A.

DISCUSSION

As the result of this work, maps showing the location of diseased areas are available from which area statements of the extent of the disease on a compartment, block, permit or overall basis are readily obtainable. The mapping confirmed that the disease is most heavily concentrated around the Darling Scarp, there being a strong association between dieback areas and valleys, water-gaining sites, roads and logging activity. The only sizable areas adjoining the Darling Scarp which are relatively free of this disease have not been logged since the turn of the century.

Phytophthora cinnamomi can be readily transported for considerable distances in soil carried on logging and roading equipment. The pathogen has never been isolated from areas of healthy forest. To minimize the artificial spread of inoculum, hygiene logging prescriptions have been implemented by the industry. This separates the logging of healthy and diseased forest into two distinct operations. Dieback plans are essential tools in the planning of logging strategy, the separation of diseased from healthy coupes, the selection of access routes and the discovery of the disease in poorly accessible areas previously considered healthy.

The plans produced have also been used to provide a stratification for the selection of inventory plots. As shown in Table 3, the differences in salable volume between air photo types are considerable and have increased the efficiency of the survey. Volume estimates by disease classes are now available for several permit areas, thus allowing coherent planning of logging operations minimizing losses of salable logs.

Data obtained from field checks indicate that the mapping has been quite reliable. The extent of the diseased areas has been underestimated by 0.5 per cent for the severely affected and by 10 per cent for the moderately affected types. The reason for the underestimation is that photographic tone is not affected until a high percentage of trees have died. The overall underestimate of 6 per cent is considered to be quite acceptable for the broad planning stage for which these data are used. The area errors for healthy forest are negligible, whilst those for the swamp type may be large.

Reliability values for healthy forest are good (96 per cent). Those for swamp types vary (72-96 per cent) with the type of field check employed. It is considered that the higher value is closer to the actual figure. Swamps and creeks are readily identifiable on the aerial photographs. They have, however, a very large perimeter per unit area. With the strip line check, large expanses of swamp were deliberately avoided because of their low economic value. The swamp and creeks encountered were usually quite narrow and it was not uncommon to find these 40-60 m either side of their expected positions.

Reliability values for diseased forest ranged from 61 to 73 per cent. With moderately affected and severely affected types, the values were as low as 35 and 53 per cent respectively. An area interpreted as either moderately or severely affected, often contained a mixture of these two types. The disease is patchy in nature and the diseased areas have a large perimeter per unit area. Small pockets of healthy forest are commonly found within a dieback area. The minimum area outlined in the aerial photograph was 2 ha whereas the unit size used in the field check was 0.08 ha. All of these factors contributed to the observed errors in reliability.

Although interpretation errors do exist, they do not invalidate operational use of the maps. For logging purposes pockets of healthy forest within a diseased area are treated as diseased. The field check lines indicate that few gross errors in interpretation occur. The bulk of the errors were restricted to either small pockets or to the boundaries between types. Few of these boundary errors would be obvious to the forester or sawmiller since neither would waste time locating his ground position accurately.

All checks were carried out in the Dwellingup Division which had been affected by a wildfire 4 years before the photographs were taken. Fire-damage areas are difficult to interpret since scorch alters the tonal contrast in the aerial photographs and the stands had not fully recovered from the effects of the fire. It is thought that the results over the whole 750 000 ha would be better than those quoted here.

The western scarp portion of the northern jarrah forest has the greatest concentration of dieback. Healthy forest in this area usually has a dense understorey of the susceptible host, *B. grandis,* thus providing good contrast

in tone. In the southern forests, interpretation from 1 : 40 000 photographs has proven difficult (J. Bradshaw, in press). In large tracts of this forest, the understorey is less dense, *B. grandis* is less common and, as the result of a change in the species composition, the understorey is often less susceptible to *P. cinnamomi.* Tonal differences on black-and-white photos are not large. Colour photographs (1 : 15 840 and 70 mm), infra-red photographs and aerial survey methods from low flying fixed wing aircraft are being used to overcome this.

Until the southern forest is mapped, a full picture of the disease situation in Western Australia will not be available. However, the bulk of the diseased forest has already been mapped and its extent and location have been determined with sufficient accuracy for the current needs of management.

II.—DISEASE ECOLOGY

INTRODUCTION

Aerial photo interpretation has indicated that the disease is not randomly distributed throughout the northern jarrah forest. The western portion of the forest area is extensively affected whereas the eastern section is relatively free of dieback. Within the western portion, there appears to be a strong association between streams, roads, cutting history and disease development. Further investigation of these aspects is warranted in order to assess their relationship to the disease.

METHOD

The Wungong, a relatively small catchment area of 13 101 ha about 40 km south-east of Perth, was selected. Of the total area, some 475 ha have been cleared for various purposes (farms, bauxite mining and pine plantation establishment), leaving a balance of 12 626 ha of forest. This catchment is considered to be typical of the jarrah forest on the western edge of the Darling Plateau and is severely affected by dieback.

A number of 31.7 m per mm plans were available for the study: soil plan divided into 10 strata, dieback plan 7 strata, roading plan 5 strata, rainfall plan 4 strata, cutting plan 5 strata, and stream plan 4 strata. Each plan was extracted separately onto specially prepared computer sheets according to a predetermined coding system. Each decision point was represented by a rectangle 4.2 x 5.1 mm, i.e., 0.22 ha on the 31.7 m/mm plans. There was a total of 6 065 decision points for each plan.

This data was processed in a computer programme written in the United States (Amidon 1964) and modified for use on the local computer by Research Officer H. Campbell. With this programme two or more sets of plans can be combined and the resultant map printed out. Tabular statements of acreages for each stratum are also available as output. These acreages are rounded off to the nearest whole number and the programme can put out up to 98 factor combinations.

With the available maps, and if all strata were present, a total of 28 000 factor combinations would have been possible. Not only does this greatly exceed the output of the programme but it would also be unwieldy to interpret. For this reason the number of factor combinations was reduced to a manageable level by lumping together similar strata.

Two, three and four-way contingency tables were calculated and analysed using the techniques outlined by Fienberg (1970). Observed values were listed and compared with expected values calculated on several different log-linear models. In a three factor analysis, nine such models can be prepared; these range from complete independence to complete dependence between the variables being tested. Then, the simplest model which best fits the observed values can be selected from the range of prepared models by means of analysis based on the chi-square statistic.

RESULTS

TWO FACTOR TESTS

Roads and dieback. The effect of roads on dieback is shown in Table 4. The area within 80 m of the road was considered near to it. The difference between the Observed and the Expected Values has been expressed as a percentage of the Expected Value to indicate the deviation of dieback distribution from randomness.

TABLE 4

Roads and Dieback Distribution

Combined Factors	Observed values (O) (ha)	Expected values (E) (ha)	$\frac{O - E}{E} \times 100\%$
Healthy forest—			
Near sealed or 1st class roads	202	256	— 21
Near 2nd to 4th class roads	2 544	3 238	— 21
Away from roads	5 778	5 029	+ 15
Diseased forest—			
Near sealed or 1st class roads	170	102	+ 67
Near 2nd to 4th class roads	1 803	1 289	+ 40
Away from roads	1 420	2 002	— 29
Swamps—			
Near sealed or 1st class roads	6	21	— 69
Near 2nd to 4th class roads	447	266	+ 68
Away from roads	248	414	— 40

The data indicates that there is more diseased forest near roads than would be expected if the disease were randomly distributed. Correspondingly, there is more healthy forest away from roads. Some roads are more closely associated with swamp types than would be expected if randomly distributed. Since topography influences road location, many low cost roads tend to hug the swamp edges.

A separate study showed that as the distance from roads increased from 80 to 240 m, the proportion of diseased forest decreased from — 29 to — 47 per cent of the expected value and the proportion of healthy forest increased from + 15 to + 24 per cent.

Streams and dieback. The pattern of dieback distribution as it is affected by streams and the topography of the adjoining valley is indicated in Table 5. 'Near streams' means within 80 m of a stream. Contours of the valleys were taken from aerial photographs.

There is much more swamp and diseased forest near streams in moderate and wide valleys than was expected on random distribution. Correspondingly there is more healthy forest away from streams or near streams with steep-sided valleys.

TABLE 5

Streams and Dieback Distribution

Combined Factors	Observed values (O) (ha)	Expected values (E) (ha)	$\frac{O-E}{E} \times 100\%$
Healthy forest—			
Near streams in wide valleys	189	777	— 76
Near streams in moderate valleys	272	453	— 40
Near streams in steep valleys	125	112	+ 12
Away from streams	7 937	7 180	+ 11
Diseased forest—			
Near streams in wide valleys	5 162	310	+ 67
Near streams in moderate valleys	323	180	+ 79
Near streams in steep valleys	34	44	— 23
Away from streams	2 520	2 860	— 12
Swamps—			
Near streams in wide valleys	445	64	+ 596
Near streams in moderate valleys	76	37	+ 103
Near streams in steep valleys	6	9	— 30
Away from streams	175	591	— 70

Another study showed that as the distance from streams increased, the proportion of diseased forest decreased.

Rainfall and dieback. The effect of rainfall on dieback distribution is shown in Table 6. Within this catchment area the rainfall varies from 1070 to 1420 mm per annum.

TABLE 6

Rainfall and Dieback Distribution

Combined Factors	Observed values (O) (ha)	Expected values (E) (ha)	$\frac{O-E}{E} \times 100\%$
Healthy forest—			
>1,270 mm annual rainfall	4 871	5 038	— 3
<1,270 mm annual rainfall	3 653	3 486	+ 5
Diseased forest—			
>1,270 mm annual rainfall	2 259	2 006	+ 13
<1,270 mm annual rainfall	1 135	1 388	— 18
Swamps—			
>1,270 mm annual rainfall	330	415	— 20
<1,270 mm annual rainfall	371	287	+ 29

The data indicates that there is more diseased and less healthy forest in the higher rainfall areas than there would be if the disease were randomly distributed. Steep sided stream valleys containing less swamp are related to the higher rainfall zone.

Soils and dieback. Table 7 indicates the effect of soil type on dieback distribution. The soil plan used in the study was prepared by H. M. Churchward of C.S.I.R.O. from a soil survey carried out during 1965. (see Appendix I).

TABLE 7

Soil Type and Dieback Distribution

Combined Factors*	Observed values (O) (ha)	Expected values (E) (ha)	$\frac{O-E}{E} \times 100\%$
Healthy forest—			
Soil unit I	3 198	2 576	+ 24
II	2 567	2 462	+ 4
III	157	370	— 57
IV	721	895	— 19
V	179	690	— 74
VI	609	535	+ 14
VII	502	446	+ 13
VIII	166	128	+ 29
IX	187	197	— 5
X	23	225	+ 5
Diseased forest—			
Soil unit I	587	1 025	— 43
II	1 000	980	+ 2
III	337	147	+ 129
IV	494	355	+ 39
V	477	274	+ 74
VI	155	213	— 27
VII	138	178	— 22
VIII	23	51	— 53
IX	97	78	+ 24
X	82	89	— 8
Swamps—			
Soil unit I	28	212	— 87
II	78	202	— 62
III	53	30	+ 77
IV	148	74	+ 102
V	365	57	+ 544
VI	28	44	— 37
VII	19	37	— 47
VIII	0	10	— 100
IX	6	16	— 60
X	15	18	— 20

* The soil units used are described in Appendix I.

The table indicates that there is more swamp and diseased forest in soil units III, IV and V than would be expected. These three units are typical of the floor and sides of valleys, particularly in the upstream reaches where the slope of the valley becomes progressively more gradual. Though soil unit IX is not closely associated with swamps it also has a greater proportion of diseased forest than expected. It consists of yellow-brown to loamy sands on the gradual slopes which occur at the head of Wungong Brook and its major tributaries. Downslope, this unit often merges with soil unit V.

Soil units I, VI, VII and VIII, not usually associated with the development of extensive swamps, have more healthy forest than would be expected. Frequent outcrop of massive laterite and an associated thin mantle of loose sandy gravel typify soil unit I which dominates the higher topographical positions in the landscape. Soil units VI, VII and VIII range from deep gravels through gravelly sands to deep friable red clays. Steep slopes are a feature of these three units. They occur mainly in the downstream area which has been subjected to deep cutting and the exposure of country rock.

Cutting and dieback. The cutting plans used in this analysis were the "cutting by decades" records compiled by the Management and Inventory branch. Table 8 compares the decade an area was cut over with the occurrence of the disease and swamps.

TABLE 8

Decade of Logging and Dieback Distribution

Combined Factors	Observed values (O) (ha)	Expected values (E) (ha)	$\frac{O-E}{E} \times 100\%$
Healthy forest—			
Cut over before 1920	265	255	+ 4
Cut over 1920–1930	285	398	— 28
Cut over 1930–1940	1 775	2 012	— 12
Cut over 1940–1950	5 435	5 202	+ 4
Cut over 1950–1955	762	655	+ 16
Diseased forest—			
Cut over before 1920	112	102	+ 10
Cut over 1920–1930	252	158	+ 60
Cut over 1930–1940	1 062	801	+ 33
Cut over 1940–1950	1 772	2 071	— 14
Cut over 1950–1955	194	260	— 25
Swamps—			
Cut over before 1920	0	21	— 100
Cut over 1920–1930	52	32	+ 58
Cut over 1930–1940	142	165	— 14
Cut over 1940–1950	494	428	+ 15
Cut over 1950–1955	13	54	— 76

The areas cut over before 1940 have a greater proportion of diseased forest than would be expected if the disease were randomly distributed. This is particularly noticeable in the decades 1920-30 and 1930-40. There is remarkably less diseased area in the forest cut over between 1950 and 1955.

Before 1960 these areas were logged on a face using a group selection system. During the 1960-1970 period, however, salvage logging was carried out within the catchment so this data has been excluded from the analysis.

THREE FACTOR TESTS

Roads, streams and dieback. Analysis of this multidimensional contingency table showed that the best fitting model was also the most complex of the nine models available, i.e. all factors are mutually interdependent. From examination of the contribution of each two-factor dependency on reducing the error term, the following hierarchy was observed:

(1) streams and disease,
(2) roads and disease,
(3) roads and streams—weakest relationship but still highly significant.

The analysis showed that the increased incidence of diseased areas near roads cannot be attributed solely to the relationship between roads and streams. A strong positive effect of roads on increasing the incidence of disease was observed. Similarly, the increased level of disease near streams is not solely attributable to the fact that many roads are located near streams. A direct effect of streams on increasing disease incidence was observed. Although roads and streams are related, the occurrence of diseased areas is more strongly influenced by stream distribution than by road distribution.

Streams, cutting decade and dieback. In this analysis, the following hierarchy was observed:

(1) streams and disease,
(2) cutting decade and disease,
(3) streams and cutting decade—weakest relationship but still highly significant.

The occurrence of diseased areas is more strongly influenced by stream location than by the decade during which the cutting occurred, although stream distribution and cutting decade are related.

Rainfall, cutting decade and dieback. In this analysis the hierarchy sequence was—

(1) cutting decade and disease,
(2) rainfall and cutting decade,
(3) rainfall and disease—weakest, yet still a highly significant relationship.

Although rainfall and cutting decade are related, the occurrence of diseased areas is more strongly influenced by cutting decade than by annual rainfall.

FOUR FACTOR TEST

Roads, streams, rainfall and dieback. Analysis of the data showed that the model of best fit was also the most complex of the possible models, i.e., all four factors are mutually interdependent. An examination of the contribution of each two factor dependency on reducing the error term gave the following hierarchy:

(1) streams and disease,
(2) roads and disease,
(3) streams and roads,
(4) rainfall and disease,
(5) rainfall and roads,
(6) rainfall and streams.

Models (5) and (6) were the weakest relationship observed, but were still significant at the p = 0.01 level.

Although roads, streams and rainfall are interrelated, the occurrence of diseased areas is more strongly influenced by stream distribution than by road distribution. In turn, road distribution is a stronger factor than rainfall in determining the incidence of diseased areas.

DISCUSSION

Approximately 27 per cent of the forested area within the catchment has been affected by the disease and a further 5.5 per cent consists of relatively unproductive swamp associations. Current evidence indicates that the disease has been present in this area since the early 1920's. To date, diseased areas have been recorded in all of the ecological situations which were examined. The major differences between the various sites has been the degree of disease development rather than the presence or absence of the disease.

A number of tributaries drain into the Wungong Brook and approximately 14 per cent of the forest is located within 80 m of a stream in a moderate or wide valley. These sites are very susceptible to the extensive development of jarrah dieback. This appears to have the strongest effect on the distribution of diseased areas within this catchment. Most of these sites are swampy or are close to swamps. The soils are water-gaining and are usually heavier in texture. Detailed examination of soil moisture data (S. Shea, pers.comm.) shows that these sites are more suitable for the activity of *P. cinnamomi* during long periods of the year. Growth of jarrah in these areas is below average. In contrast, those sites located near streams in steep-sided valleys are not so susceptible to the development of jarrah dieback. The soils are more fertile and have better internal drainage, and swamp development is very limited.

The strong relationship between soil types and disease development is not surprising in view of the interrelationship between soils and topography in the study area. All of the soil types on which extensive disease development was observed occur on moderate to gentle slopes and are either associated with, or close to, the main drainage lines.

The quality of the jarrah forest improves whilst the susceptibility of the sites to disease development decreases with increasing distance from the streams. Proximity to roads and the length of time since cutting now become important influences on the extent of disease development. Both factors involve activity by earth-moving equipment. The road bed has usually been built up with gravel, which often came from pits within dieback areas before the introduction of hygiene restrictions. It is likely that the increased development of the disease is due to the introduction of *P. cinnamomi* into these sites as the result of man's activity. Some 40 per cent of the forested area is located within 80 m of a road; this gives some indication of the intense roading activity which is common in the northern jarrah forest. Other relevant factors which may have influenced the development of the disease is the increase of soil temperature and the alteration of soil moisture regimes

following logging. Time is also an important factor and this accounts, in part, for the lower level of disease in the areas cut over between 1950 and 1955.

Annual rainfall within the range 1070-1420 mm was the least important of the factors examined. The major effects of rainfall were observed in those sites which are not naturally water-gaining. On this higher ground, a decrease in the annual rainfall correlates with a decrease in disease development.

This study has highlighted the very complex nature of the disease. Not only is its development affected by all of the ecological factors considered, but the factors themselves are interrelated. However, as outlined, some ordering of the factors is possible.

III SOME ASPECTS OF LOGGING HYGIENE

INTRODUCTION

Aerial photo mapping indicates that less than 5 per cent of the Western Australian jarrah forest is currently affected by dieback and that many of the diseased areas occur on the poorer jarrah sites. The pathogen has never been isolated from areas of healthy forest whilst artificial inoculation with small plugs of diseased soil have initiated new centres of infection in previously healthy sites (Podger, 1972). Failure to isolate *Phytophthora cinnamomi* from healthy areas is not conclusive proof of its absence from these sites, but the evidence in Western Australia indicates that this pathogen is exotic.

Spread of the fungus by natural means is very slow compared to its distribution by the transport of soil containing infected root material. Man, with his ability to transport large quantities of soil over great distances in a very short time, is the most efficient spreader of this disease. However, no data was available on the relative quantities of soil carried by different types of equipment or on the patterns of spread

It has been recommended that logging units should be washed down with a high pressure hose whenever they are moved from diseased to healthy forest. As the effectiveness of this technique had not been tested under operational conditions, it was decided to investigate the quantities of soil carried and spread by both washed and unwashed equipment.

METHOD

The tests were carried out in the Mundaring Division during the summer, in a plantation area not affected by *P. cinnamomi* and located about 8 km north-east of the Mundaring Weir Headquarters. The following units were used:

(a) Caterpillar D 7 tractor,
(b) Caterpillar D 4 tractor,
(c) Michigan Tractor Shovel (fitted with fork lift arms),
(d) Bedford 7-tonne tip truck (one set of duals),
(e) Chevrolet 0.75 tonnes ex-military truck,
(f) Land Rover (short wheelbase).

Each of the units was bogged in a wet creek crossing and then driven slowly for 201 m along a gravelled road. A 50 per cent (one side) sample of the soil that fell onto the road in the first 151 m was collected. At 201 m, any readily removable soil was collected into bins, then the unit was thoroughly hosed and the washings collected on a tarpaulin. All samples were air dried and weighed.

In the second run, the units were bogged in the same creek and driven onto a nearby road, where they were washed thoroughly. Where necessary, large clods of earth were chipped away using a crowbar and the units were moved forward and the remainder of the tracks or tyres washed. The units were then driven slowly for 140 m along a gravelled road. The sampling and rewashing was then repeated.

The tests on the different soil types were carried out in early winter after appreciable rainfall using a Bedford 3-tonne standard gang truck fitted with

a single set of duals. The soils were a loamy sand, a lateritic gravel and a loam. The gravel test was conducted in a pit where deep piles of gravel occurred. Sampling and washing were carried out as already described.

RESULTS

The weight of soil carried and dropped by the various types of equipment is shown in Table 9, which indicates marked differences between these units. At 201 m, relatively little soil remained on the rubber-tyred units with the exception of the tractor. In contrast, considerable weights of soil were retained by the tracked equipment. The D 4, Bedford and D 7 lost the greatest quantities of soil while moving whereas the losses from the other units were relatively small.

TABLE 9

Soil Weight Carried by Unwashed Equipment

Unit	Soil Weight (kg)		
	Lost in first 151 m	On Unit at 201 m	Total on Unit
Caterpillar D7	78	662	740
Caterpillar D4	162	154	316
Michigan Tractor	20	62	82
Bedford Truck	118	4·5	122·5
Chevrolet Truck	9	3	12
Land Rover	1·3	4	5·3

The patterns of spread by the various units are shown in Figure 6. Most of the soil which fell on the road was lost in the first 30 m as shown by Table 10.

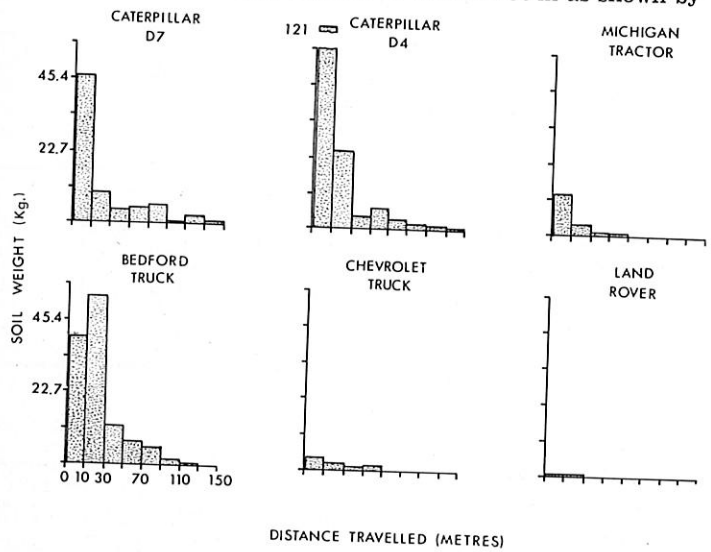

Figure 6
Soil Weight dropped from Mobile Machinery.

TABLE 10

Percentage of Soil Weight Falling onto the Road in the First 30 m.
(Total soil weight falling onto the road equals 100 per cent)

Unit	Distance		
	0–10 m	10–30 m	0–30 m
	per cent	per cent	per cent
Caterpillar D7	60	12	72
Caterpillar D4	72	15	87
Michigan Tractor	64	17	81
Bedford Truck	33	45	78
Chevrolet Truck	43	24	67
Land Rover	52	24	76

Table 11 shows that a thorough washing with a high pressure spray removed a substantial part of the soil. The D4 and D7 retained about 15 and 10 per cent respectively of the original soil weights on the unwashed units. Rubber-tyred units retained less than 0.5 per cent of the original soil weight after washing. Washing of the D7 was completed in 75 minutes, the D4 in 30 minutes and all the rubber-tyred units were washed in less than 15 minutes.

TABLE 11

Soil Weight on Equipment After Washing

Unit	Soil Weight (kg)		
	Lost in First 141 m	On Units at 141 m	Total Weight on Unit After Washing
Caterpillar D7	2·7	70	72·7
Caterpillar D4	4·1	43·6	47·7
Michigan Tractor	0·04	0·2	0·24
Bedford Truck	0·04	0·04	0·08
Chevrolet Truck	nil	nil	nil
Land Rover	nil	nil	nil

In the fortnight preceding the trial on the effects of soil type, the Meteorological Station at Mundaring Weir had recorded a total of 150 mm of rain, 32 of which fell in the 48hr-period preceding the trial. Details of these soils are shown in Table 12 and the data indicate considerable differences between the three soils tested.

TABLE 12

Mechanical Analysis and Moisture Content of Soils

Soil Type	Moisture Content	Gravel	Particles Less than 2 mm Diameter	
			Sand	Silt, Clay
	per cent	per cent	per cent	per cent
Loam	61·5	3·0	74·5	25·5
Lateritic Gravel	19·8	49·9	65·0	35·0
Loamy Sand	17·7	nil	86·0	14·0

Table 13 demonstrates that the quantity of soil carried by the Bedford varied considerably with soil type. It appears that the amount carried depends on the moisture content and the percent gravel and fines (silt and clay) in the soil. The very wet and heavy-textured loam was the most likely to remain on the vehicle.

TABLE 13

Soil Carried by the Bedford 3-Tonne Truck

Soil Type	Soil Weight (kg)		
	Lost in First 151 m	On Unit at 201 m	Total Carried
Loam	24·1	21·3	45·4
Gravel	2·2	6·3	8·5
Sand—			
First run	nil	nil	nil
Second Run	1·8	1·8	3·6

The pattern of spread for these three soils is shown in Figure 7. A rapid fall-off of soil loss with distance travelled occurred with the loam soil. For all soil types, peak losses were observed between 30 and 70 m, i.e., as the truck began to gather speed.

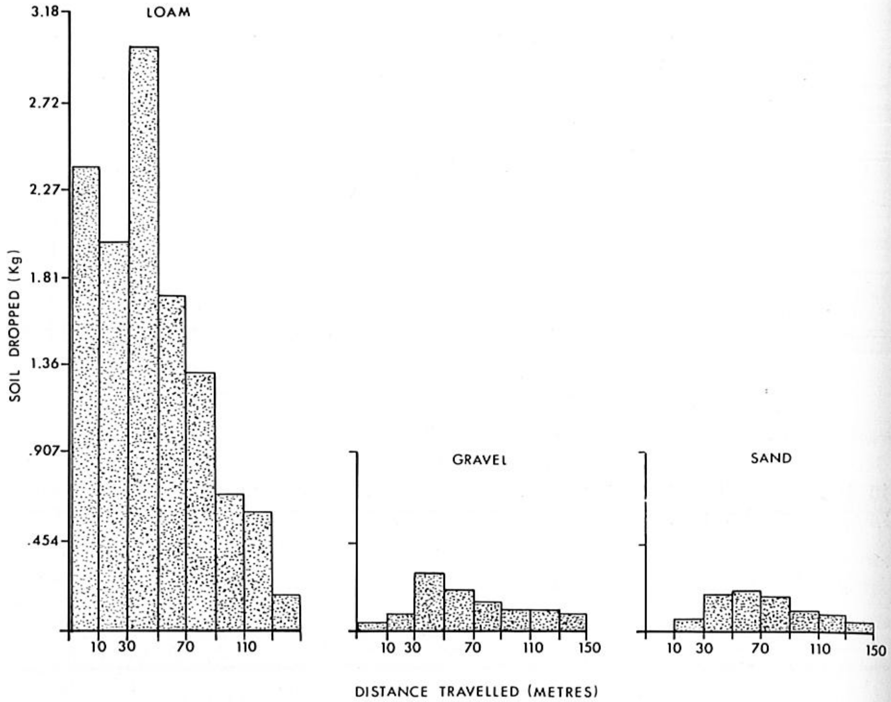

Figure 7
Pattern of spread of different soils dropped from mobile machinery.

DISCUSSION

The data presented should be used to obtain trends rather than be quoted as absolute values. Though care was taken in sampling and washing, some soil was lost. These losses were small and should not materially alter the trends observed. The soil that fell onto the road could easily be distinguished because of its colour and wetness, all but the smallest particles being picked up.

Since *P. cinnamomi* can be readily isolated from diseased soil samples weighing 90-120 g, the extremely large soil weights transported by the mobile machinery constitute a real threat to any hygiene programme. The weights tabled are air-dry equivalents and under normal operating conditions could be increased by one-sixth to one-third depending on the soil moisture content.

Most of the soil which fell onto the road was lost within the first 30 m and large clods were uncommon beyond 60 m. The probability of initiating a new centre of infection is likely to depend on both soil weight and on clod size. This indicates that the 60 m-wide strip adjacent to the diseased area is most likely to become infected during cross travel, though new infections beyond 200 m are still possible.

The ratio of soil lost to soil retained differed greatly between the units. This ratio is a function of a number of factors: tracks or rubber tyres, travelling speed, road quality and vehicle construction. The observed differences

between the D4 and D7 are due to the D7's longer track base and heavier weight, both of which lessen jolting. The general construction of the D7 also provides a number of flat surfaces which are suitable for the retention of soil. The Michigan tractor and the Land Rover were atypical in the amounts of soil retained for rubber-tyred units. In the former, a large mound of soil adhered to the large, flat towbar frame. In the latter most of the soil was retained on the sump protection plate. Both of these attachments had been fitted at Department workshops. In contrast, the two trucks were relatively efficient at self-cleaning.

The soil retained on these vehicles constitutes a further source of infective materials. The efficiency of this source is highly dependent on its later treatment. If the soil dries thoroughly *in situ* the survival of *P. cinnamomi* is much less likely. If, however, the unwashed unit is rapidly transferred to a new area on a low loader, long range spread of the pathogen to a healthy site is possible.

The data indicate considerable differences between the three soil types tested. All three soils were above field capacity at the time of the trial. This and the deliberate bogging of the truck in the sandy soil indicates that the conditions tested were relatively severe. The greatest difference between soil types was that the duals became packed with loam but this did not happen with either of the other two soils. Only the loam dropped to the road as large clods. These flew out from between the duals, when the truck began to gather speed. Soil type also affects the ease of washing: the heavier textured soils were more difficult to wash off. It is interesting to observe that, as a result of soil type, a potentially more hazardous unit (a truck with duals) in a potentially more hazardous season (winter), can in fact be less dangerous, from a hygiene point of view, than a Land Rover or a truck without duals. It is probable that the difference between the soil types tested would be even greater in summer, when the likelihood of picking up any sand or gravel would be extremely low.

Washing down greatly reduced the weight of soil retained on these units and, as a consequence, would reduce their ability to initiate new centres of infection in areas of healthy forest. Rubber-tyred units were relatively easy to clean because of their construction and ground clearance. In contrast, the D7 and D4 retained a considerable weight of soil after washing. Tracked equipment is difficult to clean completely owing to the number of hard-to-get-at places were soil can collect. Nevertheless, washing has reduced the weight of soil falling onto the road by over 95 per cent. The greater percentage retention by the D4 is probably due to its smaller size which makes it more difficult to clean.

The high pressure wash was carried out by the unit's driver. Some readily removable soil on the treads, the rear of the bulldozer blade and the track pins was often missed during the washing. This would be typical of a reasonably thorough wash carried out under operational conditions. Minor structural modifications to some of these units should be considered so as to reduce the weight of soil collected and assist the washing.

All of the units tested can transport diseased soil for considerable distances. Potential for initiating new infections varies greatly between units. The D4, the Bedford with duals and the D7 are the most efficient units for spreading diseased soil over short distances while the D7 and the D4 have a greater potential for spread over longer distances. The large soil weights involved indicate that segregated logging operations and the elimination of cross-travel from diseased to healthy areas are essential if the artificial spread of *P. cinnamomi* is to be minimized.

To be efficient, washing down must be carried out conscientiously and large clods should be chipped away with a bar. It would be best to wash tracked units on boards, moving the unit forward during the washing so as to clean the portion of the tracks previously in contact with the ground. The unit should then be moved 20-30 m in order to dislodge and wash away any soil missed in the original wash. Using this technique over 90 per cent of the soil on even the most difficult units can be removed.

A careful selection of the site, the soil type, the time of year and the type of logging unit can markedly reduce the likelihood of spreading the pathogen during logging operations. Care in the planning of a logging operation is just as important for logging hygiene as is the washing down of dirty equipment before its transfer into healthy areas.

IV *P. cinnamomi* SURVIVAL IN FOREST SOILS

INTRODUCTION

Transport of the inoculum as discussed in Chapter III is only a part of spreading the disease. The pathogen must be able to survive in its new environment until conditions suitable for growth occur.

Hepting (1964) has stated that survival of this pathogen is poor in soils dry for long periods and considers that this could prove a limiting factor. Kuhlman (1964) was unable to recover *P. cinnamomi* from soil allowed to dry naturally for two months and concluded that prolonged periods at low soil moisture are fatal to the fungus. Zentmyer and Mircetich (1965) demonstrated prolonged survival at high moisture contents but could not recover the fungus from soil allowed to dry for three months. These authors concluded that chlamydospores and oospores are not important to survival, at least under very dry conditions (3 per cent moisture content in a sandy loam soil). In the absence of data on the moisture characteristic curves of any of these soils, the applicability of this information to other soil types is restricted. In addition to this limitation, there is no information on the critical periods of survival at different moisture levels. Griffin (1963) suggests that most fungi can absorb water from pore spaces in soil at the permanent wilting point. He also states (1969) that the effect of matric suction on the survival of fungal resting structures is poorly understood.

The West Australia summers are typically hot and dry, but an uninterrupted drying cycle of 2-3 months would be rare in the southwest. Markedly different ecological sites are found within the forest area and could be expected to affect drying rates and fungal survival. Further information on *P. cinnamomi's* survival ability at varying moisture levels and in different soil types is necessary to evaluate the restrictions imposed by the jarrah forest environment.

EFFECT OF TIME AND MOISTURE TENSION

METHOD

Seedlings of *Banksia grandis* and *Eucalyptus marginata* were grown for two months in uninfected, lateritic silt and spillway sand soils collected near Dwellingup. The pots were then inoculated with pure cultures of *P. cinnamomi* grown on agar. Severe mortality in both species was observed within a month of inoculation. When most of the seedlings had died, each soil was mixed thoroughly, baited for *P. cinnamomi* (Chee and Newhook, 1965) and then screened through a 2 mm mesh. Portions of these soils were then equilibrated to the moisture potentials shown below.

Sand: 0.04, 0.10, 0.35, 1.0, 3.0 and 8.1 bars.

Silt: 0.10, 0.35, 1.0, 3.0 and 8.1 bars.

Runs from 0.04 to 1.0 bars were carried out with a pressure plate using water columns and a mercury manometer to check the tension; the other runs were carried out using a pressure membrane apparatus. A calibrated pressure gauge provided the correct tensions. All data was obtained from disturbed cores of about 70 g dry weight. Samples were soaked for 24 hours and tension was maintained until water flow had ceased for at least 4 hours.

At equilibrium, each batch was sampled for moisture and baited for *P. cinnamomi*. Fifteen samples for each soil and moisture potential were individually wrapped in polythene bags and stored at 25° C. At intervals of 2, 4, 8, 12 and 20 weeks, three replicates of each treatment were removed from storage. Two were baited separately and the other was dried at 105° C to determine moisture content.

RESULTS

Baiting of 18 samples from each soil type prior to equilibration yielded 100 per cent recovery from the silt soil and 55 per cent recovery from the sand. Characteristic moisture curves are presented in Figure 8 and depict marked differences between the two soils used. Recovery of the pathogen for the individual treatments is presented in Table 14.

Table 14

Recovery of *P. cinnamomi* from Soils at Different Moisture Tensions

Silt

Tension (bars)	Initial	Time (weeks)				
		2	4	8	12	20
0·10	2/2*	2/2	2/2	2/2	2/2	2/2
0·35	2/2	2/2	2/2	2/2	2/2	2/2
1·0	2/2	1/2	2/2	2/2	2/2	0/2
3.0	2/2	1/2	2/2	1/2	2/2	1/2
8.1	2/2	2/2	2/2	2/2	2/2	2/2

Sand

Tension (bars)	Initial	Time (weeks)				
		2	4	8	12	20
0·04	2/2	0/2	0/2	0/2	1/2	0/2
0·10	0/2	0/2	1/2	0/2	2/2	0/2
0·35	1/2	1/2	0/2	0/2	2/2	0/2
1·0	0/2	1/2	1/2	1/2	2/2	0/2
3.0	0/2	0/2	1/2	1/2	2/2	0/2
8.1	0/2	2/2	0/2	0/2	2/2	1/2

* The expression represents the fraction of replicates baited from which *P. cinnamomi* was recovered.

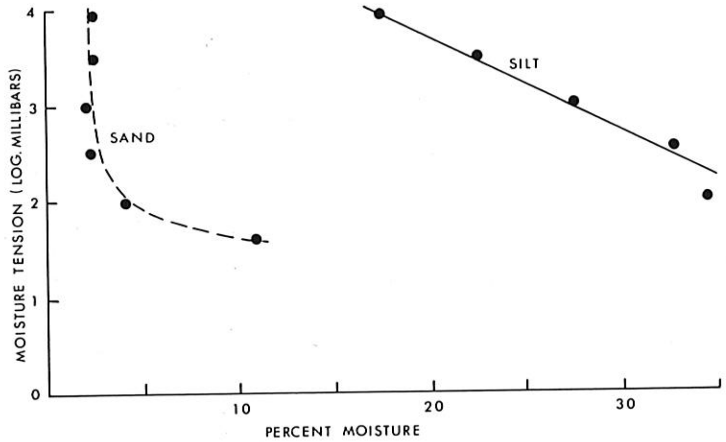

Figure 8
Moisture curves showing differences between two soils.

Excellent recoveries of the pathogen were obtained from the silt soil irrespective of either tension or time. *P. cinnamomi* was recovered from 90 per cent of the samples baited. Soil moisture contents ranged from 17.5 per cent at 8.1 bars to 34.5 per cent at 0.10 bars tension. In contrast, recoveries from the sandy soil were less regular, with an overall recovery of only 33 per cent. These lower rates of recovery could be owing to the more dispersed nature of the inoculum in this soil type. During the preparation of the samples it was noted that the sand soil contained much less root material than did the more fertile silt soil. Nevertheless, *P. cinnamomi* was recovered for up to 12 weeks in treatments with moisture contents less than 2.5 per cent, i.e., 0.35, 1.0, 3.0 and 8.1 bars.

EFFECT OF DRYING

METHOD

Silt was collected from an active dieback gully near Dwellingup and sand with a high organic matter content from a dieback swamp at Westcliffe. About 300 g of each sample was placed into 250 ml paper cups, watered thoroughly and set up in the open. The samples were shaded with 95 per cent Sarlon shadecloth attached to a low wooden frame.

The first trial was conducted during December and January. One treatment was baited immediately; the others were allowed to dry naturally for 2, 4 and 8 weeks before baiting. The second trial was run from mid-February to the end of March. Treatments in this trial were baited after drying for 1, 2, 3, 4 and 6 weeks.

The temperature of each soil type was recorded daily at 3 p.m. Prior to baiting, the soil in the cups was mixed thoroughly, one-third being removed and oven-dried to determine moisture content. The remaining soil was baited twice with four replicates using the lupin technique of Chee and Newhook (1965). Characteristic moisture curves were obtained with the filter paper technique described by Fawcett and Collis-George (1967).

RESULTS

The characteristic moisture curves for the two soils are shown in Figure 9. The Westcliffe sand has an unusual curve because of the high proportion of organic matter in that soil. Temperature and moisture data for both trials are shown in Figures 10 and 11. The soil moistures after drying periods of 2 and 4 weeks are shown in Table 15.

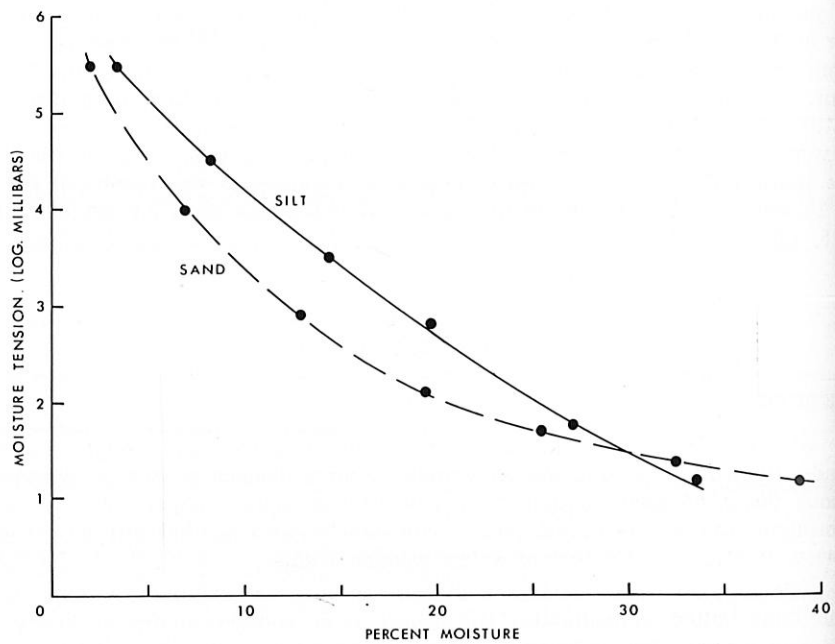

Figure 9
Characteristic moisture curves of silt from dieback gully and humisoid-sand from dieback swamp.

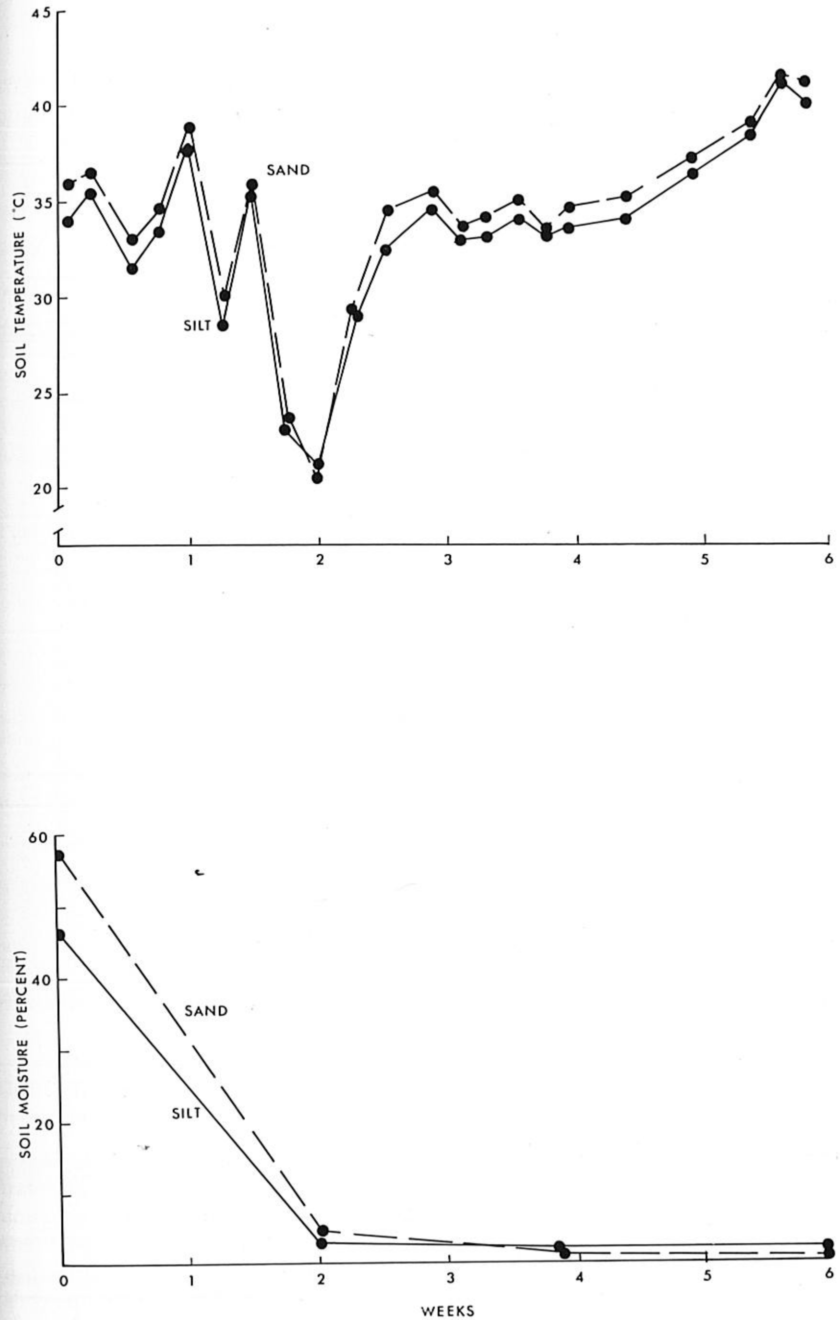

Figure 10
Temperature and moisture data for December-January trial to measure effect of drying.

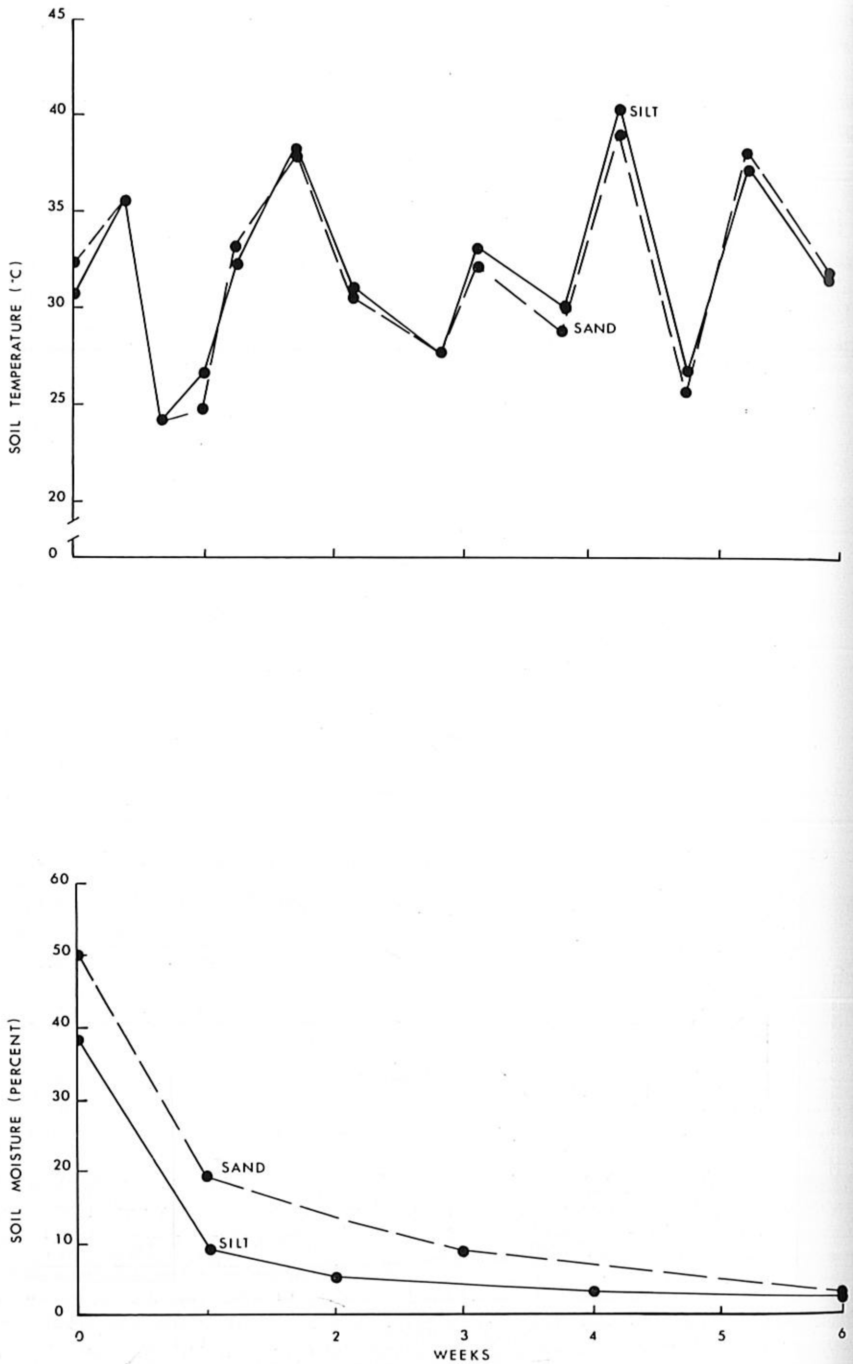

Figure 11
Temperature and moisture data. February trial to measure effect of drying.

TABLE 15

Soil Moistures After Two and Four Weeks Drying

Soil	2 weeks		4 weeks	
	Trial 1	Trial 2	Trial 1	Trial 2
	per cent	per cent	per cent	per cent
Silt	3·1	5·2	2·1	3·4
Sand	4·6	12·8	1·3	7·8

The recoveries of *P. cinnamomi* from the samples are presented in Table 16.

TABLE 16

Recovery of *P. cinnamomi* by Lupin Baiting from Dried Soils

Trial 1 :

	Drying Time (weeks)				
	0	2	4	8	
Silt	3/4	0/4	0/4	0/4	
Sand	4/4	0/4	0/4	0/4	

Trial 2 :

	1	2	3	4	6
Silt	2/4	0/4	0/4	0/4	0/4
Sand	3/4	1/4	1/4	2/4	0/4

These recoveries show interesting trends and, at first glance, an anomaly: although the pathogen could not be recovered after 2 weeks drying in the first trial, it was recovered from the sand after 4 weeks in the second trial.

A close examination of the soil moisture data explains this. In the first trial, no recoveries were obtained after 2 weeks drying which gave a soil moisture content (m.c.) of 4.6 per cent or less. In the second trial, *P cinnamomi* was recovered after 1 week (m.c. for silt and sand 8.3 and 19.0 per cent, respectively). At the two weeks sampling, the silt soil had dropped to 5.3 per cent m.c. The pathogen could not be recovered from this and later samplings. Recoveries from the sand soil continued until week 4 (7.8 per cent m.c.); by week 6 the moisture content had fallen to 3 per cent and the pathogen could not be recovered.

In these trials, recoveries of *P. cinnamomi* were obtained when the soil moisture dropped to 7.8 and 8.3 per cent for the sand and silt, respectively, and no recoveries were made at 4.6 per cent moisture in the sand and 5.3 per cent moisture in the silt. This suggests that the soil moisture threshold for fungal survival in these soils is between 5 and 7 per cent moisture content.

EFFECT OF SEASON AND LOCATION

METHOD

Lateritic silt from an active dieback gully near Dwellingup was baited for *P. cinnamomi*. One-hundred-gram samples of the soil and roots were put in bags made from 95 per cent Sarlon shadecloth and placed on three different sites (road surface, ridge top and valley bottom) in November, January and May. On the ridge tops and valley bottoms, half of the samples were placed on the soil surface whilst the other half were buried at 76 mm. (Samples emplaced in January and May were kept moist in the shadehouse until ready for use.) All sample bags were collected in early June and baited twice for *P. cinnamomi* using the lupin technique.

In a separate study, samples were placed in the field in November and treatments were baited in March, May and June. In the road surface study, silt from Dwellingup and sand from an active dieback swamp at Westcliffe were compared.

Four replicates of each treatment were used throughout the experiment. At one-month intervals between December and June, temperature and moisture data were recorded for each site. Rainfall data were obtained from the nearest weather station, located some 19.2 km northeast of the experimental areas.

RESULTS

Both soils yielded excellent recovery rates from the initial baiting. Temperature data indicate that the samples placed on the road were subjected to extremely high temperatures during the day. During the summer months, from December to April, the recorded temperature at 10 a.m. ranged from 30° C to 48° C. In contrast, the soil temperature on the ridge top at a depth of 76 mm, never exceeded 25° C and fell as low as 17° C. The valley bottom site was approximately 1.5° C cooler still. Monthly temperature replicate means are shown in Figure 12a. Moisture data obtained from additional samples showed that the soils placed on the road surface dried out more rapidly and to a lower moisture content than did the samples placed on the other two sites. At the January sampling, the moisture contents of the silt and the sand on the road surface were 1.2 and 1.1 per cent respectively. At the same time, soil moistures of 7 and 9 per cent were recorded in the ridge top and valley bottom. Samples from the top 152 mm of soil gave the per cent moisture plotted in Figure 12b. The rainfall data indicated a relatively dry summer, but with 46 mm of rain in early February. The autumn rains began about the midde of April, 330 mm being recorded between then and the completion of the experiment early in June (Figure 12c).

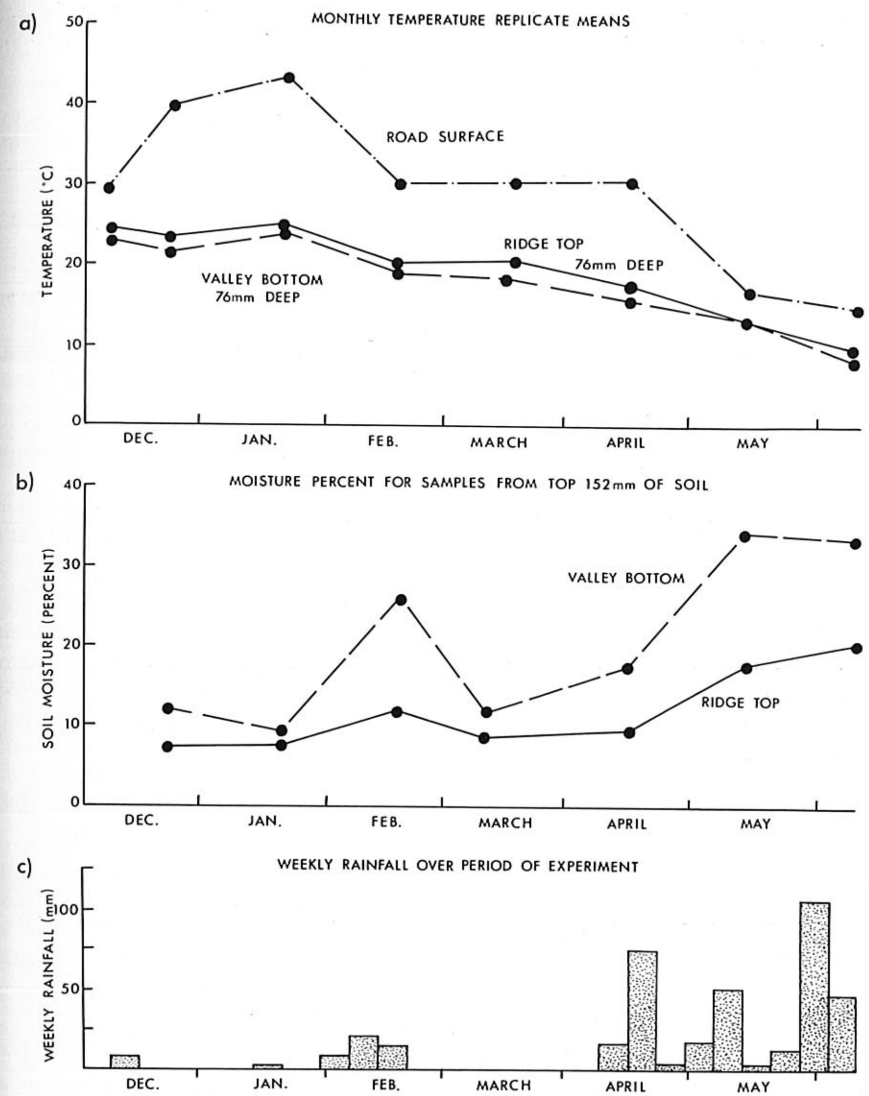

Figure 12

Temperature, soil moisture and rainfall data from trial gauging effect of season and location on recovery of *P. cinnamomi*.

The recovery rates (Table 17) would indicate that the survival of the pathogen in diseased soil and roots depends on both the season and location. The data suggest an interaction between site and season. During the cooler and wetter autumn months, the pathogen could be recovered at high levels irrespective of the site on which it was placed. During the hot, dry summer months, survival of *P. cinnamomi* was affected, even in the more ecologically suitable sites. The pathogen could not be recovered from samples exposed on a road surface during the summer. Where samples were buried at 76 mm the fungus was able to survive right through the summer months, though at reduced levels.

TABLE 17

Recovery of *P. cinnamomi* from Various Ecological Sites

Site	Placed	Baited	Recovery
ROAD SURFACE—			
Sand	November	June	0/4
	January	June	0/4 1st Trial
	May	June	4/4
	November	March	0/4
	November	May	0/4 2nd Trial
	November	June	0/4
Silt	November	June	0/4
	January	June	0/4 1st Trial
	May	June	4/4
	November	March	0/4
	November	May	0/4 2nd Trial
	November	June	0/4
RIDGE TOP—			
Silt, soil surface	November	June	0/4
	January	June	0/4 1st Trial
	May	June	2/4
Silt, buried at 3 in.	November....	June	1/4
	January	June	2/4 1st Trial
	May	June	3/4
	November	March	2/4
	November	May	2/4 2nd Trial
	November	June	1/4
VALLEY BOTTOM—			
Silt, soil surface	November	June	0/4
	January	June	1/4 1st Trial
	May	June	3/4
Silt, buried at 3 in.	November	June	1/4
	January	June	3/4 1st Trial
	May	June	3/4
	November	March	2/4
	November	May	1/4 2nd Trial
	November	June	1/4

DISCUSSION

At moisture contents just above wilting point, *P. cinnamomi* survival was not affected for storage periods up to 12 weeks at 25° C. If the soils were

dried to below wilting point, recovery rates were drastically reduced and the only positive recovery was obtained from silt with 8.3 per cent moisture. In two of the soils examined the soil moisture threshold for fungal survival was in the range of 5-7 per cent. The high recovery rate of the pathogen from a sandy soil at 2.5 per cent moisture indicates that the soil moisture threshold is highly dependent on the moisture curve of the soils.

Overseas publications (loc. cit.) indicate that the fungus could not be recovered from soil dried for 2-3 months. The current trials suggest that this period could be as short as 2 weeks, depending on the drying rate and the final moisture content reached. The available field data confirm these trends. In sites where soil moisture did not fall below 7 per cent (ridge top and valley, buried at 76 mm) survival right through the summer was recorded. In harsher sites with more rapid drying and final soil moisture contents of about one per cent, no recoveries of the pathogen were obtained.

Hine et al. (1964) have shown that long periods (one month) at continuously high soil temperatures (36° C) adversely affected the survival of *P. cinnamomi.* High soil temperatures were recorded in most trials, especially in the samples exposed on the road. Because of the large daily fluctuations, it is unlikely that temperature *per se* has affected survival.

It could be argued that the lupin technique used was unable to recover the pathogen from dry soil. All samples were rebaited on two separate occasions, approximately 2 weeks apart. Samples were kept moist between baits to provide a suitable environment for the spores. Sometimes the pathogen was recovered from one soil type and not the other, yet both were baited concurrently. All samples recovered from the field for the June baiting had been rewetted by rain since early April, yet even this did not "reactivate" the fungus. The technique, though not foolproof is sufficiently reliable to allow conclusions to be drawn.

The results indicate that fungus propagules which fall on freely drained sites or roads are unlikely to survive the harsh Western Australian summer months. On moisture-gaining sites, or wherever the inoculum is buried, the chances of survival are greater. The pathogen was able to survive the milder autumn irrespective of the site on which the samples were placed.

These data are not presented as an argument against carrying out hygiene operations during the summer months. In fact, to relax hygiene regulations during this time of year would be most unwise. Obviously these results could be influenced by seasonal differences and some survival during an unusually wet summer, or during a wet spell in a normal summer, could still occur.

Nonetheless, the results suggest that a number of sites in the northern jarrah forest do not favour the survival of *P. cinnamomi* during the hot, dry summer months which are a feature of this climate. Temperature, moisture regimes, soil type and length of exposure are significant factors affecting survival. If these are considered in the planning and execution of management programmes in the forest areas, then the chances of implementing a successful hygiene programme are markedly increased.

V MANAGEMENT OF THE DISEASE SITUATION

HYGIENE

At present, less than 5 per cent of the jarrah forest is affected by *P. cinnamomi* and this disease is largely confined to sites of lower productivity. The most severely affected areas are concentrated in a belt paralleling the Darling Scarp from Mundaring to Collie (Figure 5) where up to 30 per cent of the forest area may be affected. East of this, the level of infection gradually decreases to well below one per cent in the eastern section of the State Forest.

Spread of the fungus throughout the forest occurs through both natural and artificial propagation. Hygiene measures designed to reduce the latter have been implemented, with the co-operation of the timber industry, as a basis for the operations of the major users of the forest.

The forest area has been divided into broad zones, based on the level of infection, for operational control and for planning purposes—

Zone A Unaffected: to be logged when no other areas are available and then preferably by permits completely contained in this zone. Logging will be under strict hygiene control and along carefully selected access routes.

Zone B1 Slightly affected: logging to be restricted to affected portions only, for the time being.

Zone B2 Severely affected: logging to be concentrated in the affected portions, unaffected areas may be logged under hygiene conditions before proceeding elsewhere.

These zones correspond with the three levels of infection shown in Figure 5.

Wide-ranging selective operations for a single type of produce, e.g., poles and piles, can cover an area considerably larger than that involved in a year's logging and are, therefore, the most likely sources of new infection. This type of operation will only be considered for special purposes and then only during the summer. Heavy cutting is being done in such a way that the least possible area is subjected to traffic and disturbance each year. Pole and pile operations are confined to areas covered by trade logging, wherever possible.

Specific vehicle routes to each coupe have been designated so that unaffected areas will only be logged along clean access routes. Construction of new roads is being held to a minimum and new alignments are subjected to a hygiene check before construction. Gravel pits are subject to approval before excavation, use of fill or surfacing materials being strictly controlled.

New infections can develop from as little as 60 g of infected material. Wherever transfer of equipment from diseased to healthy sites becomes necessary the units are thoroughly washed with a high-pressure spray and the effluent is channelled into infected streams and drains.

INTENSIVE MANAGEMENT

A 14 600 ha block of high quality jarrah forest near Dwellingup was originally selected for treatment as an intensive management unit (P. Kimber, pers. comm.). Since man's activities are the primary source of new infections the area is being maintained under strict hygiene regulations. However, it is appreciated that complete exclusion of infected material over a period of many years is unlikely. An outline is given below of the efforts being made to reduce the susceptibility of sites within this area while making it a much more valuable producing unit:

(1) The most susceptible sites, e.g. flats and swamps, are being cleared, drained and planted with a dense crop of *P. pinaster* Ait. or resistant eucalypts such as *E. globulus* Labill., *E. resinifera* Sm. and *E. microcorys* F. Muell.

(2) Existing dieback patches in and around the perimeter are being salvaged and planted with resistant species.

(3) All major road surfaces and table drains have been improved. Lesser roads have been closed.

(4) Logging is restricted to the summer months.
All logging units are washed prior to entry.

(5) The forest is being assessed and treated to provide full stocking wherever necessary. Overstocked areas are thinned.

(6) Prescribed burning will be regulated to provide maximum safe litter and canopy cover.

(7) Any new foci of infection will be isolated and treated by chemical means.

The objective is to maximise the production of quality timber on this uninfected area of high potential. On the well-drained soils typical of such areas, with full canopy cover and a vigorous crop, resistance to infection should be relatively high. Susceptible lower-quality sites are being rendered less susceptible by conversion to dense stands of fast growing and resistant species. Further such units are being selected throughout the forest area.

EDUCATION

The success of the hygiene and rehabilitation programme rests heavily upon the understanding, attitudes and sustained interest of both forest managers and users. To relate the current knowledge of *P. cinnamomi* to the management of a resource which concerns foresters, sawmillers, shire councils, mining and heavy equipment contractors, farmers, the general public and politicians, is perhaps the major responsibility confronting the Forests Department. The main task of the West Australian programme has been to obtain facts as a basis for education and to guide changes in operational techniques and regulations.

To familiarise departmental staff with hygiene procedures and problems, members of the Research Branch have given lectures to the personnel of the 12 Divisions and also local shires, the Department of Public Works, the State Electricity Commission, the Department of Lands and Surveys, the Army and mining companies. A constant liaison is being maintained between the Forests Department and the timber industry. The Royal Society and the Wildflower Society have been formally addressed and releases have been made to city and country newspapers. A detailed progress report on the research into jarrah dieback has been prepared and an illustrated pamphlet, aimed at a lay audience, has been issued. In all, the preparation and dissemination of educational material concerning this disease has occupied a considerable amount of the time and effort of the research programme.

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Appendix I

Mapping Units: Wungong Brook Catchment
Soil Survey by H. M. Churchward, CSIRO, 1965

Soil Unit	Description
I	Dominated by frequent outcrops of massive vesicular laterite, associated with which is a thin but variable mantle of loose sandy gravel. This unit occupies the higher ground but extends down along the ridges towards the valley floors.
II	This unit represents areas of relatively deep gravel flanking I. Exposures of massive laterite are generally infrequent. It frequently occupies gentle slopes but also includes moderate to steep slopes. However both massive vesicular laterite and massive recemented gravel may occur as a substrate at varying depths.
III	Comprised of deep gravels in the upper ends of many of the valley floors. These gravels, which are frequently finer than those in II, are often underlain at depth by recemented gravels.
IV	Areas mantled by relatively deep gravel on moderate slopes. The substrates to these gravels vary from mottled clays to recemented gravels. This unit often occurs downslope from areas of I or II.
V	Yellow-brown earths (loams and sandy loams which frequently have a rusty appearance) over pale coloured clay. There may be a variable amount of ironstone gravel (including bog iron ore) at this interface. This unit occupies much of the valley floors, particularly in the tributaries and the upper parts of the Wungong Brook; these situations are generally swampy. Small pockets of this unit may occur on slopes adjacent to seepages.
VI	Similar to unit IV but moderate to steep slopes are dominant.
VII	This unit occupies areas which generally have steep slopes (frequently steeper than in VI) and show scattered exposures of country rock (usually granite). The soils are predominantly very gravelly sandy loams over mottled and pallid clays. This gravelly overlie varies from less than 12 inches to several feet. They vary from lateritic ironstone to country rock.
VIII	Steep to very steep slopes are general in this unit. Exposures of basic country rock are an important feature. The soils are deep, friable red clays and light clays having a variable gravel content.
IX	Areas of yellow-brown sands to loamy sands on long gradual slopes at the head of the Wungong Brook and some of its tributaries. These frequently represent outwash areas down from granite outcrops as well as sandy deposits on long gradual slopes out from elements of unit II. Downslope, as the broad flat valley floors are approached, these sands change to grey sands or may merge with the yellow-brown earths of unit V.
X	Granite outcrops. These areas are associated with steep slopes as well as with more gentle slopes.

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