Pine Deaths in the Blackwood Valley Plantations: a Recurrent Problem

by

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1. SUMMARY AND RECOMMENDATIONS

1.1 Summary

Extensive mortality of *Pinus radiata* in the Blackwood Valley plantations in 1987 and 1988 resulted in economic losses of about $10 000 000. Tree deaths were not evenly distributed throughout the plantations; on some sites all the trees died, on others some or none. Rainfall in 1986 and 1987 was well below average and the trees were assumed to have died of drought.

A **broadscale survey** of the plantations was undertaken in 1988 to determine whether tree deaths were associated with specific site and plantation factors and, if so, to recommend site specifications for future plantings as well as to determine the basal area that various sites can carry during drought years. In addition, a **health survey** of individual trees was undertaken to determine whether pathogens and pests were associated with mortality.

Tree mortality was associated with soil depth, position in the landscape, aspect and basal area of the stand. Site index has been calculated from top-height, age, soil depth, aspect and landscape position. Site classes, derived from the site index, are predicted from the site parameters and are used to predict which sites are susceptible to drought.

Four sets of symptoms (Section 4) were observed on the surveyed trees:

Healthy - no death of needles in the upper part of the crown or of the terminal shoot

Tip death - death of less than the top quarter of the crown, as indicated by dead needles

Intermediate symptoms - death of more than 25% of the crown, as indicated by dead needles.

Dead - no live needles.

Dead and intermediate trees occurred in all dominance classes, but proportionally twice as many sub-dominant and suppressed trees showed these symptoms compared with dominant trees. However, as dominant and codominant trees comprised 80 per cent of trees in the survey, they contributed 85 per cent of the affected basal area. Symptoms in dominant and codominant trees had developed more recently than symptoms in sub-dominant and suppressed trees (Section 4.2).

Predisposing stress factors affecting the growth and death of trees include climate and site (Section 5.1). The Blackwood Valley experiences a seasonal drought over summer so that tree growth and survival are dependent on stored soil water during this period. The distribution of symptoms were associated with soil depth, position in the landscape and aspect. The proportion of basal area showing symptoms increased with decreasing soil depth, increased from the lower to the upper landscape position, and was higher on sites with a north-easterly aspect. Soil depth and landscape position influence soil water storage, while aspect probably influences transpirational demand, and may have a rain-shadow effect.

Weather is an important inciting stress factor affecting the growth and death of tree (Section 5.2). Rainfall in 1986 and 1987 was well below average, but was not the lowest on record. It was, however, the lowest cumulative rainfall for any two consecutive years.

In addition, there was a greater incidence of strong north-easterly winds over these two summers and relative humidity was lower than usual in these two years. These factors affect both soil water storage and transpirational demand by the trees.

Pests and pathogens are important contributing factors which colonise weakened trees and hasten death (Section 5.3). In the pine plantations dead shoots, branches and stems were consistently associated with extensive infections by the pathogenic fungus *Sphaeropsis sapinea*. *S. sapinea* was also consistently isolated from blue stained wood. Boles of many of the dead trees were colonised by the bark beetle *Ips grandicollis*. We suggest that on some sites and at some basal areas within the Blackwood Valley plantations, soil water storage is inadequate, particularly in years of below average rainfall. These severely drought-stressed trees are then rapidly colonised by opportunistic pathogens and pests (Section 5.4).

Values of Site Index for the Blackwood Valley were calculated from the data of the broadscale survey (Section 6.1, Equations 1(a) and (b), p.23). Top-height is significantly related to age, soil depth, landscape position, and aspect. From these equations we may infer that in the Blackwood Valley top-height growth slows down in the eighth year. This conclusion is supported by independent data which show that annual basal area increment, estimated from tree growth ring widths in the health survey, increased until age seven or eight and then decreased (Section 4.3.2.). Site Index was split into four Site Classes (Section 6.2). Predicted top-heights at age thirty years are shown below, together with predicted maximum basal area that can be carried without drought loss, and the corresponding South Australian Site Classes.

Blackwood Valley Site Class	**Top-height age 30 (m)**	**Max basal area (m^2 ha^{-1})**	**S. Australian Site Class**
1	over 32.7	No limit	III to IV
2	31.4-32.7	25	IV-V
3	30.2-31.4	20	below V
4	under 30.2	unsuitable for pines	

1.2 Recommendations

1.2.1 Selection of Sites for New Plantations

The results from the broadscale survey indicate that previous soil assessments were inadequate in identifying drought prone sites. In future, soil depth to 2 m, landscape position, and aspect need to be assessed before an area is planted. The minimum recommended soil depths for Blackwood Valley Site Classes 1 and 2 for different aspects and landscape positions are shown below:

Estimated minimum soil depth (cm) required for radiata pines grown in the Blackwood Valley plantations.

Aspect	Landscape position	Site class 1	Site class 2
NE	upper slope	*	*
	mid-slope	*	200
	lower slope	*	130
All aspects apart from NE	upper slope	*	200
	mid-slope	200	120
	lower slope	130	50

*Soils greater than 2m in depth are required, however, no prediction of the depth required is possible as the maximum soil depth measured in the survey was 2m.

1.2.2 Management of Existing Plantations

The existing plantations should be evaluated in terms of the Blackwood Valley Site Classes defined in section 6.1, and each Site Class managed to the basal area specified.

Blackwood Valley Site Class	Top-height age 30 (m)	Max basal area ($m^2 ha^{-1}$)
1	over 32.7	No limit
2	31.4-32.7	25
3	30.2-31.4	20
4	under 30.2	unsuitable for pines

Options which could be considered for Site Class 3 are agroforestry and fuel reduced buffers.

Thinning of the existing plantations should be based on basal area measurement and Site Class, not on plantation age.

The economics of growing pines on each of these Site Classes should be re-evaluated.

1.2.3 Suitability of Other Species

Plots of alternative species growing within the Blackwood Valley should be assessed to see whether they are more suitable than *P. radiata* on some sites.

1.2.4 Trouble Shooting

A trouble shooting service should be developed within CALM to provide a rapid diagnosis of problems.

1.2.5 Revision of the Pine Management Guide

The broadscale survey and health survey have highlighted a number of changes that are necessary within the CALM Pine Management Guide (1988). In particular the sections on Land and Soil surveys need revising to include recommendations from this report.

2. INTRODUCTION

Pinus radiata plantations in the Blackwood Valley represent 26 per cent of the area of publicly owned and managed pines in W.A. (Department of Conservation and Land Management 1987). In 1989 they had a capital value of $\$100 \times 10^6$ and contributed substantially to the sawmilling and softwood processing industries in the south-west of the State[1]. The extent of these plantations is shown in Figure 1.

Trees died in a large proportion of these Blackwood Valley plantations in 1987 and 1988. Losses were as high as 100 per cent on some sites and the economic loss was estimated at $\$10 \times 10^6$ (Spriggins[2] personal communication). Rainfall during 1986 and 1987 was well below average and the obvious interpretation was that the trees had died as a consequence of drought. Tree deaths associated with low rainfall had occurred previously in this area. The timber in standing dead trees degrades rapidly if it cannot be salvaged, and the mortalities are a waste of resources

A **broadscale survey** of plantations in the Blackwood Valley was undertaken in 1988 to determine whether tree death was associated with specific site and plantation factors and; if so, to recommend site specifications for future plantings in this area, as well as to determine the basal area that various sites can carry during drought.

In addition, a **health survey** of individual trees was undertaken to determine whether pathogens and pests were associated with tree death.

The results from both surveys are combined in this report.

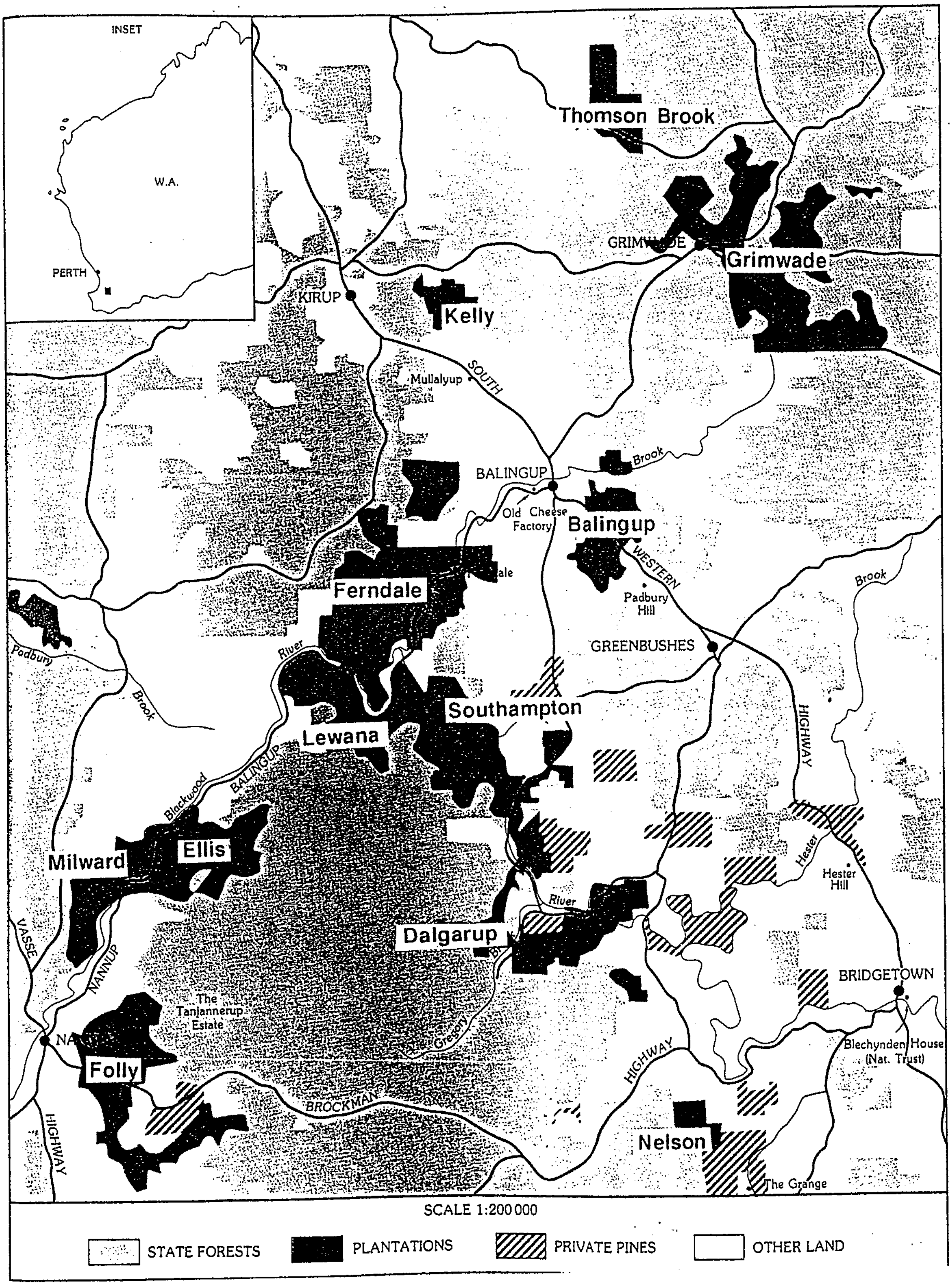
2.1 Establishment of the Blackwood Valley Pine Plantations

Harris, appointed Conservator of Forests in W.A. in 1953, reviewed the future wood requirements of the State shortly after taking up this position. This review was based on a predicted population of 1.4×10^6 by 1985 and 2×10^6 by 2000. Estimates made by Harris and Nunn (1957) indicated that there would be a shortfall in wood from local sources by the end of the century. This deficit could be most easily met by the establishment of softwood plantations. The average mean annual increment (M.A.I.) of *Pinus radiata* and *P. pinaster* plantations in W.A. was 14 $m^3 ha^{-1}$, so that 81 000 ha of pines would be required to supply the anticipated demand for wood by the year 2000 (Harris and Nunn 1957); in 1953 plantations covered only 7 159 ha (Forests Department 1954). They therefore advocated a planting programme of 800 to 2000 ha per annum, with *P. radiata* being the species of choice, because of its fast growth.

Only limited areas of State forest had soil suitable for growing *P. radiata*. Forestry policy was to maintain hardwood production on good quality sites, not to convert them to pine plantations. Suitable soils were present, however, on cleared agricultural land in the Kirup and Nannup districts of the Blackwood Valley. The main farming activity in this area was dairying but depressed butterfat prices meant that many of the farms were unprofitable (Treloar and Morison 1962). In 1954/55 the Forests Department started to

1. CALM file 025702F1701, Como
2. D.Spriggins, CALM Central Region

Figure 1 Map showing location of the *P. radiata* plantations in the Blackwood Valley area. (Adapted from Christensen *et al*, 1981)



purchase land on the open market for conversion to pine plantation (Forests Department 1955). It was estimated that about 4 000 ha of plantations could be established in this locality and an active policy of land acquisition was pursued during subsequent years(Forests Department 1957, 1958, 1961, 1970), with considerable areas of steep, rocky land which had proved uneconomic for farming being purchased (Forests Department 1957).

The Softwoods Forestry Agreements Act 1967 provided financial assistance from the federal government to all States to expand their softwood plantings, by providing loans free of interest and capital repayment for the first 10 years. In the whole of W.A. the total area established to pines between 1960 and 1967 was less than 1 214 ha per annum, with Commonwealth funds available, the Forests Department confidently expected to double this figure assuming suitable land could be found (Forests Department 1967). In the Blackwood Valley the area planted to pines increased from 1 275 ha between 1961 and 1965 to 3 757 ha between 1971 and 1975 (Table 1).

An assessment of the Blackwood Valley sites was made in the 1950's and 1960's, before pines were planted. Five site qualities were recognised, three of these occurred extensively in the valley. Site quality II was flat to gently indulating, well drained, deep, red-brown loams and sandy loams; site quality III was undulating to steep, well-drained, deep, red-brown sandy loams, while site quality IV was the steep, shallower and often rocky soils of the upper slopes and lip of the plateau. Much of the land was infested with bracken and rabbits. Site quality I covered a negligible area of the valley, while site quality V was considered unsuitable for pines. The site quality assessments were derived from the growth and yield of radiata plantations at Grimwade. An economic analysis of a 40-year rotation of pines in the Blackwood Valley, based on site quality, indicated that radiata plantations would yield a higher rate of return than rough grazing, and recommended that site quality IV should be purchased and planted, while site quality II, the valley floor, was more suitable for farming (Treloar and Morison 1962).

Site quality (productivity index) mapping, similar to a system used in South Australia, was introduced in 1958. The growth and yield data used to determine site quality were based on about 2 000 ha of established radiata plantations (Forests Department 1958). This productivity index mapping was not fully utilized because it was found to be inappropriate and too labour intensive (Hopkins[1] personal communication).

2.2 The Recurrent Problem of Drought

The plantations were not, however, without problems. In 1957 Nunn, the plantation supervisor, observed that the surveys did not give sufficient detail of areas that were unplantable because of shallow, rocky soil. The following year he gave instructions that unploughable, although still plantable, areas should be marked on soil surveys carried out prior to planting[2]. Following the dry summer of 1960/61 mortality of 1960 planted stock (Folly plantation) was 27.3 per cent (range 6.2-52.0 per cent). These losses were attributed to the steep northerly aspect, excessive insolation, inadequate cultivation, rocky shallow soil and the long, hot, dry summer[2]. In this year there was also a high incidence of dead leaders in three and four year old trees at Folly with about 100 trees ha^{-1} being affected in the worst area. This condition was least common on southern and eastern slopes. It was believed to be a consequence of fast leader growth during spring which could not be sustained during drought[1]. Subsequently in 1962 Nunn advised

1. E.R. Hopkins, CALM Como
2. CALM file 004422 F1215, Como
3. CALM file 005969 F1704, Como

Table 1: Area (ha) planted to *Pinus radiata* in the Blackwood Valley

Planting Period	**31-35**	**36-40**	**41-45**	**46-50**	**51-55**	**56-60**	**61-65**	**66-70**	**71-75**	**76-80**	**81-85**	**TOTAL 1931-1985**
KIRUP DISTRICT												
Grimwade	7.3	2.8	2.6	39.3	115.1	463.4	550.2	493.6	15.9	460.8	49.2	2200.2
Ferndale							5.4	386.4	1647.5	519.7		2559.0
Kelly							50.0	1.4		142.2		193.6
Balingup									55.5	633.9	266.9	956.3
Southampton										579.8		579.8
Savage Creek										118.1		118.1
Thomson Brook										416.5	221.4	637.9
NANNUP DISTRICT												
Folly						457.3	279.9	152.5	753.3	7.5	13.0	1663.5
Lewana							388.2	853.3	351.8	13.6	44.7	1651.6
Brockman								40.1	20.5			60.6
Milward						497.0	1.1		165.1			663.2
Ellis					6.2				741.1	532.0		1279.3
Dalgarup										908.3	15.0	923.3
Nelson										228.9		228.9
TOTAL	7.3	2.8	2.6	39.3	121.3	1417.7	1274.8	1927.3	3750.7	4561.3	610.2	13715.3

against planting rocky areas because of poor results in the past[1]. In the same year, when land at Lewana was being prepared for pine establishment, it was estimated that up to 20 per cent should not be planted because of rocky outcrops and steep slopes[1].

Dead tops and spot deaths of radiata planted at Folly in 1956 occurred in 1967, following low rainfall the previous year. Over half the trees were affected on the worst site[2]. Dead tops and deaths continued at Folly during 1968 and 1969 in trees planted in 1956 and 1957. Some deaths occurred in Milward plantation. The worst areas at Folly were mapped using aerial photography in 1969 and some areas were salvage thinned that year[2]. A thinning trial was established in Folly and Lewana plantations in order to determine the basal area that could be supported on drought-prone sites. Unfortunately, the trial was put in after the dry winter of 1969 and many of the retained trees in the thinned plots died the following summer (Butcher[3] personal communication).

In 1970 there was extensive mortality in both Folly and Milward plantations in stands planted before 1960. Aerial photography was again used to map the affected areas in stands planted in 1956 and 1957 at Folly, and apart from the compartments which had been salvage-thinned the previous spring, there were virtually no unaffected areas in these plantings. As deaths had been increasing since 1967, following years of normal as well as low rainfall, it was thought that deaths could be a function of age and stocking density as well as drought[4]. Assessments carried out in 1970 showed that in unthinned areas(153 ha) 21.5 per cent of the standing volume had been lost to drought and secondary effects, a further 31.5 per cent could be utilized as thinnings, leaving a standing crop of between 70 and 106 m^3 ha^{-1} on affected sites[1]. The original soil survey map (F.D. Plan No. 1052 (c)) would not have given an accurate prediction of the most drought prone sites. *Ips* occurred in dead stems but it was not considered an important factor in limiting the marketability of live trees[5].

Further deaths occurred in 1972 in Folly and Lewana plantations. Another assessment was carried out which reinforced the previous observations that the problem was one of water availability which was dependent on stocking, soil depth, aspect, and slope position. Stand density became important somewhere between 34 and 46 m^2 ha^{-1} depending on soil depth. Once stand density exceeded 46 m^2 ha^{-1} deaths could be expected[6].

In 1973 a soil survey of Ferndale plantation in the Kirup district showed that shallow soils (depth less than 50 cm to rock) and therefore drought-prone sites, occurred in 26 per cent of the area planted between 1968 and 1971 and 41 per cent of the area designated for future plantings[7]. It was suggested that a thinning trial should be established to determine the stocking rate for shallow sites, but this was not implemented (McKinnell[8] personal communication). It was confidently expected that implementation of the Silviculture 70 system (Pine Management Guide 1988), whereby stands were thinned to 740 stems ha^{-1} at age 4 to 5, would solve the drought problem. Stands planted between 1963 and 1970 would gradually be brought into the new system and deaths would no longer occur[7].

1. CALM file 004422F1215, Como
2. CALM file 005969 F1704, Como
3. T.B. Butcher, CALM Como, personal communication.
4. CALM file 005972F1704, Como
5. CALM file 004422F1215
6. CALM file 005946F1708, Como
7. CALM file 005897F1704, Como
8. F. McKinnell, CALM Como, personal communication

2.3 Utilization of Thinnings

The importance of thinning in reducing the incidence of drought deaths was emphasised by the results of the 1970 assessment at Folly plantation. The management prescription for the Blackwood Valley plantations specified thinning at age 12 to 14 years depending on site quality (Treloar and Morison 1962). The original plan drawn up by Nunn[1] based on thinning at age 15 and every five years after, required a small case baulk saw mill, capacity 10 000 m^3 per annum to start operating in the Nannup area by 1972[2]. In 1966 the Shire of Nannup approached the Minister for Forests about the possibility of establishing a plant for treating pine thinnings within the Nannup District. The Forests Department, through the Minister, replied that it anticipated that the first thinnings would be milled at the Consolidated Pine Industries (C.P.I.) case plant at Busselton. This was a large mill which had been established in 1964 and was using thinnings from the Margaret River and Ludlow plantations[2]. The C.P.I. mill started taking thinnings from the Nannup plantations in 1969, but ceased operating the following year[3] due to decreased demand for wooden crates because of competition from cardboard containers (Forests Department, 1970).

By the early 1970's the plantations around Nannup covered about 3 000 ha, there had been recurrent problem of deaths in trees over nine years of age especially on steep, north-facing slopes with shallow soils. Thinning was behind shedule; in 1973 only half of the 1956 plantings and 1 per cent of the 1959 plantings had been thinned[1]. Because of the steep slopes, Nannup plantations were much more difficult to work in than those at Grimwade. As fallers were paid the same rate for both localities it is not surprising that they were reluctant to work at Nannup. In addition, with the closure of the C.P.I. mill, the main markets for chip and baulk logs were in the metropolitan area, and these could be supplied more economically from plantations closer to Perth[1].

In 1976 Westralian Plywoods-Hearn Industries (Wesply) opened a particle board plant at Dardanup. This was expected to clear the backlog of thinning from the Blackwood Valley as well as providing a market for future chip logs[4]. Site assessment methods developed in 1973 were confidently expected to identify shallow soil sites whilst implementation of Silviculture 70 would improve plantation management so that the effects of drought would be minimized.

Unfortunately extensive dead tops and tree deaths occurred yet again in the Blackwood Valley plantations in 1986, 1987 and 1988.

1. CALM file 004422F1215, Como
2. CALM file 0005918F1704, Como
3. CALM mill records, Bunbury
4. CALM file 004718F1307, Como

2.4 Stress Factors Causing Tree Decline and Death

When trees die it is usually because of a combination of factors. Pine deaths in the Blackwood Valley plantations have occurred consistently after dry winters but not necessarily in all stands. For example, in Folly plantation following the dry winter of 1969, higher mortality occurred in unthinned 14 year old stands compared with thinned stands (see Section 2.2). Thus mortality is determined not just by weather, but also by stand density. In addition, site factors such as soil depth, aspect and slope position were recognised as affecting mortality in Folly and Lewana plantations in 1972 (see Section 2.2). Pests and diseases may also contribute to tree death: *Ips grandicollis* infested some of the dead trees at Folly in 1970; pathogens were not investigated.

Manion (1981) has suggested that the multiplicity of factors which cause tree decline and death fall into three groups:

2.4.1 Predisposing Factors

Predisposing factors are long-term factors such as climate, soil type, aspect, landscape position, genotype, stand structure and stocking. These factors weaken trees growing in inappropriate locations.

2.4.2 Inciting Factors

Inciting factors are short-term factors such as drought, frost and insect defoliation which produce a sudden injury from which the tree has difficulty recovering.

2.4.3 Contributing Factors

Contributing factors are long term factors such as bark beetles, canker and root-rot fungi which are able to invade only a weakened host. They are often very conspicuous but are best regarded as indicators of a severely stressed or dying tree.

We have found this framework useful in trying to assess the many physical and biological factors affecting the Blackwood Valley pine plantations. We have, therefore, presented our data from the broadscale survey and health survey carried out in 1988, together with other relevant information, in terms of the predisposing, inciting and contributing factors which affect the radiata plantations of the Nannup and Kirup districts.

3. METHODS

3.1 Broadscale Survey

A broadscale survey was carried out in the Blackwood Valley pine plantations with the aim of identifying the soil, site and plantation parameters that influenced the occurrence of death in the plantations following the dry winters of 1986 and 1987. Sampling areas were selected on the basis of plantation age and severity of impact. Plots were located randomly within the selected areas. The distribution of plots within the Blackwood Valley plantations is shown in Table 2. The minimum plot size was 25 x 25m, or 20 trees, thus plot size depended on stocking density, with plot size increasing as stocking density decreased. The survey was carried out during spring 1988 (mid-August to mid-November). The parameters evaluated at each of the 253 sample plots are outlined below.

3.1.1 Tree Parameters:

top-height(of 50 tallest trees ha^{-1})
stocking density (stems ha^{-1})
basal area (m^2 ha^{-1})

for each tree:

tree diameter (d.b.h.o.b.)
crown health (1 unaffected, 2 tip death, 3 intermediate symptoms, 4 dead)
dominance class (1 dominant, 2 codominant, 3 sub-dominant, 4 suppressed)
estimate of how long ago the effect occurred (0-6, 6-12, > 12 months)
presence or absence of *Ips grandicollis* exit holes at breast height

3.1.2 Soil Parameters:

profile description (after Northcote 1973) including:

horizon depths*
colour
texture
mottles - abundance
coarse fragments - abundance and size
penetrable depth (probe)
root depth
pH
surface fragments - size and abundance.

*Soil depth was determined from the horizon boundaries soil depth was determined. Soil depth was defined as either the depth to saprolite (C horizon) or to rock (generally granite or laterite) if the saprolite horizon was not present.

Table 2: Broadscale survey plots

Plantation	**Number of plots**	**Range of planting years sampled**	**Number of plots sampled in each planting year**
Grimwade	24	1958-67	'58x1, '60x1, '63x7, '64x1, '66x4, '67x10
Lewana	34	1961-66	'61x6, '63x10, '64x5, '65x3, '66x10
Folly	23	1963-71	'63x8, '70x4, '71x11
Ferndale	30	1968-74	'68x13, '69x1, '70x1, '73x8, '74x7
Ellis	38	1974-76	'74x5, '75x15, '76x18
Balingup	53	1975-80	'75x5, '76x2, '77x22, '80x24
Dalgarup	41	1976-78	'76x3, '77x9, '78x29
Kelly	10	1979	'79x10
Total	253		

3.1.3 Site Parameters:

landform:

aspect
position in landscape (crest, upper slope, mid-slope, lower slope, valley)
slope type (concave, uniform, convex)
slope angle (degrees from horizontal)

site:

slash abundance (from thinning and pruning)
proximity to wind damage
proximity to thinning

3.1.4 Site History

age
fertilized (yes, no)
time since thinning
time since pruning

3.2 Health Survey

A systematic survey to determine the general health of trees was carried out in Ellis plantation, with additional sampling in Lewana plantation, between September and December 1988. Plantation histories are given in Table 3. At Ellis plantation trees were sampled at upper, mid-slope and lower slope positions. At each sample point, about 20 m inside the plantation, the best and worst tree in terms of general health were selected from the five closest trees. These two trees were examined in a systematic manner; the following data were collected on the standing tree, and after felling, and in the laboratory:

3.2.1 General:

dominance class
tree height
overbark diameter at 1.4 m
underbark diameter at 1.4 m
ring widths (1978-1987) at 1.4 m
Ips emergence holes at 1.4 m
blue stain in pruning wounds

3.2.2 Crown:

health of terminal shoot
number of live, dead or partly dead branches in each major whorlRpresence of cones
presence of pustules on the cones
symptoms on live needles
superficial phloem cankers in the stem
phloem and associated wood cankers in the stem
blue stained wood
rots

Table 3: Plantation histories of pines used in the health survey

Location	Planting date	Culling date	Stems ha^{-1} in 1988	No. trees examined
Ellis plantation, upper slope	1976	-	1 100	20
Ellis plantation, mid slope	1975	1978	500	20
Ellis plantation, lower slope	1975	1978	500	20
Lewana plantation	various	various	various	14

3.2.3 Root Collar and Roots:

dead phloem
dead wood

Soil samples were taken for baiting for *Phytophthora.*
Insects were collected opportunistically.
Samples were returned to the laboratory for fungal isolations.

3.3 Data Analysis

3.3.1 Climatic and Weather Data

Rainfall, and wind frequency data were derived from both Bureau of Meteorology records and Departmental records. Annual rainfall and mean monthly rainfall for the period 1915 to 1988 for Kirup, Greenbushes, Nannup and Bridgetown and for 1925 to 1988 for Balingup is discussed in Sections 5.1.1 and 5.2.1. Bureau of Meteorology wind frequency data for Donnybrook for the 31 year period 1957 to 1987 are discussed in Sections 5.1.1 and 5.2.1. Department wind records for Kirup are for the six month period November-April for the years 1984-1988.

3.3.2 Broadscale Survey Data

The data were analysed firstly by pooling the tree data for all plots. The frequency in each "death class" was compared with the expected frequencies for dominance classes using the chi squared test. Similarly the time of symptom appearence was compared between the four dominance classes.

A multiple regression model predicting top-height(height of the tallest 50 trees ha^{-1}) on the basis of soil depth, landscape position and aspect was calculated (Section 6.1). The site index could be divided into four classes which had large differences in the proportion of trees showing symptoms. These site factors are examined individually and in combination in relation to predicted tree growth.

3.3.3 Health Survey Data

The height, diameter at 1.4 m, dominance class and basal area increment between 1978 and 1987 were compared between the most healthy and least healthy trees sampled at Ellis plantation. Student t-tests, ANOVA and chi squared tests were used as appropriate.

4. PATTERN OF TREE DECLINE AND DEATH

The decline and death of trees following the 1986-1987 drought was not evenly distributed within the plantations. The distribution of affected trees was influenced by both stand factors and site (environmental) factors.

4.1 Symptoms of Decline

The Crown Health rating is outlined below.

4.1.1 Healthy

No evidence of needle death on either the apical or branch shoots. Normal crown recession from the bottom of the crown is not considered.

4.1.2 Tip Death

This category ranged from any evidence of needle or stem death of the apical shoot through to the death of the top 25 percent of the crown (Fig 2).

4.1.3 Intermediate

Ranged from 25 percent of the crown showing needle death through to almost dead trees.

4.1.4 Dead Trees

No live needles evident on any part of the crown.

4.2 Influence of Stand Factors on the Occurrence of Symptoms Within Stands, Broadscale Survey Data.

By pooling the population of trees that were assessed in the 253 temporary plots established during the broadscale survey, it was possible to examine the trends in tree decline and death between the dominance classes and to determine when the trees in the various dominance classes were affected.

4.2.1 Dominance Class

The proportion of trees showing symptoms of decline increased progressively from the dominant class to the suppressed class with respectively 28, 34, 45 and 52 per cent of dominant, codominant, sub-dominant and suppressed trees showing symptoms. Compared with dominant trees, proportionally twice as many sub-dominant and twice as many suppressed trees were either dead or intermediate classes (Table 4).

In terms of actual numbers of trees affected, far more dominant and codominant trees were affected as these classes accounted for the largest proportion of the population (Table 5). Sub-dominant and suppressed trees accounted for approximately 30 per cent of the severely affected trees (dead and intermediate). When the proportion of basal area that was affected is considered, the contribution of sub-dominant and suppressed trees declines still further, as they accounted for only 15 per cent of the severely affected basal area, compared with 85 per cent for dominant and codominant trees (Table 5).

While proportionally more sub-dominant and suppressed trees were affected, the lower overall proportion of these trees in the population, and their small size (low basal area) make them relatively less important when considering the impact on the plantations.

Figure 2 Symptoms of decline used in the broadscale survey:

Live = no dead needles
Tip death = dead needles in the top 25 percent of the crown
Intermediate = more than 25 percent of the crown affected
Dead = no live needles

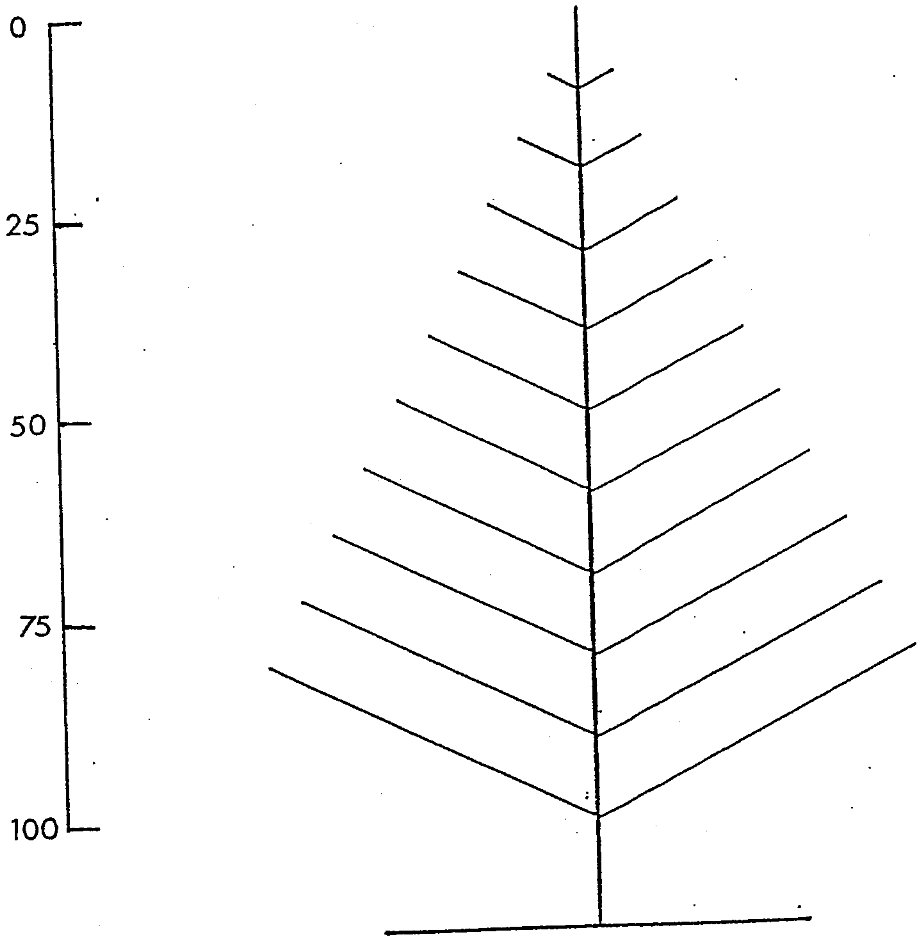


Table 4: Influence of dominance class on percentage trees in each symptom class (broadscale survey).

Dominance class	Sample Size	Live (%)	Tip death (%)	Intermediate (%)	Dead (%)
Dominants	1993	72	14	3	11
Codominants	3636	66	14	4	16
Sub-dominants	1032	55	16	7	22
Suppressed	331	48	23	7	22
TOTAL	6992				

Table 5: Influence of dominance class on the percentage of basal area in each symptom class (broadscale survey).

	Live		Tip Death		Intermediate		Dead		Total	
	*BA	%	BA	%	BA	%	BA	%	BA	%
Total basal area* in each symptom class (m^2)	261.7		55.7		17.9		51.3		386.6	
Dominants		42		37		36		30		40
Codominants		50		50		47		55		50
Sub-dominants		7		11		14		13		9
Suppressed		1		2		3		2	1	

*BA in m^2 is the sum of basal area of all the trees in each class that were measured in the survey.

4.2.2 Timing of the Appearance of Symptoms in Different Dominance Classes

Based on the appearance of the needles in the affected part of the crowns, trees were categorised as having been affected within the 6 months prior to the survey, 6-12 months previously or more than 12 months previously. Of the trees with either tip death or dead crowns, a greater proportion of sub-dominant and suppressed trees were affected more than 12 months prior to the survey, corresponding to death in the first year of the drought (Table 6). Conversely a greater proportion of dominant and sub-dominant trees with tip death or dead crowns were affected within the 12 months immediately prior to the survey (Table 6). Trees with intermediate symptoms tended to have been affected within the year prior to the assessment. This trend was most obvious in dominant and codominant trees (Table 6). The trend for trees with intermediate symptoms to have been affected within the year prior to assessment suggests that this class of trees is a transitional class between mildly affected trees (tip death) and dead trees. This was supported by a reassessment of some plots 6 months after the survey when it was found that most of the trees with intermediate symptoms had subsequently died. Despite the change in proportion of tip death, intermediate and dead trees in each time-of-death category, it is apparent from the chi-square analyses of time-of-death by dominance classs, that for each death class the suppressed and sub-dominant trees were affected before the dominant and codominant trees.[1]

It appeared that a greater proportion of suppressed and sub-dominant trees showed symptoms and they tended to be affected before the dominant and codominant trees. As the water stress increased, dominant and codominant trees were affected and this constituted a much more serious impact on the capacity of the plantations to produce wood.

4.3 Growth Data from the Ellis Plantation Health Survey

4.3.1 Symptoms

The symptoms on trees examined in the health survey were consistent with the symptoms observed on trees in the broadscale survey, except that the proportion of trees in the tip death, half dead and dead classes was greater than in the general population (Table 7). In the Ellis plantation health survey the proportion of trees in the live and tip death classes in the most healthy trees was significantly higher than in the group of least healthy trees ($\chi^2 = 23.13$, $P < 0.001$) (Table 7).

The broadscale survey showed that the severity of symptoms increased with decreasing dominance class (Table 4). The data from the Ellis Plantation health surv·· supported this observation: trees in the most healthy group were significantly taller ($P < 0.001$), had a significantly greater underbark diameter at 1.4m ($P < 0.001$) and in a higher dominance class ($P < 0.001$) than the least healthy trees (Table 8).

4.3.2 Annual Increment

The annual area increment at 1.4 m of each tree in the health survey was calculated from growth ring widths. Mean area increment for both the most healthy and least healthy trees increased until age 7 or 8 (1983 and 1984) and then declined. This occurred at all slope positions and at stocking densities of both 1100 and 500 stems ha^{-1} (Fig 3). This decreased in annual area increment occurred before the low rainfall years of 1986 and 1987 (Section, 5.2.1). Similar decreases in area increment at an early age have been recorded at Grimwade (Fremlin[2] personal communication) and in New Zealand (Jackson *et al* 1983).

1. Detailed analysis available from J.F. McGrath
2. R. Fremlin, CALM Central Region

Table 6: Timing of symptom appearance vs dominance class

Dominance class	*Time of symptom appearance (months prior to sampling)	Severity of symptoms					
		Tip death		Intermediate symptoms		Dead	
		No.	%	No.	%	No.	%
Dominants	0-6	38	15	25	37	37	17
	6-12	109	41	36	54	143	66
	12	116	44	6	9	35	16
		263		67		215	
Codominants	0-6	67	14	47	34	85	14
	6-12	182	37	72	52	302	50
	12	242	49	19	14	215	36
		491		138		602	
Sub-dominants	0-6	18	11	11	14	26	11
	6-12	39	23	42	59	96	42
	12	111	66	18	26	109	47
		168		71		231	
Suppressed	0-6	6	8	5	22	3	4
	6-12	9	12	8	35	21	29
	12	60	80	10	43	49	67
		75		23		73	
	class total	997		299		1121	
	TOTAL					2417	

*Time of symptom appearance is relative to sampling in spring 1988.

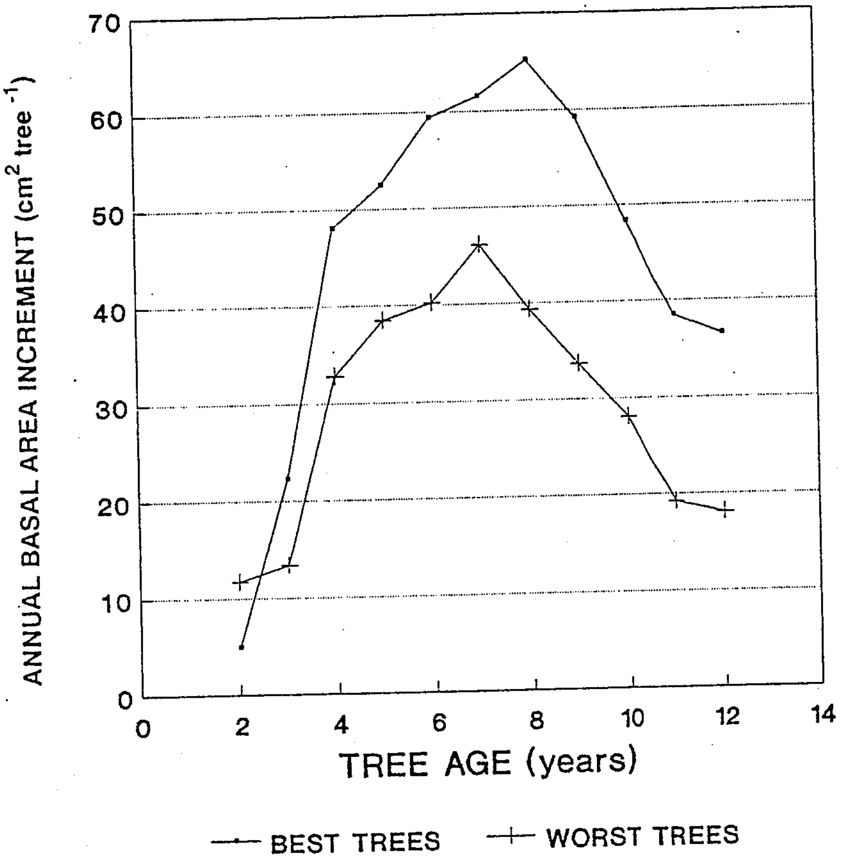
Table 7: Proportion of trees in each symptom class in the broadscale and health survey.

Symptom Class	Broadscale survey (%)	Health survey, Ellis plantation		
		All trees (%)	Most healthy (%)	Least healthy (%)
Live	64	27	50	3
Tip death	15	27	47	7
Intermediate symptoms	5	6	3	10
Dead	16	40	0	80
Number of trees examined	6992	60	30	30

Table 8: Height, diameter and dominance class of trees in the Ellis plantation health survey.

	Most healthy trees	Least healthy trees
Sample size	30	30
Mean height (m)	19.8	16.6
Underbark diameter at 1.4m (cm)	25.7	20.1
Dominance class (no. of trees)		
Dominant	15	1
Codominant	14	10
Sub-dominant	1	18
Suppressed	0	1

Figure 3 Relationship between age and mean annual basal area increment (cm^2 $tree^{-1}$) at 1.4m for the best and worst trees sampled in the health survey at Ellis plantation.



4.3.3 Tree Form

Tip death can result in the formation of multiple leaders so that the final tree has poor form. Athough many of the trees surveyed had a dead terminal shoot, it was evident that leader death and forking had occurred several times during the life of the trees (Table 9). Most of the forks occured above 12m. Of the trees examined, only 7 per cent had the potential to produce unforked stems.

Table 9: Death of terminal shoot, or stem dividing into more than one leader in the Ellis plantation health survey.

	Most healthy trees	Least healthy trees
Number of trees examined	30	30
Current leader dead	15	29
Previous leader dead or position of forking:		
Top third of crown	13	5
Mid third of crown	3	2
lower third of crown	2	2
Trees with live leader and no forks	4	0

5. STRESS FACTORS AFFECTING TREE DECLINE AND DEATH

5.1 Predisposing Factors

5.1.1 Climatic Factors

Monthly rainfall distribution patterns for Kirup, Balingup, Greenbushes, Bridgetown, and Nannup are presented (Fig 4). Rainfall distribution is seasonal with between 87 and 92 percent of rainfall falling in the seven months April to October. Thus a prolonged summer drought occurs annually, with tree growth and survival during this period being determined by the available water stored in the soil profile at the end of spring.

The summer weather pattern in the south of Western Australia is dominated by the passage from west to east of high pressure systems. This leads to the prevailing morning winds during the period November to April being from the east or south east (Fig 5). The pattern in the afternoon is influenced by the diurnal heating of the land mass producing a sea breeze which results in the predominant afternoon wind being a moist westerly (Fig 5). The role of the east winds will be explained later (Sections 5.1.2 and 5.4).

5.1.2 Site Factors

The three 'site factors' that had the largest impact on the occurrence of symptoms were soil depth, position in the landscape (upper, mid, lower) and aspect. Although these factors are interactive, for simplicity, the main effects will be presented independently.

5.1.2.1 Soil Depth- When live basal area (trees with tip death and live trees) is plotted against soil depth it is apparent that as soil depth increases the maximum basal area that can be carried on a site increases (Fig 6). However, for any soil depth there are a number of instances where the basal area is considerably less than the maximum. Reasons for the scatter of plots below the maximum may be: the interactive effect of other site factors reducing the maximum basal area that can be carried at any soil depth; the occurrence of "over kill" where plots above the carrying capacity of the site "over thin" when exposed to severe stress; plots may not yet have reached their maximum carrying capacity.

As soil depth presumably provides an indicator of the quantity of water available to the trees, it was thought that examining the depth to a heavy clay may provide a better indicator of available soil volume. When live basal area was plotted against soil depth to heavy clay (Fig 7) no relationship was obvious, suggesting that the heavy clays found in the Blackwood Valley were penetrated by *P. radiata* roots. Similarly, after adjusting soil depth for the quantity of rock and gravel in the profiles, the relationship between soil depth and live basal area was no longer obvious.

5.1.2.2 Position in Landscape- Five landscape positions were recorded in the survey (crest, upper slope, mid-slope, lower slope, valley). Because of the small number of plots that fell in the crest and valley positions these categories were combined with the upper slope and lower slope categories respectively, thus creating three categories of

Figure 4 Annual rainfall distribution at five locations (Kirup, Balingup, Greenbushes, Bridgetown, Nannup) in the Blackwood Valley.

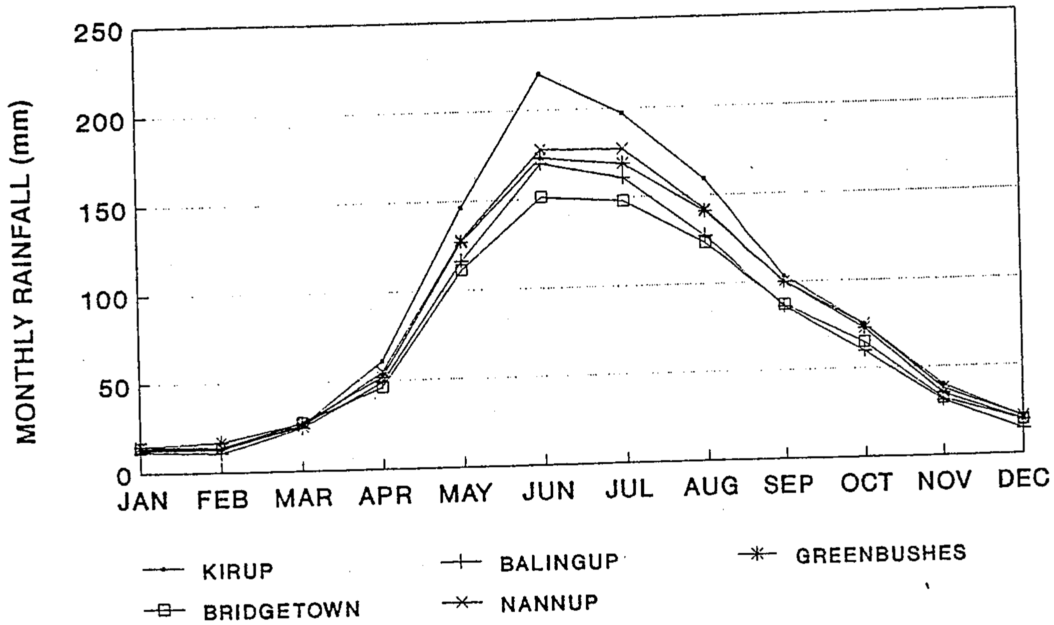


Figure 5 Windroses for 9.00am and 3.00pm for Donnybrook for a period of 31 years (1957-1988) showing wind direction and strength. Number in the centre of each windrose is the percentage of calms recorded.

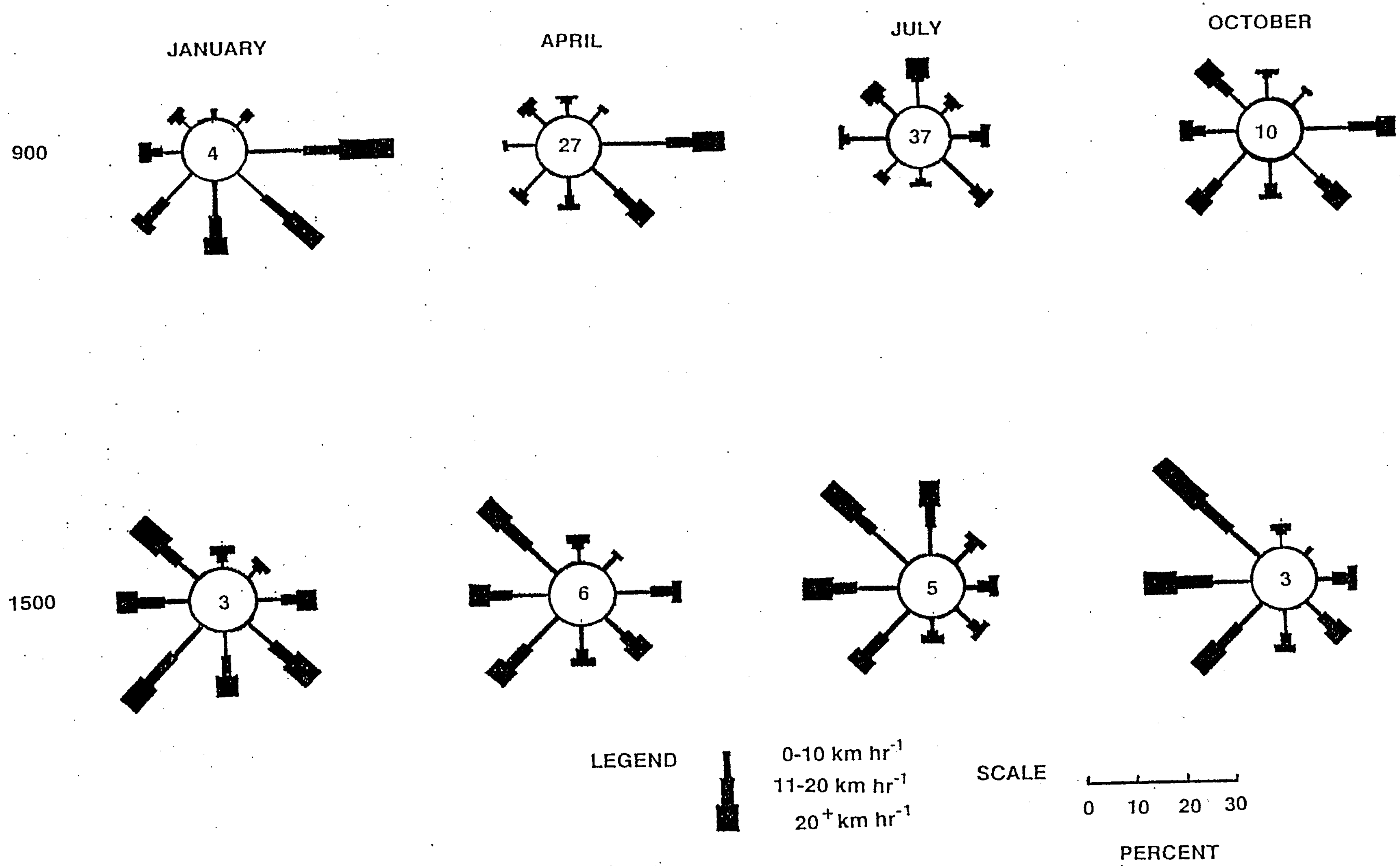


Figure 6 Relationship between soil depth (cm) and surviving basal area (m^2ha^{-1}), (live trees and trees with tip death) broadscale survey data. Note: numbers in figure refer to multiple data points.

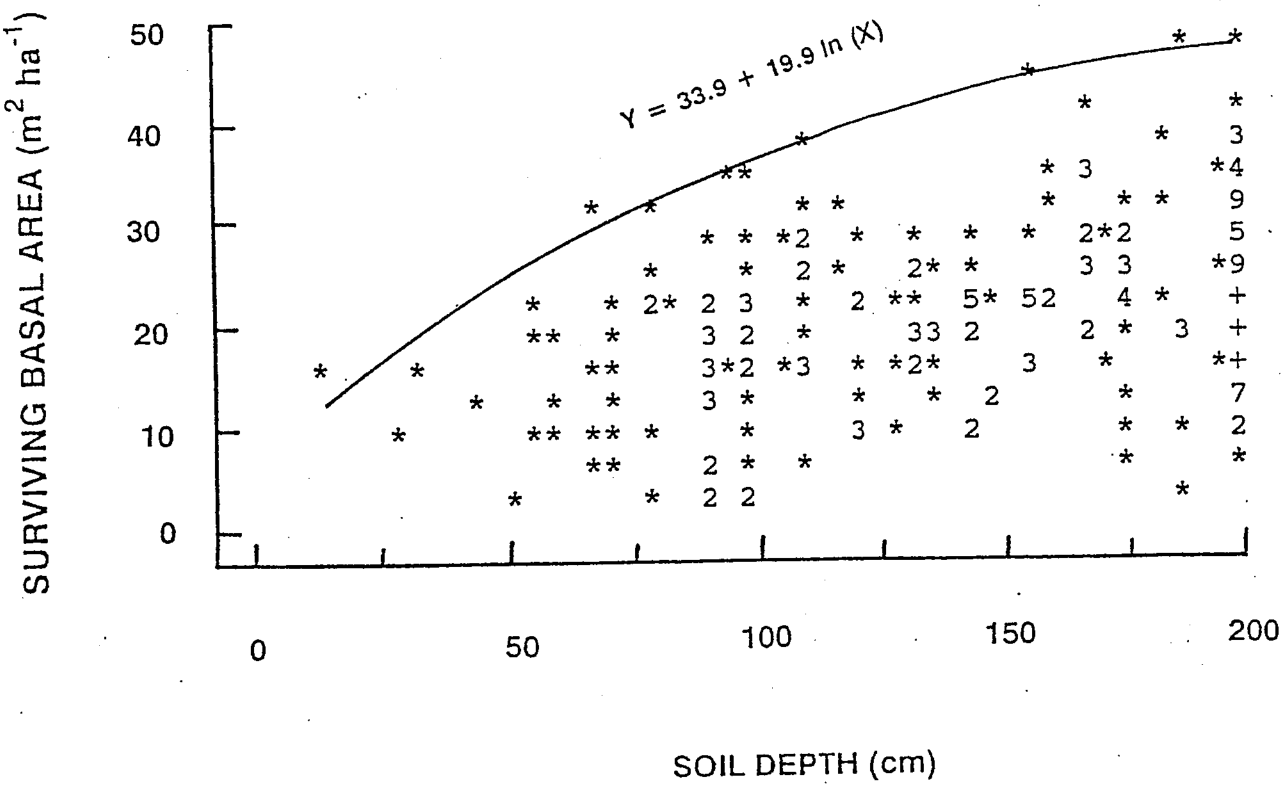
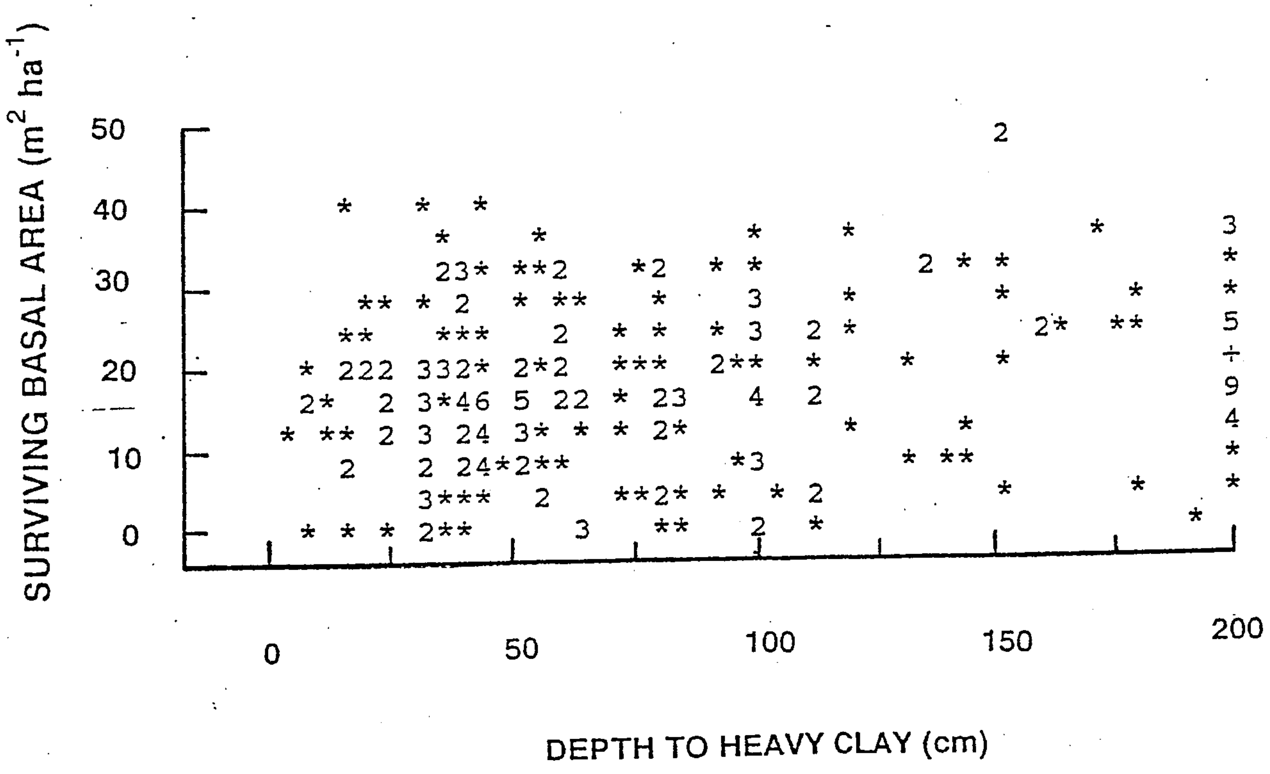


Figure 7 Relationship between depth to clay (cm) and surviving basal area (m^2ha^{-1}) (live trees and trees with tip death) broadscale survey data. Note: numbers in figure refer to multiple data points.



landscape positions (upper, mid and lower slope). The proportion of affected basal area increases from the lower to the upper landscape position (Table 10). Even without taking the interactive effects of soil depth, aspect, and initial basal area into account the overall effect of landscape position was significant at $P < 0.08$. Presumably the effect of landscape position is related to drainage with the upper slope being a water shedding zone and the lower slope being a water gaining zone, but there may also be a microclimate effect.

5.1.2.3 Aspect- Various splits of aspect were tried to determine whether aspect had an influence on the pattern of death. A moving mean of the percentage of basal area affected, was calculated by swinging a 90^{o} segment at 45^{o} intervals. The resulting "moving mean" is plotted in Figure 8 for both the severely affected category (dead and trees with intermediate symptoms) and the all affected category (dead, intermediate and tip dead trees). A greater proportion of the basal area was affected on north easterly aspects. The worst affected zone was a 90^{o} sector from 335^{o} to 65^{o}. The mean percentage of the basal area that was severely affected in this sector was 24.9 compared with 16.9 in the remaining 270^{o} sector, and this difference was significant at $P < 0.02$. It is also obvious from Figure 8 that a similar proportion of the basal area had tip death in all the sectors. The greater impact on north-east slopes is probably not related to soil depth as there was no difference in mean soil depth between the north-east sector and the remaining sector (Table 11).

Aspect also had a significant effect on top-height and site index (see Section 6), this suggests that the drier environment on the north-east slopes has had a long term influence on tree growth, not just an acute effect during dry periods. The most common effect of aspect on tree growth occurs via higher solar radiation on north and west aspects (southern hemisphere) and south-west aspects (northern hemisphere) (Einspahr and McComb 1951). The greater incidence of symptoms in the north-east sector suggests that a factor other than radiation is involved, possibly the desicating effect of the prevailing east winds during summer, or possibly a rain shadow effect, since winter rain drives in from the south-west.

5.1.3 Interaction Between Aspect, Slope, Landscape Position, Soil Depth of Decline and Basal Area on the Occurrence of Symptoms

There was a general trend for soil depth to increase from the upper to the lower slopes. This trend was most obvious for slopes less than 10^{o}, and much less evident on steep slopes greater than 10^{o}. In general, slopes less than 10^{o} had slightly deeper soil than slopes greater that 10^{o}. This trend was most obvious in the lower slope position. There was no difference between soil depth on the north-east and south-west slopes (Table 11).

An interesting feature of the data was that the steep slopes had higher mean initial basal areas. This is probably because thinning is more difficult on steep slopes and thus, in some cases, thinning occurred later than on the shallow slopes. The combined effect of the shallower soils and higher initial basal areas on the steep slopes resulted in a greater proportion of trees being severely affected on steeper slopes compared with shallow slopes (Table 11).

As already outlined a greater proportion of trees were affected in the north-east sector and there was a progressive increase in the proportion of trees affected from the lower to the upper slopes. Taking into account the influence of slope on soil depth and initial basal area Figure 8 shows that the greatest proportion of trees was affected on north-east, upper slopes greater than 10^{o} while the least effect occurred on the lower slopes less than 10^{o} irrespective of aspect. On north-east facing slopes greater than 10^{o}, landscape position had little effect on the occurrence of symptoms with all positions in

Table 10: Influence of position in the landscape on the mean percentage of the basal area that was severely affected i.e. intermediate and dead (broadscale survey).

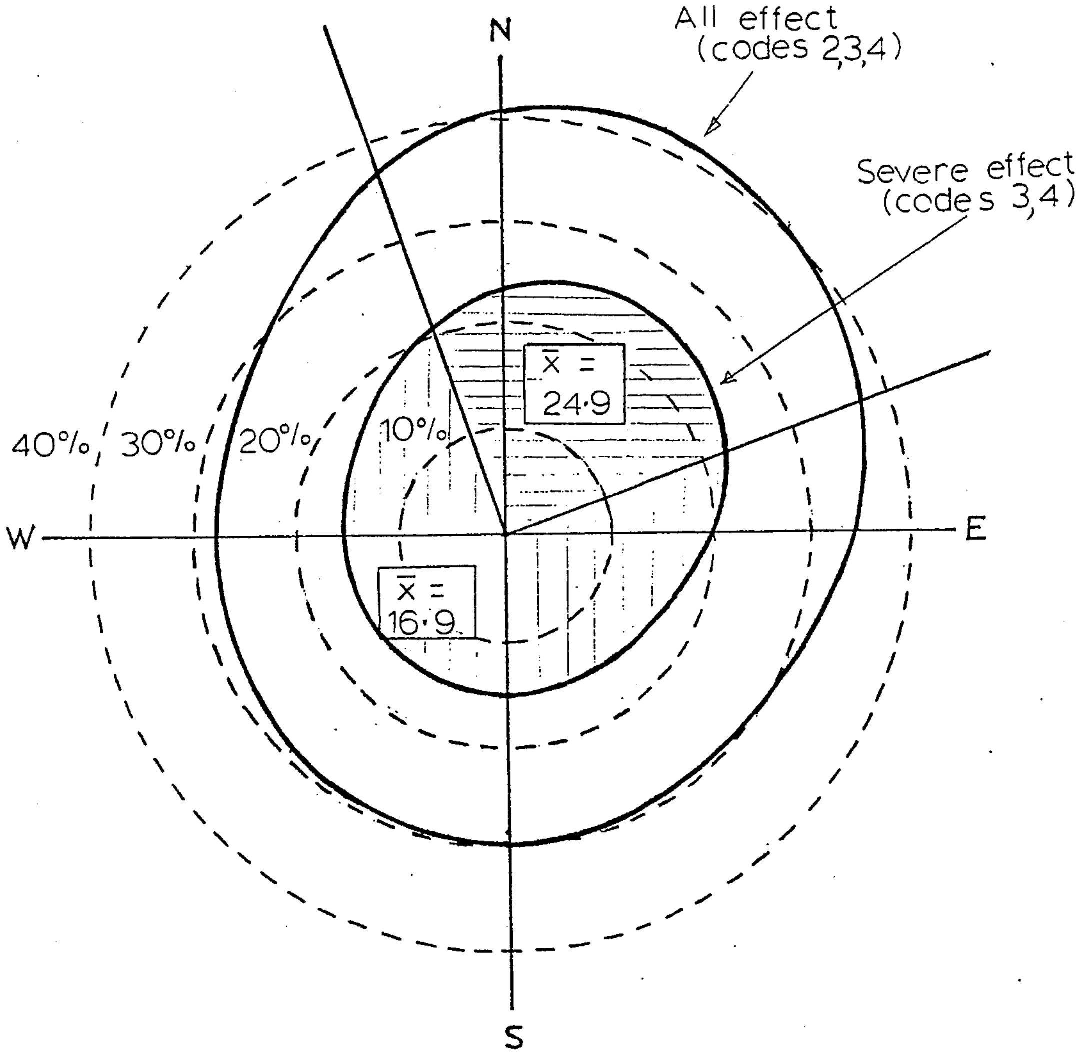
Position	Sample size	Mean percentage affected	Std error
Upper slope	95	22.4	2.9
Mid slope	112	18.2	2.0
Lower slope	45	12.6	2.8

Trend tested by regression $F = 5.15$, $P < 0.03$

Table 11: Interaction between aspect, slope, landscape position on soil depth, basal area and occurrence of symptoms (broadscale survey).

Aspect	Slope	Landscape position	Mean soil depth (cm)	Mean basal area (m^2ha^{-1})	% Severely affected Mean	% Severely affected Max
NE	$> 10^o$	upper	148	26.5	35.6	91.3
		mid	143	29.3	28.7	67.4
		lower	151	28.2	31.3	59.6
		mean	149	27.9	32.2	
NE	$< 10^o$	upper	139	24.6	19.0	69.0
		mid	158	22.9	14.1	48.0
		lower	188	27.8	1.5	6.4
		mean	164	24.2	13.2	
SW	$> 10^o$	upper	140	30.8	27.2	91.8
		mid	151	27.0	21.2	78.2
		lower	159	30.6	13.1	69.8
		mean	146	29.2	21.9	
SW	$< 10^o$	upper	165	21.7	10.1	87.4
		mid	157	25.1	12.6	74.9
		lower	184	21.7	4.4	30.6
		mean	158	23.3	10.5	

Figure 8 Relationship between aspect and the occurrence of decline symptoms in the broadscale survey. The inner envelope is the percentage of basal area that was severely affected (dead and trees with intermediate symptoms), the outer envelope is for all the affected basal area (dead, intermediate, tip death). The mean percentages are for the former.



the landscape having a large proportion of the trees affected. In general the maximum percentage affected reflected the overall (mean) trends.

The influence of steep slopes appears to be an effect of shallower soils and higher basal areas. Thus slope *per se* does not have a strong effect on the pattern of symptom occurrence. This is reflected in the fact that slope was not a significant driving variable in the model relating site index to environmental parameters (Section 6).

5.2 Inciting Factors

5.2.1 Weather

The last 20 years has been a period of relatively low rainfall in the Blackwood Valley (Figs 9 A-E). However, at none of the five recording centres was the rainfall in either 1986 or 1987 the lowest on record. Lower rainfall has been recorded at each station on between two and five occasions. However, the two-year period 1986-1987 had the lowest cumulative rainfall for any two consecutive years. Consecutive dry years are reasonably common in the region as "dry periods" of between two and five years have occurred four times since 1950 depending on the recording centre (Figs 9A-E). For example at Kirup dry periods occurred during 1952-1954, 1958-1960, 1968-1969, 1975-1979, 1984-1989 (Fig 9A). Thus dry periods are reasonably frequent events in the Blackwood Valley.

Windroses for the period November to April for Kirup (Figure 10) show an overall summer pattern of east, south-east winds in the morning and westerly sea breezes in the afternoon. The most obvious feature is the stronger winds and greater frequency of north-east winds during the summer of 1987-88.

The dry conditions during the 1986-1987 and 1987-1988 summers are shown by the lower relative humidity values for these years compared with the years before and after this period (Fig 11). The relative humidity was lower in November 1986 and 1987 than 1984 and 1985, and continued to decline until the following February (Fig 11). Thus the two-year dry period was characterised by low winter rainfall, dry summers with low relative humidity and strong east to north-east winds.

5.3 Contributing Factors

5.3.1 Diseases[1]

5.3.1.1 Needles- Symptoms could be recognised only on live needles, not dead ones. Brown spots and brown tips were common on live needles of trees in both Ellis and Lewana plantations, they were not investigated. There were no symptoms of *Dothistroma* needle blight or *Cyclaneusma* (=*Naemacyclus*) needle cast.

5.3.1.2 Stems and Branches- Stem cankers in both the phloem, and phloem and wood could only be recognised in moist, not dry, stems and branches. They were abundant in the sampled trees in both Ellis and Lewana plantations. Phloem cankers were more common than cankers which occurred in both phloem and wood (Table 12). The incidence of cankers increased with increasing height above the ground (Table 12).

There was blue stained and discoloured wood in many of the sampled trees, it was not confined to trees with dry stems (Table 13). Blue stained wood was more common than discoloured wood. No rots were found.

1. Full details of the pathological examinations available from E.M. Davison.

Figure 9 Annual rainfall for Kirup, Greenbushes, Bridgetown, Nannup for the period 1915-1988 and for Balingup for the period 1925-1988.

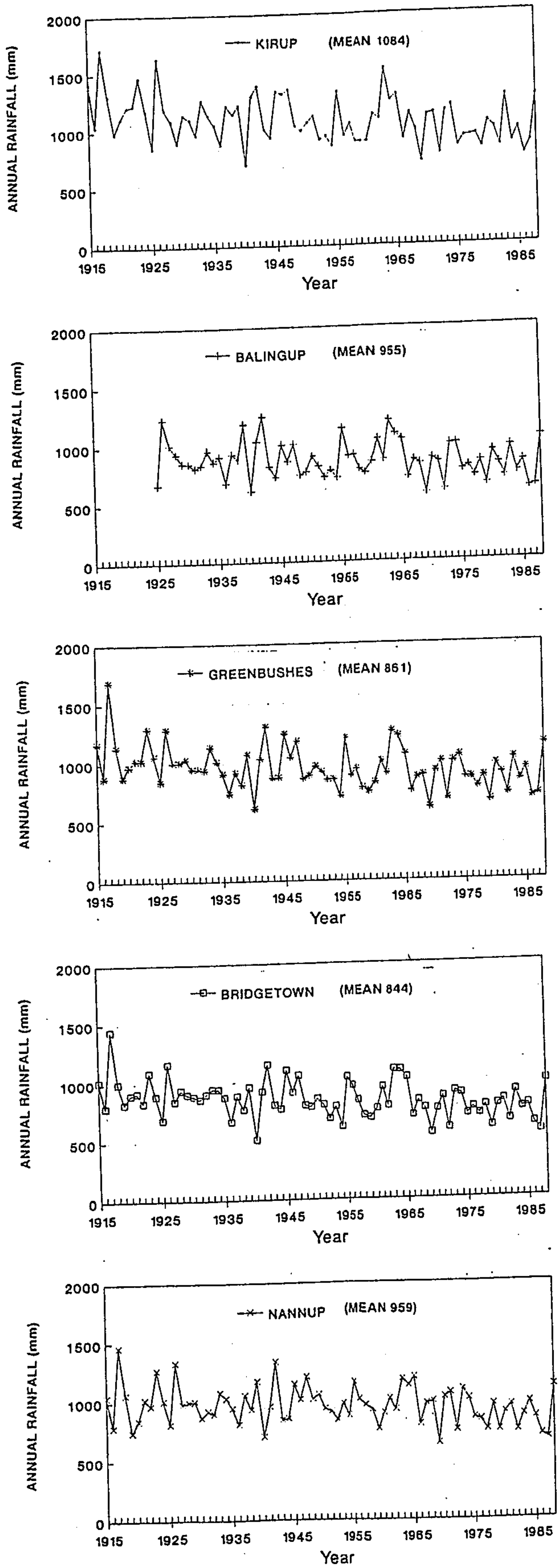


Figure 10 Windroses for Kirup for 1984 to 1988 at 9.00am, 12.00 midday, 3.00pm. Showing wind speed and direction. Data are for Nov, Dec, Jan, Feb, Mar, Apr. Number in the centre of each windrose is the percentage of calms recorded.

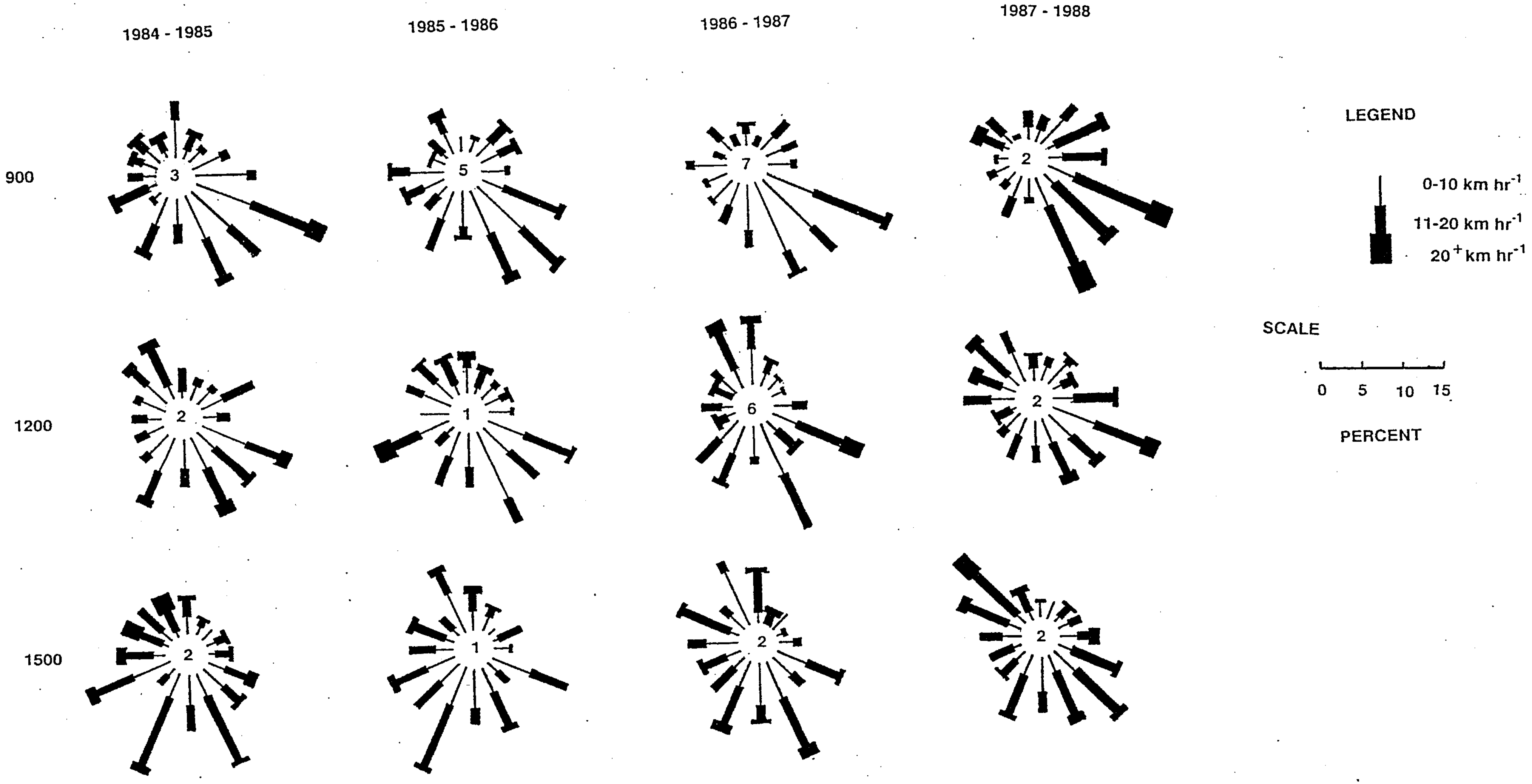


Figure 11 Mean relative humidity at 9.00am and 3.00pm at Kirup for the summers before the drought (1984-1985) and the years during the drought (1986-1987).

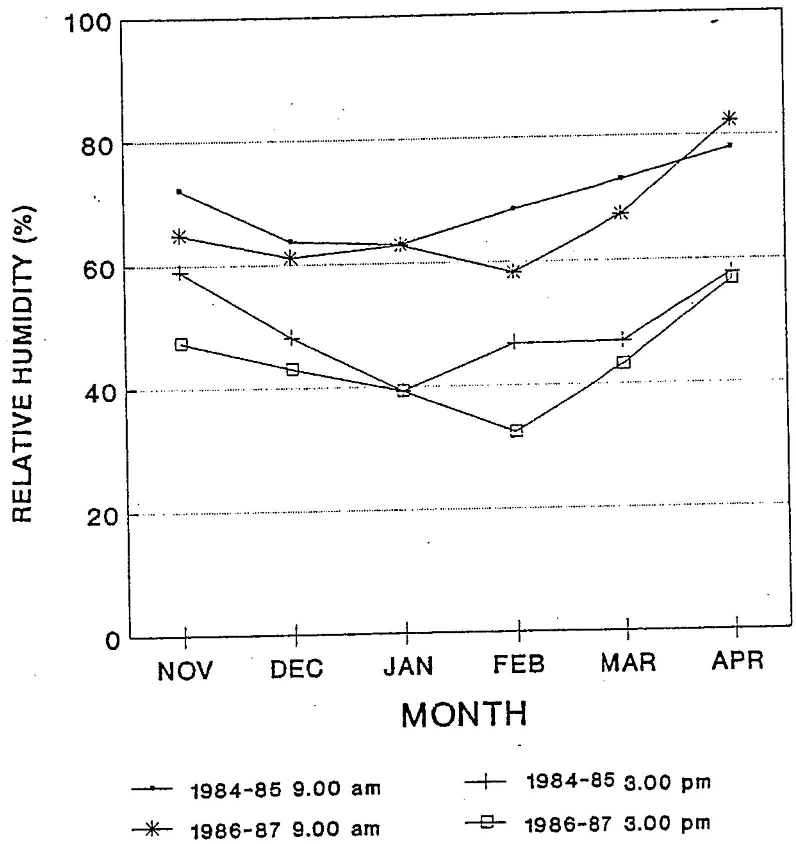


Table 12: Stem cankers on trees in the Ellis plantation health survey.

	Most healthy trees	Least healthy trees
Number of trees examined	30	30
Top third of crown:		
dry stem	1	20
cankers in phloem	21	9
cankers in phloem and wood	15	9
Middle third of crown:		
dry stem	0	17
cankers in phloem	21	11
cankers in phloem and wood	11	8
Lower third of crown		
dry stem	0	15
cankers in phloem	25	14
cankers in phloem and wood	9	11
Pruned stem		
dry stem	0	15
cankers in phloem	14	12
cankers in phloem and wood	5	11

Table 13: Symptoms in wood of trees in the Ellis plantation health survey.

	Most healthy trees	Least healthy Trees
Number of trees examined	30	30
Top third of crown:		
dry stem	1	20
blue stained wood	10	30
discoloured wood	3	1
Middle third of crown:		
dry stem	0	17
blue stained wood	4	29
discoloured wood	2	0
Lower third of crown:		
dry stem	0	15
blue stained wood	1	0
discoloured wood	0	26
Pruned stem:		
dry stem	0	15
blue stained wood	1	0
discoloured wood	0	23

The pine pathogen *Sphaeropsis sapinea* was isolated from 93 per cent of the sampled phloem cankers, from 100 per cent of the samples of blue stained wood and from 75 per cent of the samples of discoloured wood. Pathogenicity tests in *P. radiata* done elsewhere have shown that *S. sapinea* can cause cankers and dieback of the current year's growth (Chou 1976) but it cannot infect older stems unless they are severely drought-stressed (Chou 1987). In addition to causing stem cankers, *S. sapinea* is a well known cause of blue stained wood (Gibson 1979).

In addition to *S. sapinea, Ceratocystis ips* was recovered from 23 per cent of the sampled phloem cankers and from 8 per cent of the discoloured wood samples. *C. ips* is carried by the bark beetle *Ips grandicollis* and is not an aggressive pathogen (Parmeter *et al* 1989)

Although *S. sapinea* can infect pine stems, it can also infect green cones and fresh slash. Of the trees examined at Ellis plantation, 98 per cent had symptoms of *Sphaeropsis* infection on their cones.

5.3.1.3. Root Collars, Roots and Soil- Dead phloem and discoloured wood was present in the root collars and roots from trees in both Ellis and Lewana plantations. These symptoms were more abundant in the least healthy than the most healthy trees (Table 14). *S. sapinea* was recovered from 62 per cent of the samples phloem cankers and from 55 per cent of the discoloured wood samples. *C. ips* was recovered from 10 per cent of the phloem cankers and 18 per cent of the discoloured wood.

No *Phytophthora* spp. were recovered from either the roots or from soil samples. *Pythium* and *Fusarium* were common in the soil (Table 15).

5.3.2 Pests

5.3.2.1 *Ips grandicollis*- In the broadscale survey the presence of exit holes at breast height caused by the bark beetle *Ips grandicollis* was recorded. This facilitated data collection but would have underestimated the number of infested trees. Very few live trees had any evidence of infestation by *Ips* at breast height. The percentage of trees with evidence of *Ips* infestation increased from about 3 per cent for trees showing tip death to over 70 per cent for dead trees (Table 16). By plotting the proportion of the basal area in each plot that was infested by *Ips* against the proportion of basal area that was showing symptoms (tip death, intermediate, dead) (Fig 12) it is obvious that the proportion of trees infested with *Ips* did not exceed the proportion of the basal area showing symptoms. Conversely, in a large proportion of the plots a lower proportion of the trees showed evidence of *Ips* infestation at breast height than the proportion showing symptoms.

Data collected in the health survey supported these observations. *Ips* infestation of the butt was mainly confined to dead trees, but not all dead trees were infested (Table 17).

I. grandicollis is usually considered a secondary pest, colonising pine debris within eight months of felling or pruning (Neumann 1987). It can, however, attack living trees if oleoresin pressure is low. Breeding attacks occur in the lower part of the stem in drought-stressed or physically damaged trees during summer (Morgan 1967). The observations of *Ips* infestation made in the broadscale and health surveys were of the incidence of breeding attacks. These observations support the hypothesis that *Ips* attack is a consequence, not a cause, of decline and that death is due to other factors (Morgan 1967; Neumann 1987). In addition to breeding attacks on stressed trees, feeding attacks occur in the upper part of the crown of live trees. Feeding attacks can be distinguished from breeding attacks because the beetles attack the sapwood, not just the bark (Morgan 1967). Evidence of feeding attacks were observed in the health survey, they did not appear to be common, but consistent records were not kept.

Table 14: Symptoms in root collars and roots of trees in the Ellis plantation health survey.

	Most healthy trees	Least healthy trees
Root collars:		
Number examined	30	30
Dead phloem present	2	21
Discoloured wood present	2	20
Roots:		
Number examined	150	150
Dead phloem present	33	109
Discoloured wood present	15	103

Table 15: Soil baiting for *Phytophthora*, Ellis plantation health survey

	Most Healthy Trees	Least Healthy Trees
Number of soil samples	30	30
Fungi isolated:		
Phythophthora	0	0
Pythium	22	19
Fusarium	27	30
Cylindrocarpon	7	4

Table 16: *Ips* infestation of the butt in the different symptom classes, broadscale survey data.

Symptom class	Total number	*Ips* exit holes (%)
Live	4514	0.4
Tip death	997	3.3
Intermediate symptoms	299	11.1
Dead	1121	70.9

Figure 12 Relationship between the proportion of the basal area showing decline symptoms and the proportion of the basal area that was infested by *Ips grandicolis*.
Note: numbers in figures refer to multiple data points.

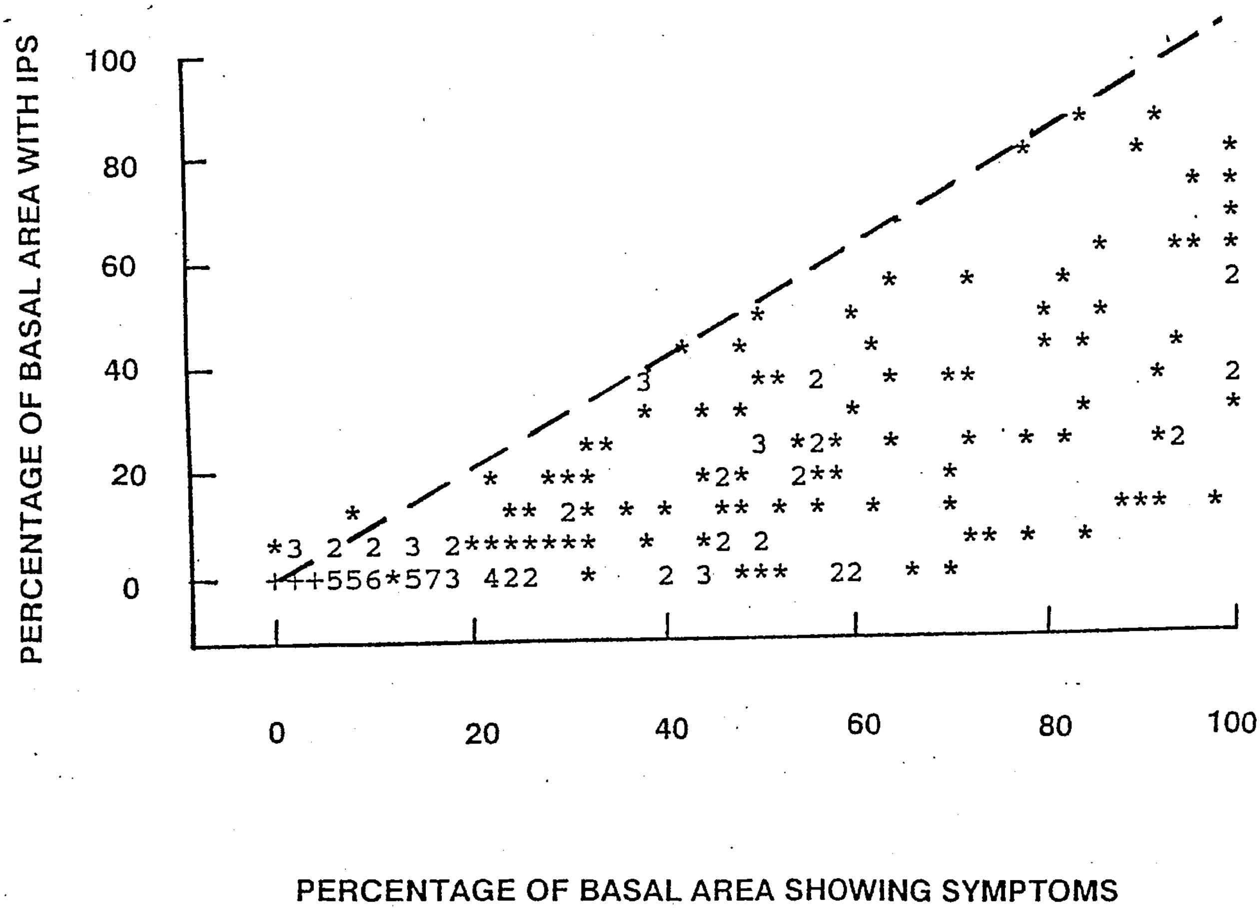


Table 17: *Ips* infestation of the butt, Ellis plantation health survey.

	Most healthy trees	Least healthy trees
Number of trees examined	30	30
Number of trees with no live needles	0	24
Number of trees with *Ips* emergence holes at 1.4 m	1	17

5.3.2.2 Other Insects- Apart from *I. grandicollis* no other insects were collected in large numbers.

5.4 Suggested Progression of Symptom Development

Following establishment, the rapid height and diameter growth of pines is dependent on the availability of water and nutrients. The seasonal rainfall of the Blackwood Valley (Fig 4) implied that soil storage of water (determined by soil depth, landscape position, and aspect) and demand for that water (determined by stand basal area and aspect) is of paramount importance in determining the productivity of stands. Figure 3 indicates that on one site, annual area increment did not continue to increase in years of normal rainfall, after age 8, suggesting that the available water was fully exploited by this age.

In years of below average rainfall eg 1986 and 1987 (Fig 9), problems associated with water availability are likely to be exacerbated, particularly on shallow soils carrying a stand with a high basal area. If, in addition, there is an increase in the frequency and strength of dry, north-easterly winds (Fig 10) and lower relative humidity (Fig 11) during the following summer, problems of water availability are further compounded, particularly on north east facing slopes (Fig 8). Although they were not measured, we predict that xylem pressure potentials would be lowest on such sites.

The pine pathogen *Sphaeropsis sapinea* and the bark beetle *Ips grandicollis* appear to be ubiquitous within the Blackwood Valley plantations. Although *S. sapinea* can cause dieback of the current year's growth, infection of older stems can only occur in trees with low xylem pressure potentials (Chou 1987). The massive infections causing extensive phloem death and blue stained wood seen at Ellis and Lewana plantations (Tables 12,13 and 14) can only have occurred in severely drought-stressed trees. Similarly, breeding attacks by *Ips* is most likely to occur in drought-stressed trees.

The pattern of symptom development (healthy, tip death, intermediate, dead trees) is consistent with water deficits occurring throughout the tree, but being most severe in the terminal shoot. In the leader, invasion by *Sphaeropsis* occurs from existing, small infections, with the pathogen spreading down the phloem and pith and spreading laterally into the wood. Further invasion of the main stem develops from existing phloem cankers or from infected branches. *Ips* invades the dead and dying bark. Thus the symptoms observed are consistent with severe drought stress in sites and in stands predisposed to drought, incited by the weather conditions in 1986-1988, with *S. sapinea* contributing to symptom expression.

6. PREDICTING WHICH SITES ARE SUSCEPTIBLE TO DROUGHT STRESS

The conceptual model of the interactions between environmental factors and stand factors that influenced the drought impact is presented in Figure 13. To predict the liklihood of drought impact we first predicted site index and then examined the relationship between initial basal area and surviving basal area in each site index class.

6.1 Relationship Between Height Growth and Age

The relationship between top-height and age is shown in Figure 14. Although, as expected, there is a strong relationship between age and top-height, there is still considerable variation that is not explained by age alone. Part of this variation is attributable to the same environmental factors that influence the occurrence of drought death. The regression between top-height and age, soil depth, position in the landscape, and aspect accounts for 86 per cent of the variation. The relationship was not improved by adding slope to the equation, presumably because the main effect of slope in decreasing water availability is taken into account by soil depth and position in landscape.

The equations which link the elements of the model are:

Equation 1 (a):

$$\text{TOP-HEIGHT} = \exp(3.57 + 0.000525 * S + 0.0377 * T - 0.0405 * A - 7.89/Y)$$

N = 231
R-squared (adj) = 86.2%
F = 359.79 P < 0.001

Where:- S is augured soil depth in centimetres
T is topographic position (upper = 1, mid = 2, lower = 3)
A is aspect of slope (335 to 65 degrees = 1, other = 0)
Y is age of trees in years

If information on soil depth is unavailable, then equation 1(b) may be used with slight loss of accuracy.

Equation 1(b):

$$\text{TOP-HEIGHT} = \exp(3.65 + 0.0416 * T - 0.0424 * A - 7.97/Y)$$

N = 231
R-squared (adj) = 85.3%
F = 445.15 P < 0.001

From these regressions, accepting the standard forestry relationship of:

SITE INDEX = top-height * exp (k/age)

Where k is a constant representing the age at which height growth stops accelerating and starts slowing down, then we may infer that growth of *Pinus radiata* trees in the Blackwood Valley starts to slow down at about 8 years old. This is less than the average

Figure 13 Conceptual model of the interacting factors that effect the susceptibility of plantation trees to drought.

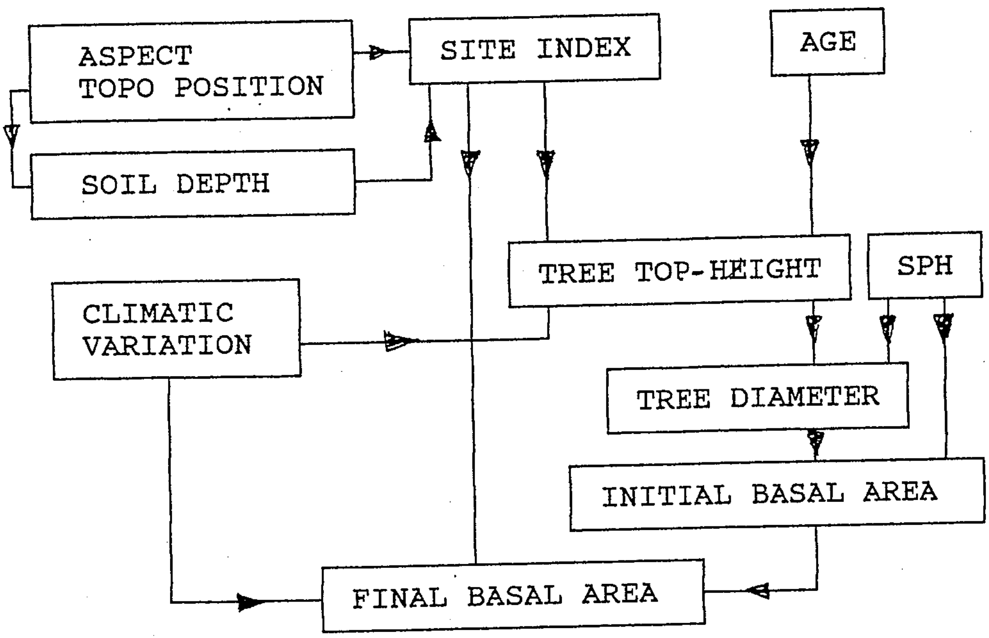
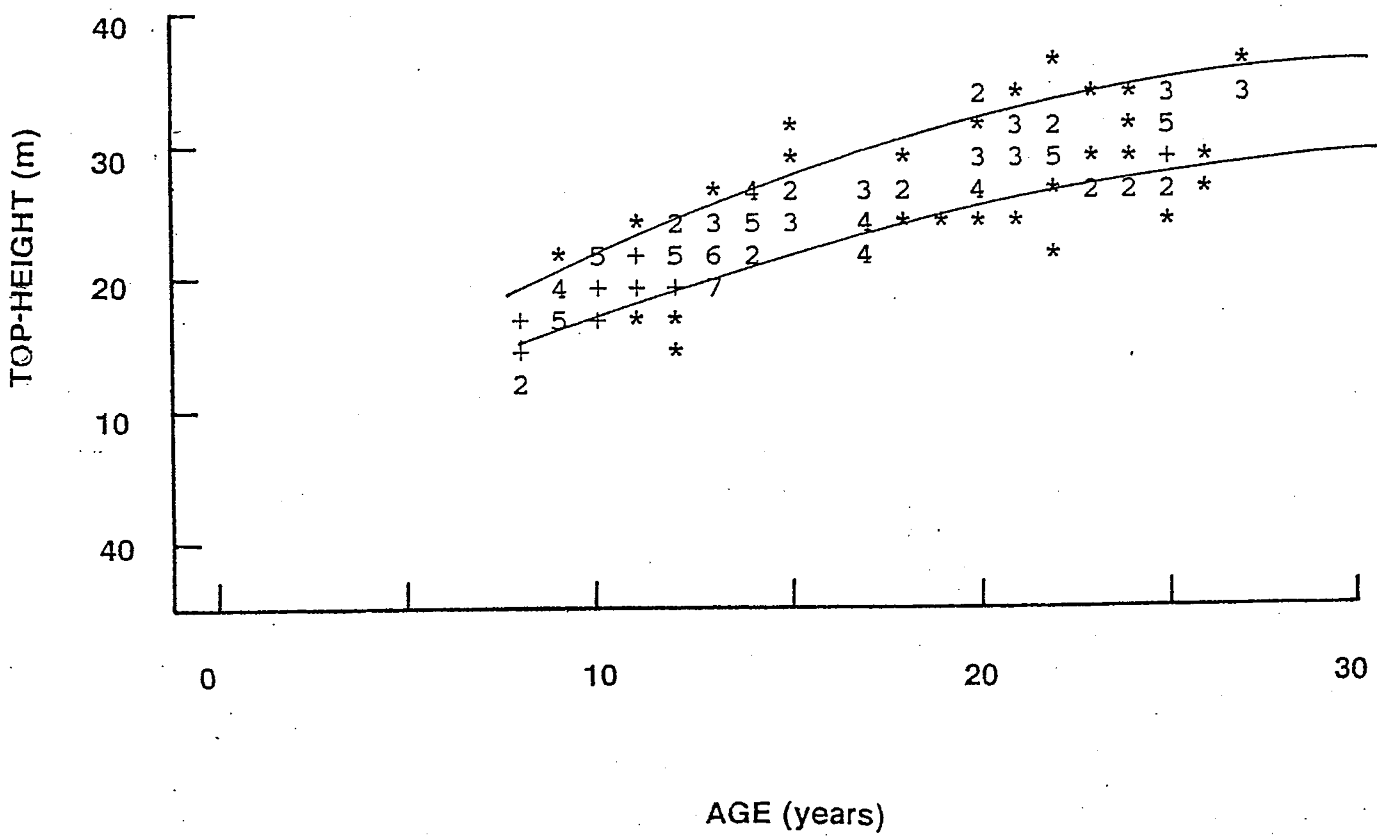


Figure 14 Relationship between top-height (50 stems ha^{-1}) and age.
Note: numbers represent multiple data points. The upper curve represents the predicted height growth for a deep (2m), lower slope, south-west facing site. The lower curve the predicted curve for a shallow (50 cm), upper slope, north-east facing site.



of nearly 10 years calculated by the CALM Inventory Section for the whole south-west of Western Australia. Again, site index can be estimated in two ways, with (Eqn 2a) or without soil depth (Eqn 2b).

Equation 2 (a):

SITE INDEX = exp (3.57-0.000525 * S + 0.0377 * T-0.0405 * A)

Equation 2 (b):

SITE INDEX = exp 3.65 + 0.0416 * T-0.0424 * A)

For simplicity, this SITE INDEX can be split into four SITE CLASSES (as defined in Table 18). It was found that a split on the logarithmic scale gave clearer separation.

6.2 Relationship Between Basal Area and Mortality

For the data set available we can estimate the proportion of the initial basal area that is likely to survive a drought such as the one that occurred in 1986/1987. The term survive means to suffer no more than tip death as defined for this survey (i.e. tip death ranged from browning of the apical needles to death of the top 25 per cent of the crown). It was assumed that the majority of trees suffering tip death remained alive and recovered because when a sample of plots were revisited several months after the broadscale survey had been completed, the proportion of trees in the live and tip death classes had not changed, indicating that trees showing tip death had not progressed further.

Equation 3

Surviving BA = Init BA/(exp(1.04 * class + 0.0501 * Init BA-6.4) + 1)

n = 251
R-squared (adj) = 55%

The relationship, as defined by the above Equation 3, between final, or surviving basal area, and the initial basal area on the site is shown in Figure 15. A plot of predicted values versus actual values is shown in Figure 16.

The relationship between initial basal area and surviving basal area varied between the four proposed Site Classes. Progressing from Site Class 1 to Site Class 4 a greater proportion of the sites suffered serious loss of basal area. This is demonstrated by the histograms of the percentage of plots in each of the categories (Fig 17). Respectively Site Classes 1, 2, 3 and 4 had 84 per cent, 68 per cent, 50 per cent, 35 per cent of plots with greater than 90 per cent survival.

Increasing basal area over the range measured had little effect on the surviving basal area in Site Class 1. As already noted, a small proportion of sites classified as Site Class 1 had a high proportion of dead basal area, however these plots were not the result of high initial basal areas (Fig 18A). It is possible that some sites were incorrectly allocated to the various site classes. For Site Class 2 there was an increase in the proportion of trees showing symptoms when the basal area was above 25 m^2ha^{-1}. Some Site Class 2 plots retained high surviving basal areas (Fig 18B). For Site Class 3 the limit above which serious loss of basal area could be expected was less well defined than for Site Class 2, above 20 m^2ha^{-1} there was an increased liklihood of serious loss of basal area (Figure 18C). There was a high likelihood of losing a large proportion of the initial basal area at any basal area on Site Class 4 (Fig18D). On this Site Class all plots with initial basal areas above 25 m^2ha^{-1} lost some basal area. This contrasts with the other three Site Classes where some plots retained a high proportion of their basal area even at high initial basal areas.

Table 18: Site index and 30 year top-height in proposed Site Classses

Site class	Site index (m)	Top-height at 30 years (m)
1	over 42.52	over 32.7
2	40.85 - 42.51	31.4-32.7
3	39.25-40.84	30.2-31.4
4	below 39.25	below 30.2

Figure 15 Relationship between initial basal area and predicted surviving basal area for the four Site Classes proposed for the Blackwood Valley plantations.

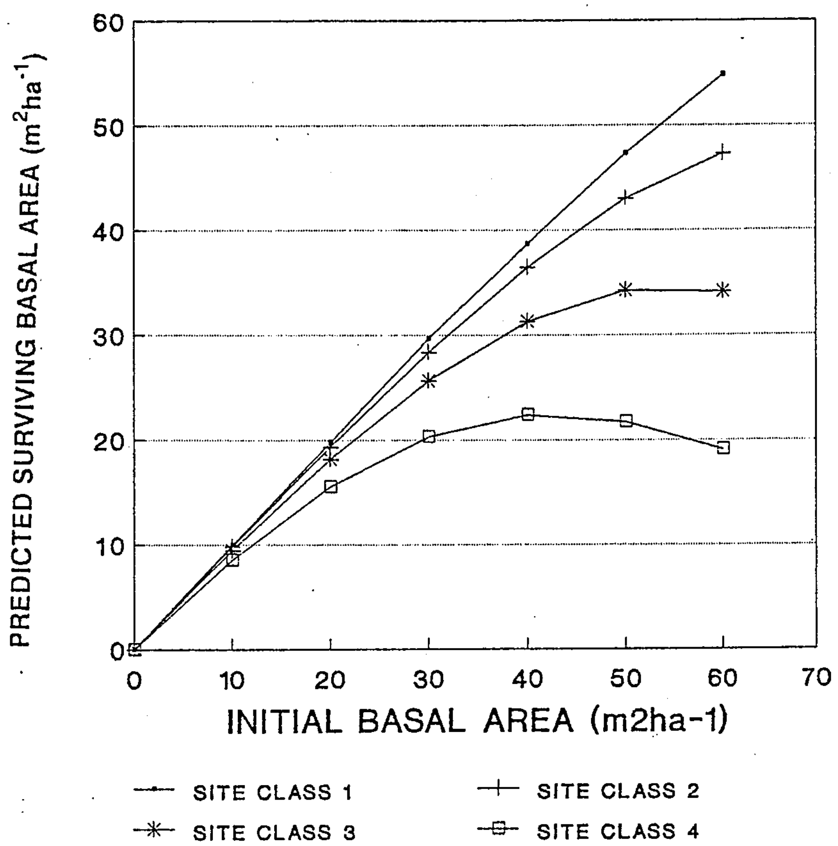


Figure 16 Relationship between actual surviving basal area and predicted surviving basal area (correlation coefficient R^2 = 0.55, n = 251) Note: numbers in figure represent multiple data points.

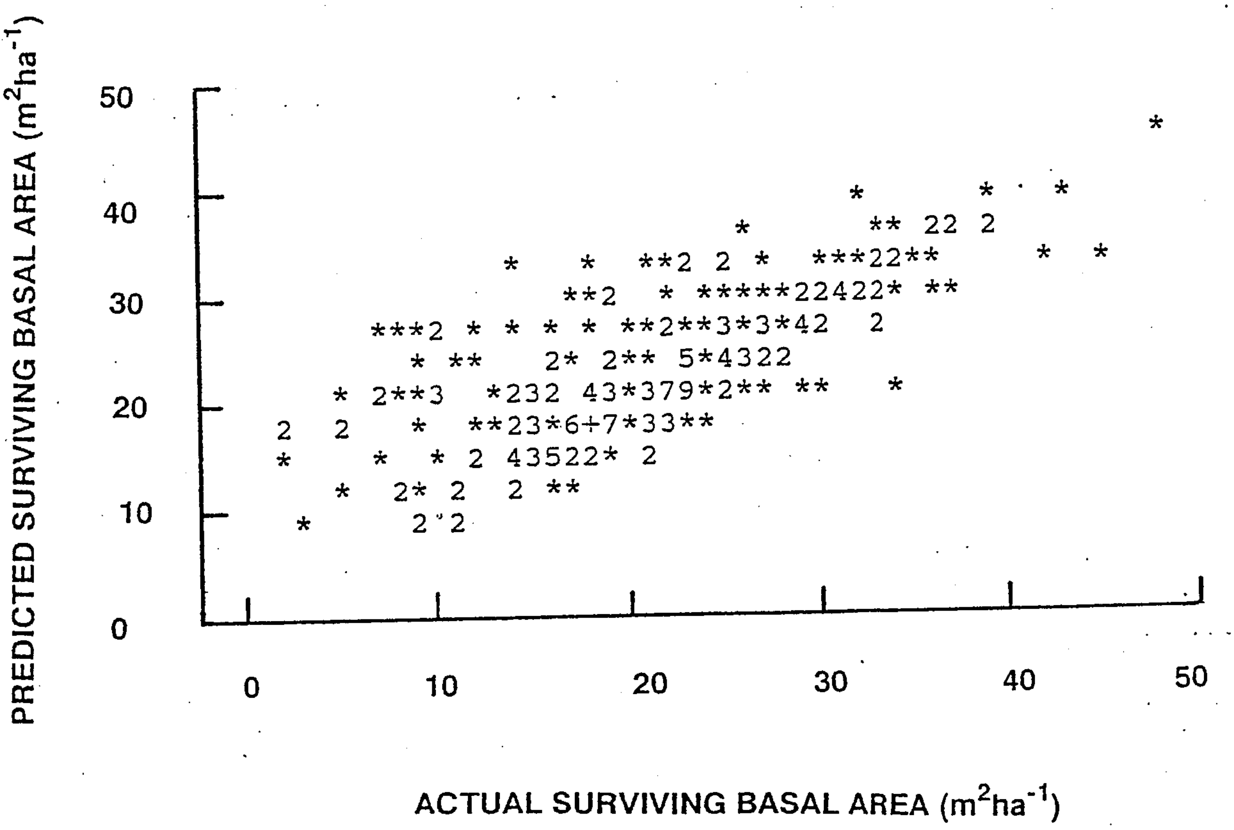


Figure 17   Histograms of the percentage of plots in each survival category for each Site Class.

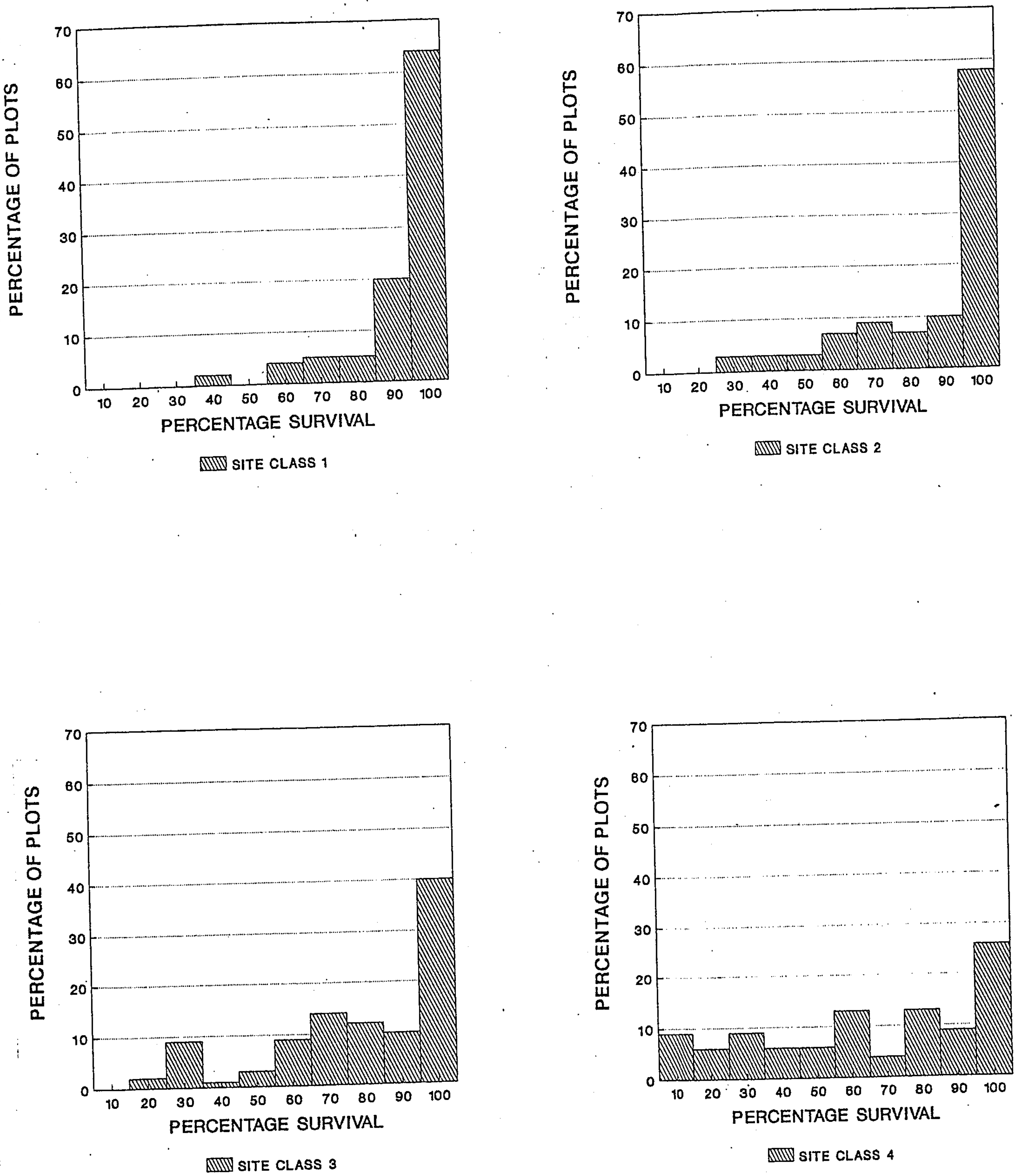
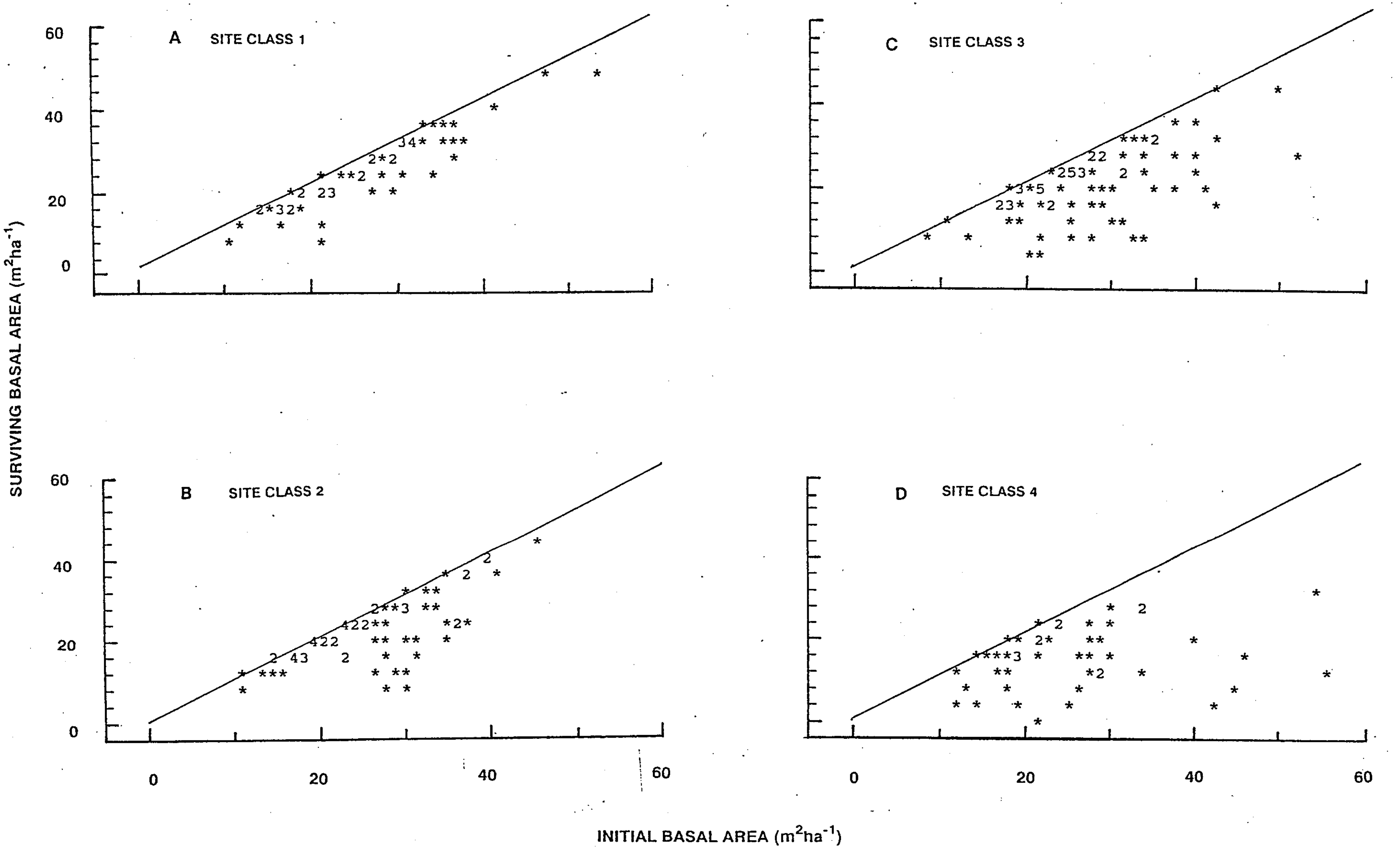


Figure 18 Relationship between initial basal area and actual surviving basal area for each Site Class. The solid line indicates the 1:1 line.



The loss of a small proportion of basal area on some of the Site Class 1 plots and on some of the plots with low basal areas on Site Classes 2 and 3 was noted (Fig 18 A,B, C). This suggest that all the sites in the Blackwood Valley suffered some drought stress during the 1987 and 1988 summers. This indicates that even the good sites (Site Class 1,2) are at risk in conditions drier than those experienced in the most recent drought.

To illustrate the differences between the four Site Classes the calculated top-height at 30 years of age, surviving basal area, and soil depth are shown in Table 19. For each of these parameters there was a large decline from Site Class 1 to Site Class 4.

The mean soil depth for the lowest Site Class (4) was slightly more than 1 m. Thus even on soils that were previously considered good for the growth of *P. radiata*, (A and B class soils, with root penetrable depth greater than 90 cms, see Pine Management Guide 1988), serious drought death could occur. From the data it is obvious that soils previously considered as marginal, and thus plantable (C-class:50-90 cms), have a high probability of being severely affected by drought.

Comparing the predicted top-heights at age 30 for the Blackwood Valley with the South Australian site quality system (Lewis *et al* 1976) indicates that the best Blackwood Valley Site Class (Site Class 1) falls between SA site index III and IV, Site Classes 2 and 3 fall between SA site index IV and V and site-class 4 is below SA site index V. A comparison with the South Australian site index system is not strictly valid as our site index data was derived from 50 trees ha^{-1}, whereas the SA system use uses top-height measurements of the tallest 75 trees ha^{-1}.

Table 19: Effect of Site Class on mean top-height at 30 years, mean surviving basal area and mean soil depth.

Site class	Number of plots	Top-height (m)	Surviving basal area ($m^2 ha^{-1}$)	Soil depth (cm)
1	56	33.2 (0.1)	24.9 (1.2)	191 (2.4)
2	69	31.9 (0.1)	22.1 (0.9)	171 (3.8)
3	80	30.9 (0.1)	21.0 (0.9)	142 (4.6)
4	47	29.5 (0.1)	15.5 (1.1)	108 (5.3)

Note: numbers in brackets are standard errors.

7. GENERAL DISCUSSION

Soil type was the main factor determining the selection of the Blackwood Valley as suitable for radiata pine plantations (Section 2.1). Detailed site assessments prior to planting however, indicated that although the soil was of a suitable type, it might be of inadequate depth to support tree growth through a complete rotation. Tree mortality after low rainfall years indicated a problem of water availability which was dependent on stocking, soil dpeth, aspect and slope position (Section 2.2). Our broadscale survey has confirmed the importance of these stand and site factors. It has also allowed us to predict which sites, as yet unplanted, will be suitable for a 30 year sawlog rotation of pines. The broadscale survey has, however, indicated that there are many sites within plantations where stands will become drought affected in years of below average rainfall. These pine plantations are predisposed to drought because of two main factors. The first is the markedly seasonal nature of the climate, which results in approximately 90 per cent of the annual rainfall falling in the seven months from April to October. Thus the plantations rely on stored moisture to survive the annual summer drought. The second major factor is the low water-storage capacity on some of the valley sites because of the steeply incised nature of the topography, which results in relatively shallow soils and water shedding zones in the mid and upper portions of the slopes.

In addition to the summers being dry, they are the periods during which the evapotranspiration demand of the plantations is highest due to the lower relative humidity and higher temperatures. The stronger and more frequent east and north-east winds experienced during the summer in the drought years would have contributed to the evapotranspiration demand. This is the most likely reason that the north-easterly facing slopes were more seriously affected by the drought. Another reason may be that the winter rain drives in mostly from the south-west, leaving north-east slopes in a rain-shadow.

The site factors that had a major influence on tree decline and death were related to the capacity of the site to store moisture and to the demand for water during summer. Soil depth obviously determines the overall capacity of a site to store water, and as such is probably the most important factor in determining whether a site is susceptible to drought. Although it is possible to derive a regression model excluding soil depth (see Section 6), by doing so some sensitivity is lost. Attempts to correct for the reduction of soil volume because of either the amount of rock in the profile or the nature of the clay, decreased the importance of soil depth as a parameter influencing the pattern of drought impact. This was surprising, and suggests that a more detailed investigation of the influence of soil parameters, such as bulk density and clay structure, on tree growth in the Blackwood Valley may be rewarding.

One overriding conclusion is that the soil depth necessary for *P. radiata* to survive droughts of the intensity experienced in 1986-1987 is greater than that which was previously thought necessary. For plantations with basal areas above 25 m^2 ha^{-1} a soil depth of almost 2m is necessary to guarantee that the plantation will survive similar droughts virtually unscathed.

The major influence of topographical position on the impact of droughts is probably via a drainage effect, with the upper slopes being water-shedding and the lower slopes water-gaining zones. The influence of aspect is likely to be an effect of greater evapotranspiration demand owing to the desiccating effect of the east and north-east winds. This probably explains why the shallow, upper slopes, facing north-east were the sites that were worst effected. These sites would have both a low water storage capacity and a high water demand.

The impact of basal area as an index of the water demand by the trees on a site varied between the four Site Classes delineated for the Blackwood Valley. Increasing basal area over the range measured had little effect on the surviving basal area in Site Class 1. The limit above which serious basal area loss could be expected was 25 m^2ha^{-1} and 20 m^2 ha^{-1} respectively for Site Classes 2 and 3. For Site Class 4 serious basal area loss occurred at all initial basal areas. Site Classes 1 and 2 can probably be managed using current silvicultural procedures. It may be possible to manage Site Class 3 for sawlogs under a widespaced silvicultural regime (eg: agroforestry, fuel reduced buffers). Alternatively, these sites might be suitable for short rotation, unpruned, unthinned stands for chip logs. It is probably impossible to manage areas classified as Site Class 4 as they are extremely drought prone.

The dominant and codominant trees contributed most of the loss in basal area on all sites. This is despite the fact that the supressed and sub-dominant trees are more likely to be affected by drought and its associated effects. The suppressed and sub-dominant trees only account for a small proportion of the initial basal area and thus do not contribute as much to the overall impact on the plantations.

The model of the relationship between site factors and the decline and death of *P. radiata* presented here only strictly relates to dry periods of the intensity and duration of the 1986-1987 period. Droughts of longer duration or greater intensity would have a more severe impact on the Blackwood Valley plantations than predicted by the current model. As the frequency of consecutive dry years in the Blackwood Valley is high (four or five in the last 40 years, depending on recording centre) it would appear that plantation management should be conservative.

8. RECOMMENDATIONS

8.1 Selection of Sites for New Plantations

The results from the broadscale survey have indicated that previous soil survey procedures were inadequate in identifying drought prone sites. In future soil depth to 2 m, landscape position and aspect need to be assessed before an area is planted. The minimum recommend soil depths for Blackwood Valley Site Classes 1 and 2 for different aspects and landscape positions are shown below:

Estimated minimum soil depth (cm) required for radiata pines grown in the Blackwood Valley plantations.

Aspect	Landscape position	Site class 1	Site class 2
NE	upper slope	*	*
	mid-slope	*	200
	lower slope	*	130
All aspects apart from NE	upper slope	*	200
	mid-slope	200	120
	lower slope	130	50

*Soils greater than 2m in depth are required, however, no prediction of the depth required is possible as the maximum soil depth measured in the survey was 2m.

8.2 Management of Existing Plantations

The existing plantations should be evaluated in terms of the Blackwood Valley Site Classes defined in section 6.1, and each Site Class managed to the basal area specified.

Blackwood Valley Site Class	Top-height age 30 (m)	Max basal area (m^2 ha^{-1})
1	over 32.7	No limit
2	31.4-32.7	25
3	30.2-31.4	20
4	under 30.2	unsuitable for pines

Options which could be considered for Site Class 3 are agroforestry and fuel reduced buffers.

Thinning of the existing plantations should be based on basal area measurement and Site Class, not on plantation age.

The economics of growing pines on each of these Site Classes should be re-evaluated.

8.3 Suitability of Other Species

Plots of alternate species growing within the Blackwood Valley should be assessed to see whether they are more suitable than *P. radiata* on some sites.

8.4 Trouble Shooting

A trouble shooting service should be developed within CALM to provide a rapid diagnosis of problems.

8.5 Revision of the Pine Management Guide

The Blackwood Valley surveys have highlighted a number of changes that are necessary within the CALM Pine Management Guide. In particular the sections on Land and Soil assessment need revising to include the changes recommended from this report.

ACKNOWLEDGEMENTS

This report summarises the work of many people from the Department of Conservation and Land Management. In particular we wish to thank P. Jenkins, B. Read, J. Schutz, R. Hingston, I. Dumbrell, A. Wills and A. Woodward who carried out the broadscale survey and collected additional data needed for its interpretation, and F. Tay and D. Peroni who carried out the health survey. We thank D. Spriggins and J. Kaye from the Central Region for their support for the surveys, and the Nannup and Kirup offices for financial assistance for the health survey. Staff from the Nannup office are also thanked for providing fellers and back-up help in the health survey. We thank W. Frost for indentifying the insects.

P. Christensen's continued interest throughout this work is gratefully acknowledged.

Finally we wish to thank N. Allday for patiently typing the many drafts of this report and M. Lewis for editorial corrections.

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Future Pine Care in the Blackwood Valley

Pine Deaths in the Blackwood Valley Plantations: a Recurrent Problem

by

J.F. McGrath, D. Ward and E.M. Davison

Brief Summary

Extensive mortality of *Pinus radiata* in the Blackwood Valley plantations in 1987 and 1988 resulted in economic losses of over $700 per ha. Tree deaths were not evenly distributed throughout the plantations, on some sites all the trees died. Rainfall in 1986 and 1987 was well below average and the trees were assumed to have died of drought.

A broadscale survey of the plantations was undertaken in 1988 to determine whether tree deaths were associated with specific site and plantation factors and, if so, to recommend site specifications for future plantings as well as to determine the basal area that various sites can carry during drought years. In addition, a health survey of individual trees was undertaken to determine whether pathogens and pests were associated with mortality.

Tree mortality was associated with soil depth, position in the landscape, aspect and basal area of the stand. Site index has been caluclated from top-height, age, soil depth, aspect and landscape position. Site classes, derived from the site index, are rpredicted from the site parameters and are used to predict which sites are drought prone.

Blackwood Valley Site Class	Predicted top height at age 30 (m)	Predicted maximum b.a. (m^2 ha^{-1}) above which mortality will occur
1	>32.7	no limit (over the range of sites measured)
2	31.4-32.7	25
3	30.2-31.4	20
4	<30.2	unsuitable for pines

The pine pathogen *Sphaeropsis spapinea* was consistently associated with dead shoots, branches and stems, and with blue stained wood. Boles of many of the dead trees were colonised by the bark beetle *Ips grandicollis*..

RECOMMENDATIONS

Selection of Sites for New Plantations

The results from the broadscale survey have indicated that previous soil survey procedures were inadequate in identifying drought prone sites. In future soil depth to 2 m, landscape position and aspect need to be assessed before an area is planted. The minimum recommend soil depths for Blackwood Valley Site Classes 1 and 2 for different aspects and landscape positions are shown below:

Estimated minimum soil depth (cm) required for radiata pines grown in the Blackwood Valley plantations.

Aspect	Landscape position	Site class 1	Site class 2
NE	upper slope	*	*
	mid-slope	*	200
	lower slope	*	130
All aspects apart from NE	upper slope	*	200
	mid-slope	200	120
	lower slope	130	50

*Soils greater than 2m in depth are required, however, no prediction of the depth required is possible as the maximum soil depth measured in the survey was 2m.

Management of Existing Plantations

The existing plantations should be evaluated in terms of the Blackwood Valley Site Classes defined in section 6.1, and each Site Class managed to the basal area specified.

Blackwood Valley Site Class	Top-height age 30 (m)	Max basal area (m^2 ha^{-1})
1	over 32.7	No limit
2	31.4-32.7	25
3	30.2-31.4	20
4	under 30.2	unsuitable for pines

Options which could be considered for Site Class 3 are agroforestry and fuel reduced buffers.

Thinning of the existing plantations should be based on basal area measurement and Site Class, not on plantation age.

The economics of growing pines on each of these Site Classes should be re-evaluated.

Suitability of Other Species

Plots of alternate species growing within the Blackwood Valley should be assessed to see whether they are more suitable than *P. radiata* on some sites.

Trouble Shooting

A trouble shooting service should be developed within CALM to provide a rapid diagnosis of problems.

Revision of the Pine Management Guide

The Blackwood Valley surveys have highlighted a number of changes that are necessary within the CALM Pine Management Guide. In particular the sections on Land and Soil assessment need revising to include the changes recommended form the surveys.

Comparison of the proposed site survey system and the current soil classification system.

Worked example, Brockmans Property

A soil map drawn from the soil classification system used by CALM is based on a grid of sample holes to a depth of 0.9m. A soil map drawn from the proposed site survey system would integrate soil depth to 2m together with topograpical position and aspect at each sample point.

Brockmans property was surveyed using both the current soil classification system and the proposed site survey system, the two maps are shown in Figure 1. The unsurveyed areas shown in Figure 1B were covered with virgin and regrowth forest and deemed unplantable.

The current soil survey classifies 96% of the Brockmans property as plantable (grades B and C) while the proposed site survey system classifies only 33% of the surveyed area as suitable for pine plantation (site classes 1 and 2) (Table 1). A further 40% could be planted to pine (site class 3) but plantation basal area **must not exceed 20 m^2 ha^{-1}** if extensive mortality is to be avoided.

Table 1: Brockmans property, comparison of the area in each class using the current CALM soil classification system and the proposed site survey system.

Current soil classification		Proposed site survey system	
Soil grade*	**Area (%)**	**Site Class****	**Area (%)**
B	21	1	19
C	75	2	14
D	2	3	40
E	2	4	27

*Defined in the Pine Management Guide
**Defined in this report.

Costing

Drought years are common in the Blackwood area (see accompanying report). This estimate is based on losses following the 1986/87 drought.

	Cost (ha^{-1})	**Loss (ha^{-1})**
Current soil classification system	$5	$700
Proposed site survey system	$8	nil.

Figure 1: BROCKMANS PROPERTY

A: SURVEY MAP USING CURRENT SOIL DESCRIPTION

B: SURVEY MAP USING PROPOSED SITE DESCRIPTION SYSTEM