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IN THIS ISSUE

CALM
science
NUMBER ONE

CALM
science
VOLUME ONE NUMBER ONE DECEMBER 1993

WESTERN AUSTRALIAN
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Message from the Director of Science and Information, Department of Conservation and Land Management

I an delighted to launch *CALMScience*, the new science journal of the Department of Conservation and Land Management in Western Australia.

The intention in publishing this journal is to provide a sharper focus for communicating CALM's many and varied research outcomes. *CALMScience* replaces the Department's previous titles, namely Research Bulletin, Technical Report and Occasional Paper. The Department's existing journal Nuytsia will continue to disseminate new information concerning plant systematics and taxonomy.

Our initial aim is to publish two issues of *CALMScience* each year, with each issue containing about 100 pages of peer reviewed papers reflecting the diversity of the research undertaken by the Department. From time to time longer papers, or papers on a particular theme, will be published separately (but in identical format) as a *CALMScience* Supplement. Supplements will be available for sale separately.

I am confident that *CALMScience* will be well received by those interested in the science of nature conservation, sustainable utilization and land management. The new journal indicates an enhanced awareness by staff of the Department of the need to disseminate the information required to demonstrate that land management in Western Australia is based on sound science and that the utilization of our unique biota is sustainable.

Dr J.A. Armstrong
Director
Science and Information Division
November 22, 1993

CALMScience 1(1): 3–18 (1993)

Structure of invertebrate communities in relation to fire history of kwongan vegetation at Tutanning Nature Reserve

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ABSTRACT

Trends in abundance and composition of the ground-dwelling invertebrate communities were studied over 10 months (May 1988–February 1989) in different-aged kwongan vegetation within Tutanning Nature Reserve. Habitat structure and floristic composition were also assessed. Twenty-nine taxonomic groups of invertebrates (predominantly orders) and 125 species of Araneae (spiders) were identified. Invertebrate abundances peaked during spring (September, November) and generally showed no site preferences. Composition of the spider fauna in the oldest site (last burnt in 1932) was markedly different from that of the other sites during spring. This was related to the structural composition of the litter and the presence of emergent sheoaks (*Allocasuarina huegeliana*). The trends found in this study suggest that fire does not exert a long-term influence on the structure of the invertebrate communities in these semi-arid ecosystems.

INTRODUCTION

Native vegetation in the semi-arid wheatbelt areas of Western Australia largely occurs as small, disjunct patches of woodlands and shrublands remaining in a landscape cleared largely for agriculture (Brown and Hopkins 1983; Main 1987). The shrubland components of these remnants, termed 'kwongan' (Beard 1976), have been extensively studied in terms of their floristic composition (Brown and Hopkins 1983; Brown 1989), modes of nutrition (Lamont 1984), and responses to fire (Bell *et al.* 1984). However, no invertebrate community surveys have previously been conducted in this vegetation type. Consequently, the richness and composition of the invertebrate community inhabiting kwongan and the effects of fire and other disturbances upon these organisms are as yet unknown.

It has been postulated that fire effects should become more prolonged as aridity increases (Hopkins 1985; Hutson 1985; Majer 1985). In their studies, Hutson and Veitch (1983) and Majer (1985) found a positive association between invertebrate recovery following fire, and rainfall. This may reflect faster plant growth and also higher rates of litter accumulation and nutrient recycling following fire as rainfall increases.

From research conducted in the more mesic forested areas of the south-west of Western Australia, where rotational burning is implemented as a management tool, invertebrate communities have shown a wide range of responses to burning. From studies of prescribed burning in jarrah (*Eucalyptus marginata*) forest, Koch and Majer (1980) found that invertebrate species richness was reduced for at least three years following burning, while Springett (1976) suggested invertebrate populations may not recover from burning within a normal five- to seven-year burning rotation. By contrast, Abbott (1984) found that the majority of soil and litter fauna recovered within three years of burning. In dry sclerophyll forest in Victoria, Neumann and Tolhurst (1991) concluded that a spring burn, and to a lesser extent an autumn burn, temporarily reduced the abundance of invertebrates involved in the decomposer cycle, particularly Collembola, larval Diptera and earthworms. Consistent with the majority of studies, however, is the finding that there is a strong association between litter density and soil and litter invertebrate abundance (e.g. Campbell and Tanton 1981; Hutson and Veitch 1983, 1985; Majer 1985; Raison, Woods and Khanna 1986; Postle 1989).

This study aimed to examine the long-term influence of fire on the structure of invertebrate communities (and spiders in particular) and their habitat in three semi-arid kwongan sites at Tutanning Nature Reserve in the Western Australian wheatbelt. The study utilized space-for-time substitution (SFT), whereby sites with different fire histories were contemporaneously sampled to explore relationships between fire and invertebrate community structure. Limitations of the SFT approach in answering disturbance ecology questions have been discussed by Pickett (1989). Despite its limitations, this approach was adopted as a preliminary strategy to gather baseline information, since no previous research had examined this topic. The work forms part of longer-term experimental research examining the impact of fire on vertebrate and invertebrate communities at Tutanning.

STUDY SITE—TUTANNING NATURE RESERVE

Location, Climate, Soils and Vegetation

Tutanning Nature Reserve (32°31'S, 117°23'E) is situated approximately 150 km south-east of Perth (Fig. 1) and covers an area of 2140 ha. The area has a mediterranean-type climate with an annual average rainfall of 454 mm, most occurring between April and August. Temperature varies between a mean maximum of 31.7°C in January and a mean minimum of 5.6°C in August.

Vegetation communities within Tutanning are closely related to soil type and topography, though Nyagba (1976) noted that several soil boundaries transgress vegetation boundaries. The lateritic and granitic uplands are characterized by *Dryandra* and *Petrophile* shrublands with open woodlands of powderbark wandoo (*Eucalyptus accedens*). The breakaway faces containing sandy loams support brown mallet (*E. astringens*) or *E. accedens*, while lower gravel slopes support communities of wandoo (*E. wandoo*). Stands of sheoak (*Allocasuarina huegeliana*) characterize granite outcrops and gritty sand deposits (Nyagba 1976; CALM 1988).

Although kwongan vegetation in Tutanning represents only about 3 per cent of the reserve's area, it contains more than half the species recorded there (Brown and Hopkins 1983). The three kwongan sites examined in this study were situated on the midslope position. Soils showed a duplex profile with an A horizon comprising grey or brown sand and lateritic gravels to a depth of 10–25 cm, overlying a sandy clay B horizon.

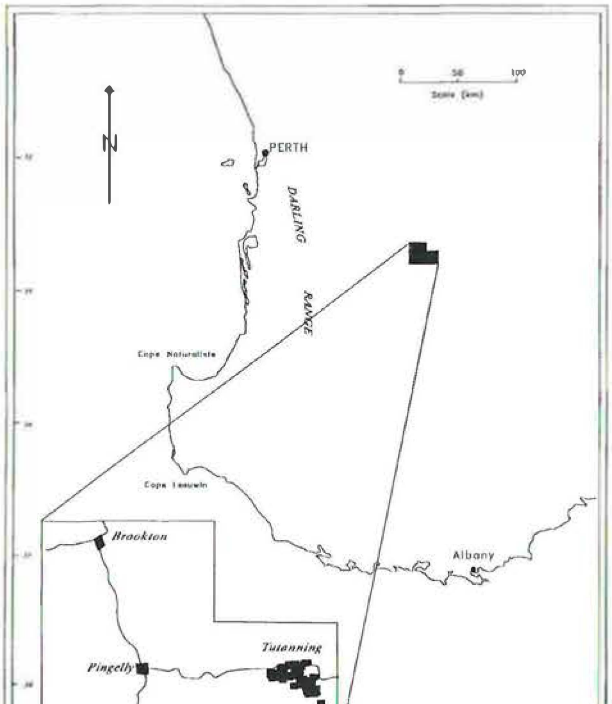

Figure 1. Map of south-west Western Australia showing the location of Tutanning Nature Reserve.

Fire History

Fire has formed an integral part of Tutanning's history. Figure 2 shows the most recent fires on the reserve and the location of the three study sites in areas last burnt in 1932, 1940, and 1965. The 1965 site was also burnt by wildfire in 1940 and was subjected to some agricultural disturbance in the late 1950s. All fires are believed to have been escapes from clearing burns on adjacent land but their intensities are unknown. The 1965 site was also prescription burnt at moderate intensity in March 1990 after the present study was completed.

METHODS

Two sampling grids were placed at each site to enable within- and between-site variation in the data to be examined. Each grid comprised 16 pitfall traps spaced at 5 m intervals, which created a 4 x 4 matrix within a 15 m x 15 m square (Fig. 3). The contents of the four pitfalls in each corner were bulked to form four replicate samples (see later).

Habitat Assessment

Vegetation structure was measured at four permanently-marked habitat points located 1 m north, south, east and west of each pitfall trap (see Fig. 3). There were thus 16 habitat points per replicate sample. Structural attributes were also assessed over the entire grid.

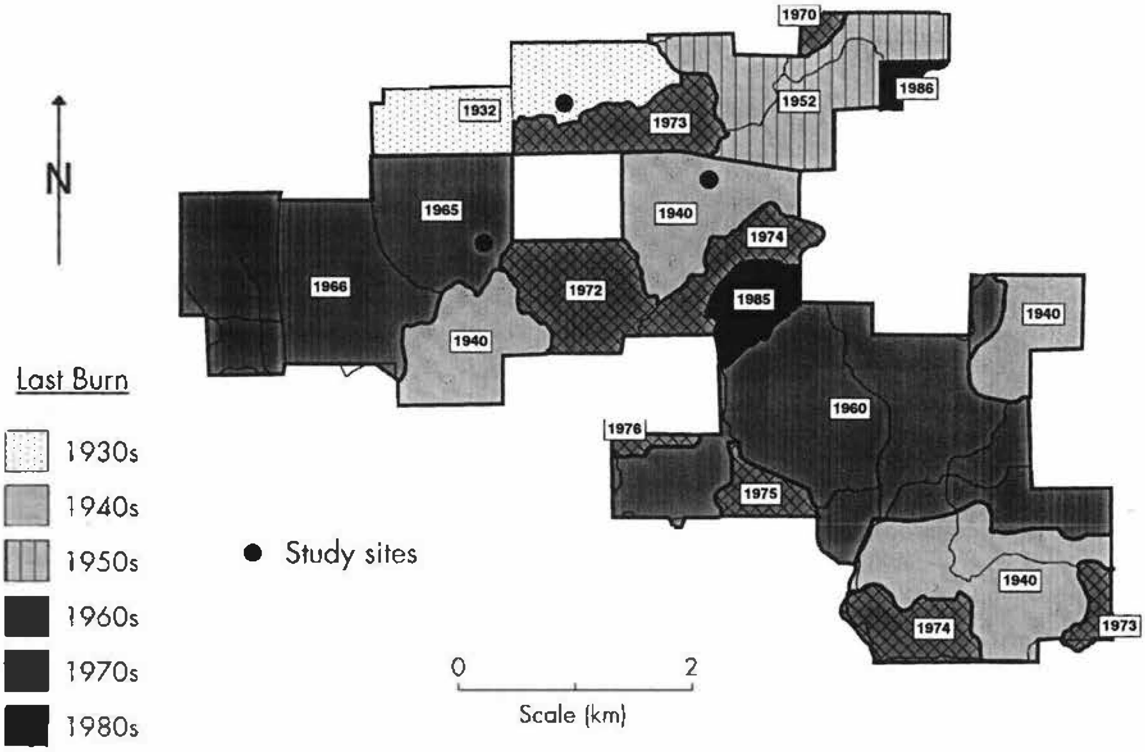

Figure 2. Tutanning Nature Reserve—fire history.

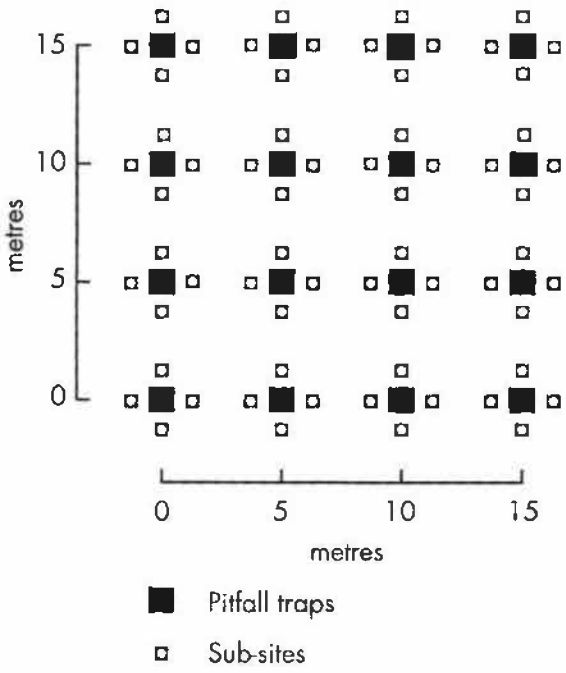

Figure 3. Layout of an invertebrate sampling grid.

(a) Habitat point measurements

The following attributes were recorded at each habitat point:

1. Leaf litter cover (percentage) in a 30 cm x 30 cm area scored as 0=absent, 1=1–25 per cent, 2=26–50 per cent, 3=51–99 per cent, and 4=100 per cent. The midpoint value of each percentage cover category was then used to calculate a percentage cover value per replicate using the following formula:

$$C = \frac{\sum fm}{16}$$

where: C = percentage cover value
f = frequency of observation
m = midpoint of percentage cover category

An analysis of variance and Scheffe test (Scheffe 1953; Zar 1984) were utilized to examine differences in percentage cover values between the three sites. A coefficient of variation (Zar 1984) was calculated from the mean percentage cover value of litter for each site.

2. Number of units of woody litter (dead/down branches or logs >5 mm diameter) bisected by a plane 50 cm each side of the habitat point. Woody litter diameter categories were 1=5–10 mm, 2=10–25 mm, and 3=>25 mm.

The frequency of occurrence of woody litter falling into these three categories was totalled for each replicate (i.e. 16 habitat points) and log linear analysis of variance conducted on these data. A value of one was added to each frequency prior to statistical analysis to compensate for zero scores.

3. Number of touches of vegetation on 12 intervals of a vertically held levy rod. Height intervals (cm) used were: 1=0–12.5, 2=12.6–25, 3=26–50, 4=51–75, 5=76–100, 6=101–125, 7=126–150, 8=151–175, 9=176–200, 10=201–250, 11=251–300, 12=>300.

These data were used to calculate the horizontal and vertical distribution of foliage. The horizontal distribution of foliage was calculated by dividing the number of habitat points within each replicate which had a recorded contact by the number of habitat points within each replicate (16). This was then converted to a percentage and analysis of variance used to identify any site differences.

Site differences in the vertical distribution of foliage were examined by using log linear analysis of variance on the frequency of observations in each of the levy rod intervals. A value of one was added to the frequency of each of the classes to compensate for zero values. The vertical distribution of foliage was also assessed for each site by dividing the total number of plant contacts per levy rod interval by the number of rods which touched any vegetation. This was used to create a vertical profile of plant cover density.

4. Majority of touching vegetation in intervals 1–12 alive (1) or dead (0).

The percentage of live standing vegetation per site was calculated by tallying the number of 'alive' recordings per site, and dividing this by the number of habitat points which had a recorded contact. These data were transformed to natural logarithms and analysis of variance used on the transformed data to assess site differences.

5. Maximum height (cm) of living understorey vegetation (<3 m) within 20 cm of the levy rod. These data were subjected to an analysis of variance to examine differences between sites.

(b) Grid measurements

The following site characteristics were measured or estimated over each entire grid:

1. Percentage of total live foliage in each of five layers *viz.* 0–0.5 m, 0.6–1.0 m, 1.1–2.0 m, 2.1–5.0 m, and >5 m.

2. Percentage canopy cover (>2 m) derived from four readings (N,E,S,W) of a canopy densiometer taken over the centre of each grid.

3. Projected foliage cover (percentage) of understorey vegetation (<2 m).

4. Percentage of soil surface which is sand <2 mm, gravel 2–4 mm, gravel 5–10 mm, and gravel >10 mm.

Measurements of these site characteristics were then averaged for each site and standard errors calculated.

Floristics

Plant species falling within a radius of 5.64 m (100 m^2) of the centre of each grid were recorded (presence/absence) by A. Hopkins and J. Harvey in early November 1988. Site differences in plant species richness were examined by using log linear analysis of variance.

Hierarchical Classification Analysis (HCA) of the presence/absence data used the average-linkage method and squared Euclidean distance measure (Gauch 1982). Similarity of the plant species composition of the six grids was examined using Sorensen's (1948) 'quotient of similarity' QS=2c/a+b where a= the number of species in sample A, b= the number of species in sample B, and c= the number of species common to samples A and B. HCA was also performed on Sorensen's similarity index to examine whether these groupings differed from those identified by HCA on the presence/absence data.

Invertebrate Sampling

Pitfall traps were used to sample the invertebrate fauna. The limitation of this sampling technique is outlined by Southwood (1978) and Adis (1979). Although limited in its efficiency for comparing different community types and estimating absolute invertebrate populations, Southwood (1978) notes that this method can be used to assess the relative abundance of invertebrate populations in similar habitat types. Pitfall trapping was also selected because of its ease of operation.

Each pitfall trap consisted of a plastic cup (90 mm diameter, 110 mm deep), placed inside a sleeve of PVC piping, enabling pitfall traps to be set and removed with minimum disturbance to the surrounding soil and litter. This design of trap is similar to that described by Majer (1978a).

When in use, each pitfall was half-filled with Galt's solution which consisted of 5 per cent sodium chloride, 1 per cent potassium nitrate, 1 per cent chloral hydrate, a trace of glycerine, and the remaining 93 per cent water. Traps were operated for ten consecutive days for each of the months of May (autumn), July (winter), September and November (spring) in 1988, and January and February (summer) 1989. At the end of each ten-day sampling period the contents of the four pitfall traps in each corner of a grid were bulked to form four replicate samples. Each sample was labelled according to the sample time, site, and position on the grid. Samples were fine-sieved in the field and transferred from Galt's solution to 70 per cent ethanol. Sand-filled cups were placed in the PVC sleeves to close the pits.

Invertebrates were sorted to class level using a stereo microscope. Arachnids and insects were subsequently identified to order level, the latter with the aid of keys described in CSIRO (1970). The abundance of each taxonomic unit was then recorded for each sample. Hymenoptera Formicidae (ants), Coleoptera adults (beetles), and Araneae (spiders) were placed in separate vials, the latter taxon being identified to species level. Collembola were not included in taxonomic sorting.

Statistical Analysis of Invertebrate Data

Computer analysis of the invertebrate abundance data employed the SAS and Systat programs. Log linear analysis of variance (AOV) was used on the abundance values to examine site preferences, time of sampling (months), and grid (within-site) differences in the invertebrate data. All abundances were raised by a value of one to compensate for zero abundances.

Scheffe's pairwise comparison tests were performed on those groups showing significant differences between months. These tests grouped together months with similar means. Similarly, Scheffe's tests were performed on those taxa showing significant differences between sites, identifying any site which had unusual abundance characteristics.

Statistical Analysis of Spider Data

Spiders were identified using the keys of Main (1980) and Mascord (1980) and with the assistance of Dr Louis Koch. A species reference collection was created for future research purposes. Community parameters calculated from the spider abundance data included: total number of individuals, species richness, diversity, and the evenness of species distribution calculated as: $J' = H'/\log_e S$ where H' = the information content of a sample, and S = the number of species (Pielou 1975).

Similarity of species composition and abundance was examined using Hierarchical Classification Analysis (HCA), utilizing the average-linkage method to cluster groups and squared Euclidean distance as the distance measure (Gauch 1982). This analysis procedure used the totals for each of the eighteen month/site combinations, and then clustered these combinations so that similar communities were grouped together.

TABLE 1

Mean percentage litter cover values, standard errors and coefficient of variation (V) for the three sites (n=8).

SITE	MEAN	STANDARD ERROR	V(%)
1932	48.8	4.3	24.9
1940	29.7	1.2	11.8
1965	32.0	2.4	21.6

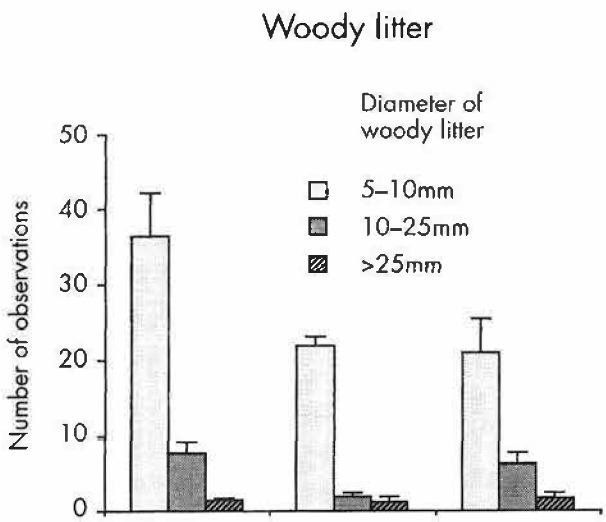

Figure 4. Site differences in the mean frequency of the three woody litter classes (n=8). Standard errors shown as bars above the means.

RESULTS

Habitat Assessment

(a) Habitat point measurements

Scheffe's pairwise comparisons revealed that the 1932 site had a significantly higher mean percentage litter cover value than the other sites ($p<0.05$). Table 1 shows the mean percentage cover value, standard error and coefficient of variation for the three sites.

No significant site differences were found for woody litter abundance. However, there was a significant interaction effect between the three woody litter categories and sites ($F=3.24$, $p<0.05$), with the 1932 site scoring a much higher frequency of woody litter in the 5-10mm diameter category (Fig. 4).

Sites did not differ significantly in their canopy cover, percentage live standing vegetation and frequency of vegetation 'touches'. The interaction effect between sites and levy rod interval was also not significant. Plant cover density profiles (Fig. 5) indicated that all three sites had very dense vegetation up to 0.4 m. The 1932 site showed the presence of emergents forming a sparse upper canopy at 1.4 m and above, whereas the 1940 and 1965 sites showed negligible vegetation cover above 1.4 m. However, analysis of variance did not find this difference to be significant.

Maximum vegetation heights were not significantly different between sites. However, differences between grids within sites were significant ($F=3.16$, $p<0.05$).

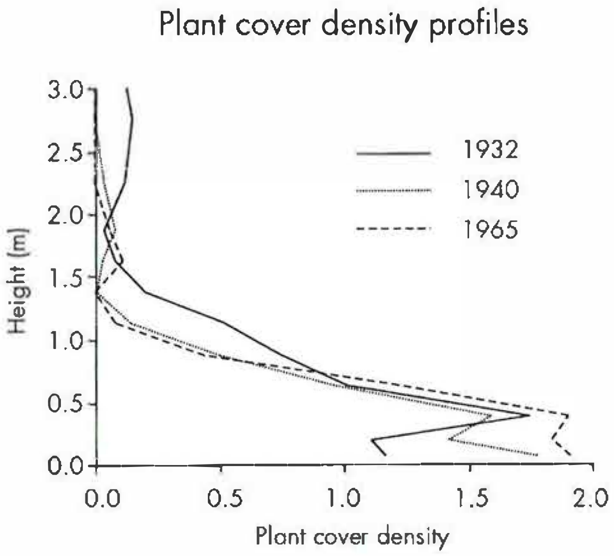

Figure 5. Vertical profiles of plant cover density.

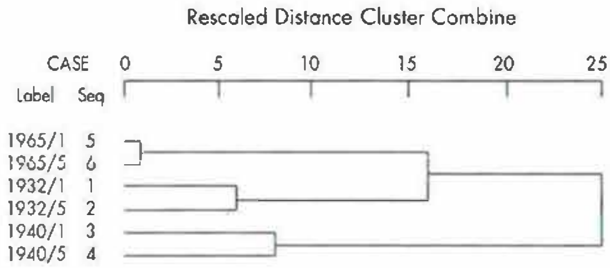

Figure 6. Dendrogram of grid groupings using Hierarchical Classification Analysis on floristic presence/absence data. The two grids are identified as 1 (replicates 1-4) and 5 (replicates 5-8).

(b) Grid measurements

The proportion (percentage) of total foliage in each of five layers (0–0.5 m, 0.6–1.0 m, 1.1–2.0 m, 2.1–5.0 m, and >5 m) was consistent with the results of the levy rod data. The percentage canopy cover (>2 m) and projected foliage cover of understorey vegetation (<2 m) also revealed trends that were consistent with the vertical structure measurements for each habitat point; these results are not discussed further.

Coarse soil fabric composition was similar for each of the three sites with over 70 per cent of coarse soil fabric comprising sand <2 mm.

Plant Floristics

Analysis of variance revealed that there was no significant difference in plant species richness between the sites.

Hierarchical Classification Analysis on the presence/absence floristic data (Fig. 6) indicated that the 1940 site separated first, and showed the least within-site similarity in plant species composition. The 1965 site showed the highest within-site similarity. Grouping of the grids on the basis of Sorensen's similarity index confirmed the trend revealed by the groupings from the presence/absence data.

Invertebrates

A total of 29 broad taxonomic invertebrate groups (class and order) was sampled: Annelida (earthworms), Scorpionida (scorpions), Pseudoscorpionida (pseudoscorpions), Opiliones (harvestmen), Araneae (spiders), Acarina (mites), Isopoda (woodlice), Diplopoda (millipedes), Chilopoda (centipedes), Thysanura (bristle-tails), Blattodea (roaches), Mantodea (mantids), Isoptera (termites), Dermaptera (earwigs), Orthoptera (grasshoppers and locusts), Phasmatodea (stick-insects), Psocoptera (book-lice), Hemiptera (bugs), Thysanoptera (thrips), Neuroptera adults (lacewings), Neuroptera larvae (antlions), Coleoptera adults (beetles), Coleoptera larvae, Diptera adults (flies), Diptera larvae, Lepidoptera adults (moths), Lepidoptera larvae, Hymenoptera Formicidae (ants), and Hymenoptera others (wasps and bees).

Formicidae accounted for over 60 per cent of the total number of invertebrates captured and this tended to mask trends in the other groups in the analyses. Thus, the data for total invertebrate abundance were analysed twice, once including Formicidae and once excluding this taxon.

With the Formicidae included, strong seasonal effects were shown for total invertebrates ($F=103.8$, $p<0.001$), with abundances peaking in summer (Fig. 7). Site differences were not apparent ($p>0.05$), but there was a significant interaction effect between months and sites ($F=4.1$, $p<0.001$) indicating variable seasonal trends between sites. Grids within sites differed significantly ($p<0.05$). Total invertebrate abundances showed similar site and seasonal trends when Formicidae were excluded, but showed a spring rather than a summer peak (Fig. 8). Furthermore, within-site differences (between grids) were no longer significant ($p>0.05$).

Only eight invertebrate taxa (Acarina, Araneae, Isoptera, Hemiptera, Coleoptera adults, Diptera adults, Hymenoptera Formicidae, and Hymenoptera (excluding Formicidae) were sufficiently abundant to indicate within- and between-site differences, and to warrant the use of further statistical analysis. All eight taxa showed highly significant seasonal effects ($p<0.001$) and interaction (months/sites) effects ($p<0.001$).

However, only the Araneae, Diptera adults, and Formicidae showed site differences ($p<0.05$). Within-site differences were only significant for Formicidae ($p<0.05$).

For the Acarina, seasonality effects were apparent ($F=118.9$, $p<0.001$) with greatest abundance occurring in January and least in May and July (Fig. 9). No site preference was shown by this taxon, though the

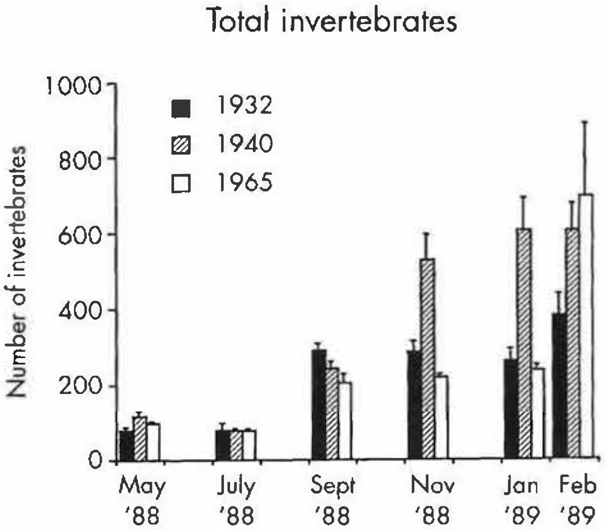

Figure 7. Ten-day means per replicate (n=8) for Total Invertebrates in the three study sites. Within-site standard errors shown as bars above the means.

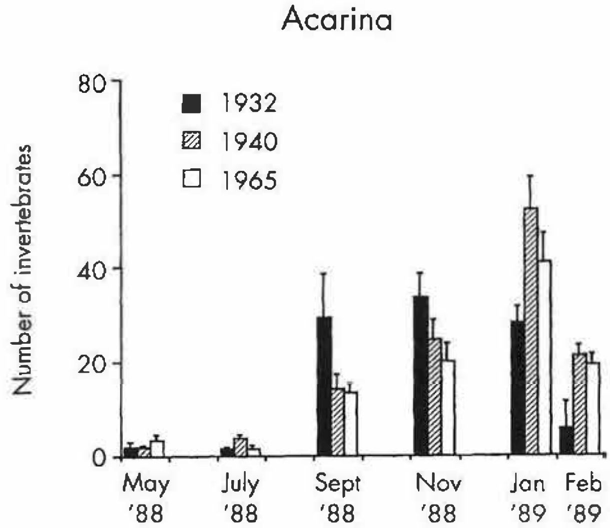

Figure 9. Ten-day means per replicate (n=8) for Acarina in the three study sites. Within-site standard errors shown as bars above the means.

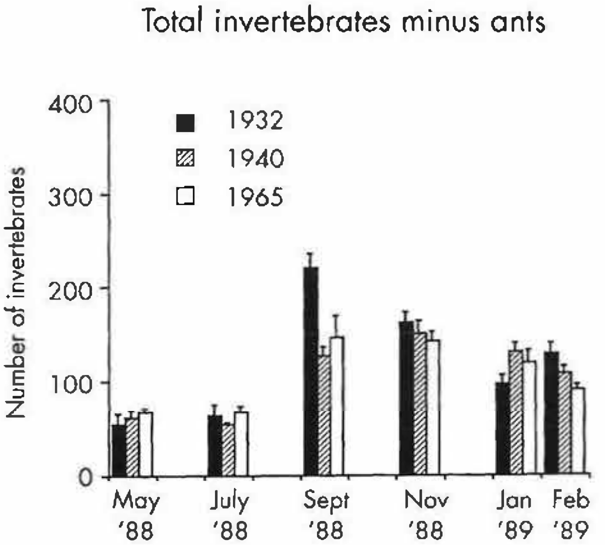

Figure 8. Ten-day means per replicate (n=8) for Total Invertebrates (excluding Formicidae) in the three study sites. Within-site standard errors shown as bars above the means.

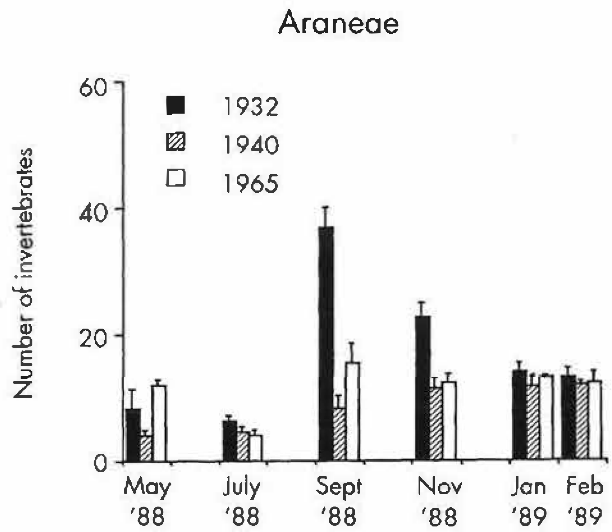

Figure 10. Ten-day means per replicate (n=8) for Araneae in the three study sites. Within-site standard errors shown as bars above the means.

interaction effect proved significant ($F=2.9$, $p<0.01$). Acarina abundance in the 1932 site increased sharply in September and peaked in November, whereas abundance in the 1940 and 1965 sites rose more gradually to peak in January.

Site and seasonality differences were apparent for Araneae ($F=13.0$, $p<0.05$; $F=26.1$, $p<0.001$, respectively; Fig. 10). Scheffe tests revealed that the 1940 site had a significantly lower abundance of spiders than the other two sites ($p<0.05$). The 1932 site had the highest abundance, but this fell just outside the 0.05 level of significance ($0.05<p<0.07$). Abundances in all sites were lowest in winter but rose during spring. Peak abundances varied between sites, giving a significant months/sites interaction effect ($F=5.6$, $p<0.001$), with the 1932 site clearly having the greatest abundance in spring. More detailed analyses of the spider data are given below.

Numbers of Isoptera were borderline for statistical analysis, but strong seasonal effects were apparent ($F=32.0$, $p<0.001$). This taxon was absent from the pitfall samples during May and July but numbers rose in

November and remained consistently high throughout summer (Fig. 11). Site differences were not apparent, although the interaction between months and sites proved to be highly significant ($F=5.0$, $p<0.001$) with the 1932 and 1940 sites peaking in February, and the 1965 site peaking in November.

Strong seasonal trends were also apparent for Hemiptera ($F=32.0$, $p<0.001$), with numbers peaking in September (Fig. 12). Although all three sites were consistent in their September peak, abundances remained higher in the 1940 and 1965 sites during the November and January samples. These different responses revealed a highly significant interaction effect between months and sites ($F=5.0$, $p<0.001$), despite there being no significant site differences.

Coleoptera adults showed highly significant seasonal trends ($F=44.2$, $p<0.001$). Numbers were highest in September and lowest in January (Fig. 13). Site differences were not apparent for this taxon. There was, however, a significant interaction between months and sites ($F=6.1$, $p<0.001$), there being a considerable difference in numbers between the 1940 and 1965 sites in the July sample.

Diptera adults showed seasonal and site effects ($F=38.7$, $p<0.001$; $F=12.8$, $p<0.05$; respectively). Abundance was greatest during spring and lowest during autumn and winter (Fig. 14). Scheffe tests revealed that numbers were significantly lower in the 1940 site. A significant interaction effect between months and sites was also apparent ($F=5.1$, $p<0.001$), the 1932 site peaking in abundance in September, and the 1940 and 1965 sites peaking in November.

Formicidae abundance showed very strong seasonality ($F=147.4$, $p<0.001$). Numbers captured were greatest during February and lowest during July (Fig. 15). The 1965 site was consistently lower in ant abundance than the other two sites for all but the February sample, when numbers peaked above the other two sites. This was reflected in the significant interaction effect between sites and months ($F=3.2$, $p<0.01$). Site preferences were also shown by this taxon ($F=10.2$, $p<0.05$), the 1940 site having a significantly higher abundance than the other two sites. Within-site differences were also apparent ($F=4.3$, $p<0.01$), indicating that localized effects within each site were influencing captures.

Seasonal effects were also apparent for Hymenoptera, excluding the Formicidae ($F=26.2$, $p<0.001$) with the lowest numbers being recorded in the May, July, and September samples (Fig. 16). No significant site differences were found, although there was a significant interaction between months and sites ($F=4.6$, $p<0.001$) indicating that numbers fluctuated markedly between sites at different sample times.

A summary of the seasonal and site trends revealed by analysis of variance on the transformed log data is shown in Tables 2 and 3. Table 4 provides a list of the principal invertebrate groups trapped, their main food source, the season they peaked in abundance, and their site preferences.

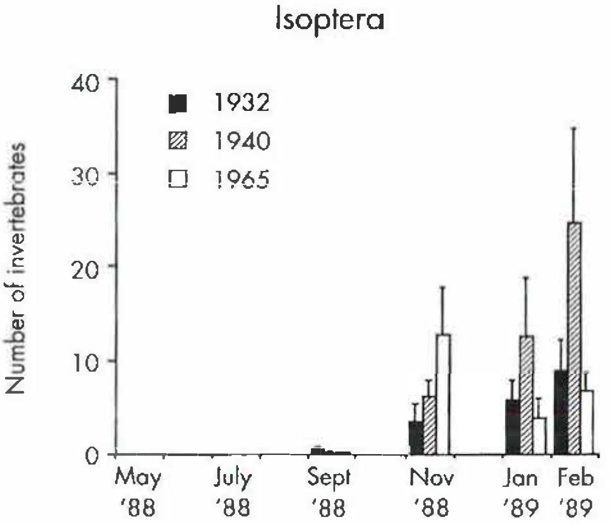

Figure 11. Ten-day means per replicate (n=8) for Isoptera in the three study sites. Within-site standard errors shown as bars above the means.

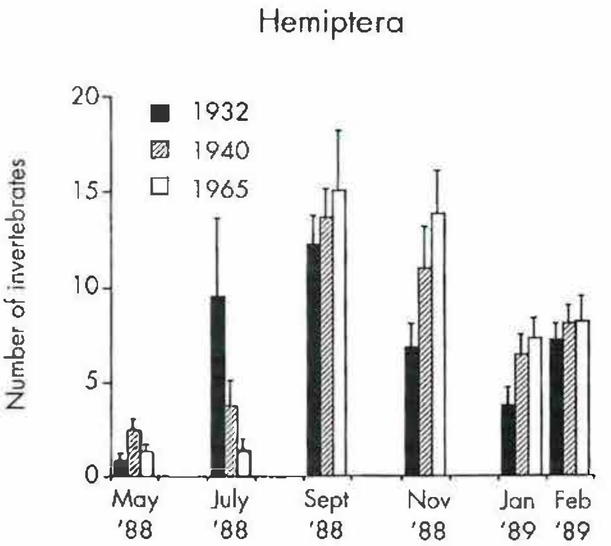

Figure 12. Ten-day means per replicate (n=8) for Hemiptera in the three study sites. Within-site standard errors shown as bars above the means.

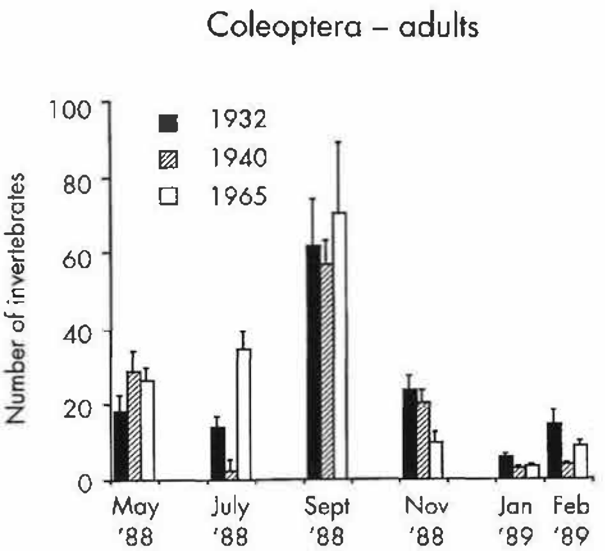

Figure 13. Ten-day means per replicate (n=8) for Coleoptera (adults) in the three study sites. Within-site standard errors shown as bars above the means.

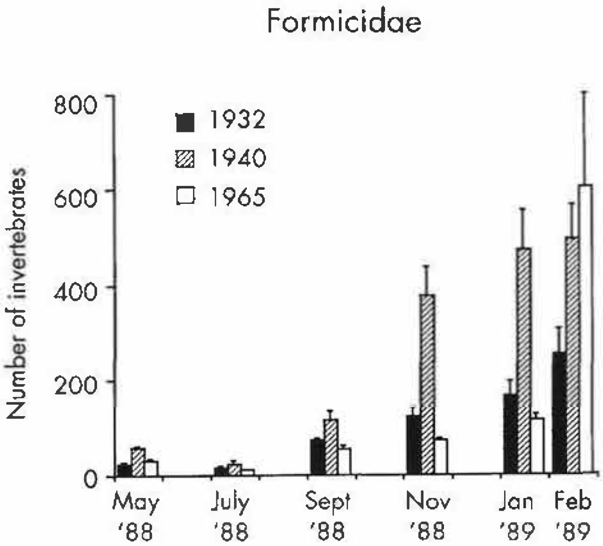

Figure 15. Ten-day means per replicate (n=8) for Formicidae in the three study sites. Within-site standard errors shown as bars above the means.

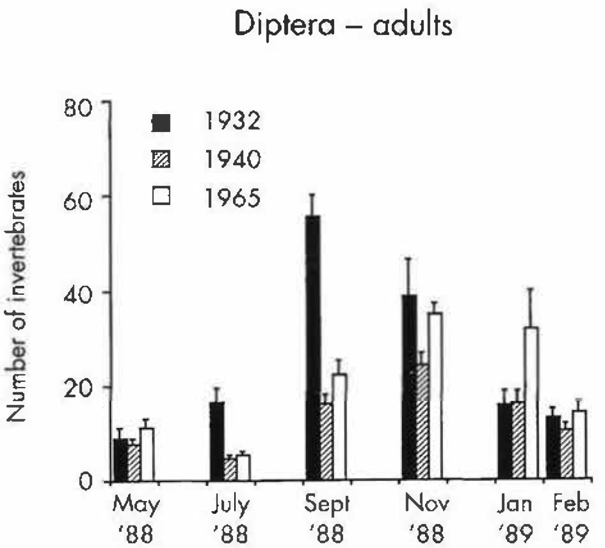

Figure 14. Ten-day means per replicate (n=8) for Diptera (adults) in the three study sites. Within-site standard errors shown as bars above the means.

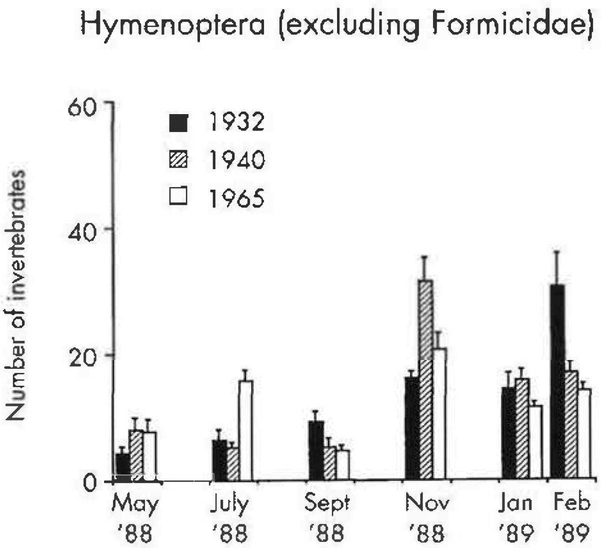

Figure 16. Ten-day means per replicate (n=8) for Hymenoptera (excluding Formicidae) in the three study sites. Within-site standard errors shown as bars above the means.

TABLE 2

Means and standard errors of invertebrate abundances per replicate according to month. The data are compared using log linear analysis of variance; ***P<0.001; NA, not analysed.

TAXON	MONTH												
	May '88		Jul '88		Sep '88		Nov '88		Jan '89		Feb '89		
	$\bar{X}$	S.E.	$\bar{X}$	S.E.	$\bar{X}$	S.E.	$\bar{X}$	S.E.	$\bar{X}$	S.E.	$\bar{X}$	S.E.	
Annelida	0.00	(0.00)	0.42	(0.18)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	NA
Arachnida													
Scorpionida	0.04	(0.04)	0.00	(0.00)	0.04	(0.04)	0.38	(0.13)	1.08	(0.29)	0.50	(0.18)	NA
Pseudoscorpionida	0.00	(0.00)	0.00	(0.00)	0.04	(0.04)	0.04	(0.04)	0.00	(0.00)	0.00	(0.00)	NA
Opiliones	0.08	(0.06)	1.88	(0.45)	0.42	(0.15)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	NA
Acarina	2.46	(0.52)	2.29	(0.46)	19.08	(3.52)	26.21	(2.66)	40.46	(3.78	23.67	(2.32)	***
Araneae	8.13	(1.27)	5.00	(0.47)	20.21	(2.96)	15.54	(1.46)	12.96	(0.79)	12.46	(0.80)	***
Crustacea Isopoda	0.42	(0.15)	0.17	(0.10)	0.33	(0.12)	1.04	(0.31)	1.50	(0.39)	3.29	(0.62)	NA
Diplopoda	1.33	(0.33)	0.67	(0.18)	1.75	(0.47)	0.00	(0.00)	0.42	(0.12)	0.42	(0.13)	NA
Chilopoda	0.17	(0.10)	0.04	(0.04)	0.29	(0.14)	0.21	(0.10)	0.17	(0.08)	0.17	(0.08)	NA
Insecta													
Thysanura	0.00	(0.00)	0.00	(0.00)	0.25	(0.09)	0.88	(0.18)	1.46	(0.36)	0.58	(0.13)	NA
Blattodea	0.04	(0.04)	0.13	(0.09)	0.00	(0.00)	0.42	(0.17)	1.08	(0.24)	0.92	(0.22)	NA
Mantodea	0.00	(0.00)	0.00	(0.00)	0.04	(0.04)	0.00	(0.00)	0.04	(0.04)	0.13	(0.07)	NA
Isoptera	0.00	(0.00)	0.00	(0.00)	0.29	(0.11)	7.46	(1.95)	7.38	(2.32)	13.42	(3.79)	***
Dermaptera	0.46	(0.17)	0.50	(0.12)	0.79	(0.23)	0.38	(0.15)	0.33	(0.14)	0.71	(0.18)	NA
Orthoptera	1.42	(0.21)	1.21	(0.28)	2.42	(0.48)	2.17	(0.37)	1.83	(0.25)	2.13	(0.30)	NA
Phasmatodea	0.13	(0.07)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.04	(0.04)	0.04	(0.04)	NA
Psocoptera	0.08	(0.08)	0.00	(0.00)	0.17	(0.10)	0.08	(0.06)	0.38	(0.20)	0.04	(0.04)	NA
Hemiptera	1.58	(0.28)	4.88	(1.56)	13.58	(1.25)	10.46	(1.27)	5.79	(0.64)	7.75	(0.61)	***
Thysanoptera	0.04	(0.04)	0.08	(0.06)	1.13	(0.26)	9.63	(1.64)	0.50	(0.15)	0.42	(0.12)	NA
Neuroptera adults	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.04	(0.04)	0.17	(0.10)	0.00	(0.00)	NA
Neuroptera larvae	0.04	(0.04)	0.00	(0.00)	0.08	(0.06)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	NA
Coleoptera adults	24.42	(2.63)	23.50	(2.77)	62.88	(7.47)	17.75	(2.31)	3.83	(0.54)	8.92	(1.59)	***
Coleoptera larvae	2.13	(0.44)	1.75	(0.45)	1.75	(0.45)	0.17	(0.08)	0.25	(0.12)	0.25	(0.11)	NA
Diptera adults	9.21	(1.04)	8.71	(1.53)	31.29	(4.08)	32.50	(3.04)	21.17	(3.30)	12.54	(1.03)	***
Diptera larvae	0.83	(0.25)	0.25	(0.12)	0.29	(0.13)	2.92	(2.92)	0.00	(0.00)	0.42	(0.18)	NA
Lepidoptera adults	0.04	(0.04)	0.25	(0.11)	0.83	(0.29)	1.17	(0.25)	0.63	(0.24)	0.29	(0.13)	NA
Lepidoptera larvae	0.54	(0.15)	0.54	(0.19)	0.38	(0.16)	0.21	(0.08)	0.08	(0.08)	0.17	(0.10)	NA
Hymenoptera ants	35.92	(4.16)	16.83	(2.51)	80.08	(8.18)	188.88	(35.00)	250.96	(43.20)	450.88	(74.58)	***
Hymenoptera others	6.79	(1.00)	9.08	(1.29)	6.38	(0.88)	22.71	(2.00)	13.88	(1.13)	20.50	(2.32)	***
Total invertebrates	96.29	(7.22)	78.42	(5.79)	244.79	(13.46)	341.21	(36.87)	366.38	(46.43)	560.58	(73.92)	***
Total invertebrates (excluding ants)	60.38	(4.82)	61.58	(4.54)	164.71	(12.66)	152.33	(6.51)	115.42	(6.89)	109.71	(5.72)	***

TABLE 3

Means and standard errors of invertebrate abundances per replicate according to site. The data are compared using log linear analysis of variance; *P<0.05; NS, not significant; NA, not analysed; # denotes significant differences between grids nested within sites, P<0.05.

TAXON	SITE					
	1932		1940		1965	
	$\bar{X}$	S.E.	$\bar{X}$	S.E.	$\bar{X}$	S.E.
Annelida	0.04	(0.03)	0.02	(0.02)	0.15	(0.09) NA
Arachnida						
Scorpionida	0.38	(0.11)	0.25	(0.12)	0.40	(0.13) NA
Pseudoscorpionida	0.00	(0.00)	0.01	(0.01)	0.00	(0.00) NA
Opiliones	0.44	(0.14)	0.60	(0.25)	0.15	(0.05) NA
Acarina	20.85	(2.79)	19.69	(2.84)	19.03	(1.53) NS
Araneae	16.88	(1.74)	8.69	(0.72)	11.58	(0.83) *
Crustacea Isopoda	1.33	(0.26)	1.81	(0.37)	0.23	(0.07) NA
Diplopoda	1.06	(0.24)	1.04	(0.22)	0.19	(0.06) NA
Chilopoda	0.27	(0.09)	0.10	(0.04)	0.15	(0.05) NA
Insecta						
Thysanura	0.38	(0.10)	0.42	(0.11)	0.79	(0.20) NA
Blattodea	0.65	(0.15)	0.33	(0.10)	0.31	(0.11) NA
Mantodea	0.02	(0.02)	0.04	(0.03)	0.04	(0.03) NA
Isoptera	3.10	(0.84)	7.25	(2.29)	3.92	(1.13) NS
Dermaptera	0.69	(0.12)	0.29	(0.07)	0.60	(0.15) NA
Orthoptera	1.71	(0.22)	2.58	(0.28)	1.29	(0.15) NA
Phasmatodea	0.04	(0.03)	0.04	(0.03)	0.02	(0.02) NA
Psocoptera	0.06	(0.05)	0.25	(0.11)	0.06	(0.05) NA
Hemiptera	6.69	(0.92)	7.52	(0.78)	7.81	(1.04) NS
Thysanoptera	2.15	(0.73)	0.96	(0.26)	2.79	(0.90) NA
Neuroptera adults	0.00	(0.00)	0.10	(0.50)	0.00	(0.00) NA
Neuroptera larvae	0.02	(0.02)	0.02	(0.02)	0.02	(0.02) NA
Coleoptera adults	22.85	(3.51)	22.50	(3.00)	22.29	(4.59) NS
Coleoptera larvae	1.75	(0.32)	1.00	(0.18)	0.52	(0.16) NA
Diptera adults	24.67	(2.96)	13.10	(1.20)	19.94	(2.16) *
Diptera larvae	0.60	(0.16)	1.58	(1.46)	0.17	(0.06) NA
Lepidoptera adults	0.33	(0.09)	0.96	(0.22)	0.31	(0.08) NA
Lepidoptera larvae	0.25	(0.08)	0.38	(0.12)	0.33	(0.09) NA
Hymenoptera ants	108.40	(15.68)	255.75	(35.11)	147.63	(43.04) *#
Hymenoptera others	13.46	(1.63)	13.79	(1.56)	12.42	(1.00) NS
Total invertebrates	229.08	(20.65)	361.10	(38.87)	253.65	(43.32) NS#
Total invertebrates (excluding ants)	120.69	(9.72)	98.22	(8.66)	109.42	(5.31) NS

TABLE 4

Principal groups of invertebrates showing feeding habits, main peak in occurrence and site preferences. [1]O = Order, F. = Family: [2]N.P. = No Preference.

CLASS	TAXON[1]	FEEDING HABITS	MAIN PEAK IN OCCURRENCE	SITE CHARACTERISTICS[2]
Arachnida	O.Acarina	Various	Late spring, summer	N.P.
Arachnida	O.Araneae	Predators	Spring	Low in 1940 site high in 1932 site
Insecta	O.Isoptera	Wood and grass feeders	Late Spring, summer	N.P.
Insecta	O.Hemiptera	Sap suckers	Spring	N.P.
Insecta	O.Coleoptera (adults)	Various	Spring	N.P.
Insecta	O.Diptera (adults)	Various	Spring	Low in 1940 site
Insecta	O.Hymenoptera F.Formicidae	Predators, nectar and seed feeders	Summer	High in 1940 site
Insecta	O.Hymenoptera (excluding Formicidae)	Nectar feeders	Late spring, summer	NP

Spiders

The dendrogram created from Hierarchical Classification Analysis (HCA) on spider presence/absence data using the average-linkage method is shown in Figure 17. The 1932 September sample was included in the original analysis but is not shown on the dendrogram as it was markedly different from the other month/site combinations and caused compaction of the groups. The classification was truncated at the seven-group level because dichotomies beyond this level were fragmentary and contributed little to further understanding.

HCA grouped spider communities in relation to time of sampling rather than in relation to sites. The three kwongan sites had similar spider species composition during autumn and winter, but revealed different community structure in spring and summer. These differences were particularly marked for the 1932 site during September (not shown) and November.

Table 5 provides a summary of the parameters of the spider fauna measured during the study. The number of individuals and species richness showed general peaks in spring with minimal values occurring in winter for all sites. Diversity was generally higher in late spring and summer. Overall, total numbers of spiders, species richness, and diversity were greatest in the 1932 site for the September to January samples.

Table 6 shows the total number of individual spiders according to family for each site and sampling period. No statistical analyses were conducted on these data. However, the more abundant families (notably the Clubionidae, Gnaphosidae, Salticidae, and Theridiidae) do show site and seasonal differences.

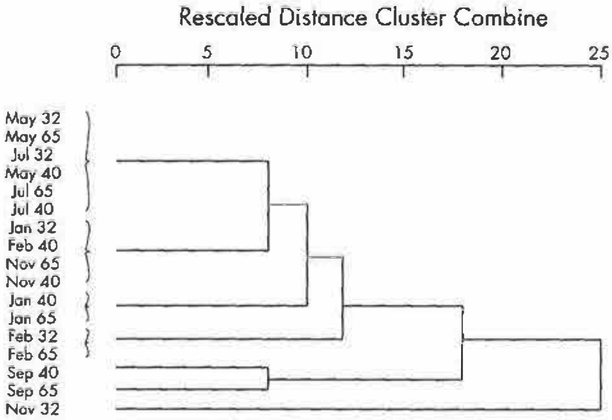

Figure 17. Dendrogram of sample groupings using Hierarchical Classification Analysis based on spider presence/absence data.

TABLE 5

Spider fauna parameters for the three sites for each sample period.

	MONTH					
	May '88	July '88	Sep '88	Nov '88	Jan '89	Feb '89
PARAMETER						
NUMBER OF INDIVIDUALS						
1932	67	50	294	182	112	105
1940	91	37	67	92	94	96
1965	37	33	124	99	105	98
SPECIES RICHNESS (S)						
1932	12	12	37	32	31	31
1940	17	14	15	23	26	25
1965	22	14	27	26	25	22
DIVERSITY (H)						
1932	2.092	2.027	2.718	2.832	2.977	2.853
1940	2.586	2.059	2.044	2.586	2.582	2.874
1965	2.249	2.391	2.653	2.762	2.560	2.369
EVENNESS (J')						
1932	0.842	0.816	0.753	0.817	0.867	0.831
1940	0.913	0.780	0.755	0.824	0.792	0.893
1965	0.728	0.906	0.805	0.848	0.795	0.767

TABLE 6

Total number of spider individuals trapped according to family, site and sample period.

	MONTH					
	May '88	Jul '88	Sep '88	Nov '88	Jan '89	Feb '89
FAMILY						
ARANEIDAE						
1932	2	0	28	7	3	3
1940	3	2	18	2	3	9
1965	6	0	15	10	6	4
CLUBIONIDAE						
1932	22	23	95	25	21	24
1940	3	4	18	19	18	5
1965	28	12	41	18	27	9
CTENIZIDAE						
1932	8	9	3	1	0	0
1940	10	12	0	0	0	4
1965	9	6	0	0	2	0
GNAPHOSIDAE						
1932	9	4	114	119	57	59
1940	3	16	26	59	47	57
1965	8	9	61	62	59	73
SALTICIDAE						
1932	0	1	30	18	18	11
1940	2	0	4	3	13	10
1965	0	1	3	7	8	8
THERICIDAE						
1932	22	13	10	0	0	0
1940	7	1	1	0	1	0
1965	42	4	1	1	1	1
THOMISIDAE						
1932	1	0	2	1	5	2
1940	1	1	0	1	1	0
1965	2	0	0	0	0	0
ZODARIIDAE						
1932	0	0	2	8	4	5
1940	0	0	0	5	7	9
1965	0	0	0	0	2	1

DISCUSSION

The major finding of this study was that invertebrate populations were similar for all three sites, implying that site history is not affecting invertebrate fauna composition in the longer term. Abundance differences were found for spiders, flies, and ants, however, and these appear to be closely related to differences in floristic composition and litter cover between sites.

Neither plant species richness nor floristic composition appear to be related to time since fire. Although all three sites were similar in terms of their plant species richness, the 1940 site showed a different plant floristic composition. This supports the findings of Brown and Hopkins (1983) who found that only a very small percentage of floristic variability in kwongan could be attributed to time since fire. However, Brown and Hopkins (1983) also suggested that floristic differences were possibly linked to differences in soil type. In this study soil types were consistent for all three sites and no differences were found in coarse soil fabric composition. Differences in soil chemical properties, however, were not assessed. Hence, the different floristic composition of the 1940 site appears to be related to environmental differences which were beyond the scope of this study.

The presence of a high litter cover and an abundance of woody litter at the 1932 site may be a result of long-term fire exclusion from this area. In his study of *Banksia* woodland, Bamford (1986) found that the litter layer became more structurally complex the greater the time after fire. The litter layer of the 1932 site, however, also appears to be influenced by the presence of emergent sheoaks (*Allocasuarina huegeliana*). This accounts for the high abundance of woody litter (5-10 mm diameter) recorded at this site. The 1932 site is only about 4 ha and is enclosed by sheoak woodland whereas the 1940 and 1965 sites are larger (each about 10 ha) and bordered by wandoo (*Eucalyptus wandoo*) on one side with sheoak on the other. The size and location of the 1932 site in relation to the surrounding woodland areas, and the prolonged absence of fire at this site, appear to be favouring the encroachment of sheoaks into the kwongan, thus affecting the structural composition of the litter layer.

Influence of Fire on Ants, Flies, and Spiders

The abundance of ants did not appear to be consistently influenced by fire history. Majer (1978b) made similar observations based on a study of different land-use types at Dwellingup, WA. The higher abundance of ants in the 1940 site may be related to this site's different floristic composition, or again, to environmental factors which were beyond the scope of this study. Higher captures in the 1940 site may also be related to the presence of one or two numerically dominant species, though an analysis of ants at a species level was beyond the scope of this study.

By contrast, the abundances of spiders and flies were significantly lower at the 1940 site. The low abundance of spiders appears to be related to litter differences and this is addressed below. It is unusual, however, that the pitfall sampling method (designed to effectively sample only the epigaeic invertebrate fauna) should capture enough flies to identify a statistically significant difference between sites. The lower abundance of flies in the 1940 site may be related to the greater within-site variability in floristic composition. However, more detailed vegetation and invertebrate data, using a variety of sampling techniques, would be required to substantiate this explanation.

Spider abundance, species richness and diversity all identified the 1932 site as being markedly different from the other two sites, particularly during spring (September, November). These characteristics of the spider fauna may be related to the high cover and variability of litter and the ecotonal nature of this site which allows spiders representative of both kwongan and sheoak to exist. The latter effect may arise through the presence of emergent sheoaks within the kwongan, which enable the spiders to cast webs and forage over a greater area than in the other two sites. The sheoaks also shade the ground, reducing desiccation and hence facilitating foraging and migration. They may also be influencing the structural diversity of the litter layer (by dropping branches and twigs), thereby providing this site with a greater array of microhabitats.

Scope and Limitations of the Study

Limitations in the pitfall sampling technique have been outlined by several authors (Southwood 1978; Adis 1979; Majer 1981). Pitfall traps sample epigaeic invertebrates only and show a bias towards the more mobile taxa (Majer 1981). In this study, the dominance of ants in pitfall captures highlights this bias. Another criticism of the pitfall trapping method is that activity, as measured by the traps, may not necessarily reflect abundance (Southwood 1978; Majer 1981). In the case of ants, surface activity peaked in summer as revealed by the large number of ants captured during this time. However, during winter and autumn when captures were low, large numbers may still have been present at the nests. The proximity of pitfall traps to ant nests was also not assessed and this may have contributed to the significant difference in ant abundance between grids nested within sites, as well as possibly influencing site preferences. Given these limitations in the pitfall trap sampling method, site and seasonal differences in abundances of ants and total invertebrates (including Formicidae) need to be considered cautiously.

A further limitation of this study is that the season of burn and fire intensity are unknown for each of the sites. Weather at the time of the burn greatly influences fire intensity. Furthermore, as Hobbs and Atkins (1988) note, most woodland and shrub communities vary greatly in their array of standing vegetation and litter composition. Weather and variability in fuel quantity and distribution combine to cause a high degree of spatial variation in fire intensity, but no data on these factors were available for this study.

To date, studies of invertebrate populations in the drier areas of Australia have been minimal, with the exception of Greenslade (1979, 1981), Edmonds and Specht (1981), and Majer (1985). There have also been no reported invertebrate community studies conducted in kwongan vegetation. A critical examination of the results of this study in the light of other research is therefore limited. Given these comparison limitations, this paper should be viewed as identifying areas where a considerable amount of research is still required.

This study utilized space-for-time substitution (SFT) to examine successional aspects of invertebrate community structure in semi-arid vegetation. Though limited in its ability to address disturbance ecology questions (Pickett 1989), SFT is of considerable value when carried out in conjunction with longer-term experimental studies. It is anticipated that this study will serve as a baseline for longer-term work at Tutanning examining the effects of prescribed burning on invertebrate (and vertebrate) communities.

CONCLUSIONS

Invertebrate populations peaked during spring, and were lowest during late autumn and early winter. The soil and litter invertebrate populations were very similar for all three sites and showed no evidence of long-term disturbance effects.

Ant abundance was highest in the 1940 site and this was possibly related to a different floristic composition at this site. This difference in floristic composition appeared to be related to environmental factors beyond the scope of this study.

The 1932 site showed a higher abundance and different community structure of spiders during spring. This was attributed to leaf litter cover and woody litter abundance providing an array of microhabitats, the presence of emergent sheoaks providing a wider foraging area, and the proximity of the kwongan to neighbouring sheoak woodland.

Leaf litter cover and woody litter abundance was greatest in the 1932 site. This site also showed the greatest variability in leaf litter cover. These litter characteristics appear related to both time since fire and the presence of emergent sheoaks.

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Estimated fuel savings for a passive solar timber drying kiln in Australia

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ABSTRACT

The fuel savings of a solar kiln with supplemental heating, compared with a conventional kiln (fossil fuel heating only) running the same drying schedule, were estimated for 30 sites around Australia, using regressions developed by Tschernitz (1986). The annual fuel savings varied from a low of 2 per cent at Hobart to a high of 38 per cent at Darwin for a 22 m³ capacity kiln. By simulated addition of extra insulation (R=1.76) to the transparent surfaces at night-time, the annual fuel savings increased to 28 per cent and 56 per cent for Hobart and Darwin, respectively. Fuel savings for a solar kiln of 84 m³ capacity were similar. In general, fuel savings for the lower southern parts of Australia were of no practical use for solar kilns without extra night-time insulation. Kilns in lower southern parts with extra night-time insulation, or kilns of either type in the remainder of Australia, had estimated fuel savings which were of practical significance. As an example in evaluating the significance of solar kilns, an 84 m³ solar kiln with extra night-time insulation was estimated to save $26 050 in electricity or $10 357 in gas heating annually in Perth. The same solar kiln was also estimated to reduce CO_2 emissions by 41 tonnes annually when heating with gas.

INTRODUCTION

In recent times CALM has received an increasing number of enquiries for solar kilns from timber producers in Western Australia, the eastern states of Australia, and Fiji. Three sawmillers in W.A. are now using CALM solar assisted kilns operationally to dry hardwoods, and three more are considering them. One sawmiller is performing operational trials upon softwood. The managers of these sawmill firms were able to see the solar kilns at the Wood Utilisation Research Centre, Harvey and assesss their performance first hand. With enquiries coming from further afield it is increasingly difficult to estimate performance because of the different climates involved.

The performance of solar kilns has been measured by several researchers in various locations around the world (Little 1984; Simpson and Tschernitz 1989), but the information available to date is insufficient to make generalizations upon new sites or new kiln designs. One measure of performance for a kiln which has supplemental heating is the proportion of heat provided by solar radiation (the solar fraction). In Sri Lanka a solar kiln with a timber capacity of 16 m³ with a wood fired burner had a solar fraction of 48 per cent during the dry season (Simpson and Tschernitz 1989). Measurements of a large commercial kiln in Mississippi, U.S.A. with 1.05 m² of water solar collectors per m³ of kiln capacity revealed a 22 per cent solar fraction over 6 months (Little 1984). Other performance ratings, such as drying efficiency, also have large ranges (Plumptre 1985).

We needed a study of possible solar contribution to the heat requirements of a kiln which would give at least a performance comparison between Harvey and other locations around Australia. This study is based primarily upon the work of Tschernitz (1986) where regressions between fuel savings and climatic conditions were developed from detailed heat load calculations for nine U.S.A. locations. Although these regressions were derived for only two kiln designs, one species (commercial red oak (*Quercus* sp.)), one thickness (25 mm) and are theoretically based, they can be used as a first approximation for solar kiln performance or inter-site comparisons.

The efficiency or performance of a solar kiln was stated by Plumptre (1985) to depend upon:

1. Latitude.
2. Climate—temperature, humidity and insolation.
3. Initial and final moisture contents of the charge.
4. Species and permeability of the timber.
5. Thickness of timber, size of stickers and shape of stack.
6. Design of kiln.

One other factor this author would also consider is:

7. Drying schedule

With this multitude of factors it is very difficult to estimate the performance of a solar kiln for a particular operation and location. As stated previously, this study is based largely on the methods of Tschernitz (1986), and attempts to reduce the complexity of the performance question by estimating kiln fuel savings, knowing the climate and latitude of the location. The estimates are performed for two specific kiln designs, while keeping factors 3, 4, 5 and 7 constant.

SITES AND CLIMATIC DATA

Thirty sites around Australia were chosen to give a broad coverage of areas that possess existing timber resources and for which sufficient climatic data were available. A few sites that are remote from log production forests were included to allow interpolation. Other sites can be evaluated with the procedure described below if sufficient climatic data are available[1].

Three climatic factors were used in this study: mean monthly values of total solar radiation, absolute humidity and temperature. These climatic factors were not available for a sufficient number of regional sites and thus estimation techniques were used from the available data to allow inclusion of some sites in this study. Mean monthly minimum and maximum temperatures were available for all sites, and their arithmetic mean was used as the mean monthly temperature of the site.

Where solar radiation data is not available it is commonly estimated from the mean monthly sunshine hours using the modified Angstrom equation (Reddy 1987):

$$\frac{\overline{H}}{\overline{H}_0} = a + b\frac{\overline{n}}{\overline{N}}$$

where $\overline{H}$ = mean monthly solar radiation on a horizontal surface
$\overline{H}_0$ = mean monthly extraterrestrial radiation for the site
a,b = empirical constants for the site
$\overline{n}$ = mean monthly hours of bright sunshine
$\overline{N}$ = mean monthly maximum of bright sunshine hours (i.e. the day length of the average day of the month)

Day length and extraterrestrial radiation are calculated from the latitude as described by Reddy (1987).

There are several ways of using this modified Angstrom equation; which are differentiated by the technique used to estimate the empirical constants. One may estimate the coefficients from world-wide correlations (Samuel 1991) or use coefficients from a nearby site with a similar climate. The accuracy of estimates from nearby sites has been questioned by Reddy (1987) and Duffie and Beckman (1991). Duffie and Beckman (1991) gave an example of estimating Madison's solar radiation from constants from the nearest meteorological station (Blue Hill), resulting in a 22 per cent discrepancy from the yearly average solar radiation measured at Madison. Even with this known inaccuracy the modified Angstrom equation is useful because of the sparseness of solar radiation data.

Initially the intention in this study was to use constants derived at each capital city for other sites in the State. This method was rejected because the relationships were not available in the literature and paired monthly values of solar radiation and bright sunshine hours were not readily available. It was decided to use the next best: mean empirical constants derived from six Australian sites over eight to fifteen years (Hounam 1969). The mean empirical constants from that Australian study (0.27 and 0.50 for *a* and *b*, respectively), were applied to the 13 sites where only sunshine hours data were available (Appendix 1).

Most sites chosen for this study had mean monthly relative humidity values at 9 a.m. and 3 p.m. only. The arithmetic mean of these two values is not necessarily the true daily mean. Erbs *et al.* (1985) described the diurnal fluctuation of relative humidity of nine United States locations as a Fourier series:

$$\overline{RH_h} = \overline{RH_d} + A(0.4672\cos(t'-0.666) + 0.0958\cos(2t'-3.484) + 0.0195\cos(3t'-4.147) + 0.0147\cos(4t'-0.452))$$

where $\overline{RH_h}$ = mean monthly relative humidity at a particular hour of the day
$\overline{RH_d}$ = mean monthly relative humidity for all hours of the day
A = mean monthly amplitude of relative humidity
t' = dimensionless time = $2\pi(t-1)/24$

OR expressed as

$$\overline{RH_h} = \overline{RH_d} + f_t A \quad (1)$$

where f_t = time factor at hour t
$= 0.4672\cos(t'-0.666) + 0.0958\cos(2t'-3.484) + 0.0195\cos(3t'-4.147) + 0.0147\cos(4t'-0.452)$

By evaluating equation (1) for the two times of the day one obtains:

$$\overline{RH_{t1}} = \overline{RH_d} + f_{t1} A \quad (2)$$
$$\overline{RH_{t2}} = \overline{RH_d} + f_{t2} A \quad (3)$$

[1] Smoothed, interpolated data may be generated for any Australian site by the ESOCLIM package (available from the Centre for Resources and Environmental Studies, Australian National University).

By substituting equation (3) into (2) and rearranging one obtains an equation for the monthly mean:

$$\overline{RH_d} = (\overline{RH_{t1}} - \frac{f_{t1}}{f_{t2}}\overline{RH_{t2}})/(1-\frac{f_{t1}}{f_{t2}}) \qquad (4)$$

OR $$\overline{RH_d} = (\overline{RH_9} + 0.246\overline{RH_{15}})/1.246 \qquad (5)$$

where $f_{t1} = f_9 = 0.128$
$f_{t2} = f_{15} = -0.520$

Equation (5) was used to estimate the mean monthly relative humidity for those sites where the local time was equivalent to solar time. It is solar time upon which the diurnal variation of relative humidity is dependent. Where the local time differed by 15 mins or more from solar time the time factors were evaluated with the true solar time entered into equation (4). No compensation was made for the relatively recent and irregular 'daylight saving' practice (where local time is brought forward an hour in some States during summer). Finally, the estimated mean monthly relative humidity values were converted to absolute humidity using ASHRAE (1985) equations.

The validity of using Erbs *et al.* (1985) equation was examined by comparing relative humidity (RH) averaged from 3-hourly readings (Bureau of Meteorology, 50 years of records) with those estimated by equation (4) from two times per day for the same period, for two sites in Australia (Table 1). The estimated mean RH for the months varied from correct to as poor as 7 RH percentage units less than the 3-hourly calculated mean. Sydney was estimated better than Perth (Belmont AMO), with annual RH errors of 2 and 6 RH percentage units, respectively. The influence of these changes upon the yearly fuel savings (using the technique described below) was assessed for the two sites. The fuel savings changed from 40.7 and 31.9 per cent for estimated RH means to 40.3 and 31.7 per cent for the calculated RH means, for a 84 m^3 kiln with extra night-time insulation in Perth and Sydney, respectively. For this study where average yearly performance is the most important outcome these errors in the mean RH are tolerable.

The sources of climatic data and the various estimation techniques used are specified for each site in Appendix 1.

Calculation Method for Fuel Savings

To calculate the amount of fuel saved by using a solar kiln with supplemental heating, one needs to calculate the energy demand (wood drying and heat losses) and the energy supplied from solar heating. The ambient weather conditions, knowledge of the kiln's size and construction, the kiln's setpoints plus the rate of drying are all required for this calculation. To be very accurate these factors must be calculated over short time periods, normally hourly. These calculations are understandably complex and time consuming, even when performed on digital computers. Confounding the problem is that each species, timber thickness, drying schedule, kiln size and insulation alters the outcome. Obviously, one needs to simplify and select certain parameters to reduce the calculation load.

Tschernitz (1986) performed the energy calculations and fuel savings for a reduced set of combinations of kiln and other parameters. Specifically, Tschernitz performed calculations on one species (commercial red oak), one thickness (25 mm) and one drying schedule (low temperature, 28 days long) for six kiln sizes in nine locations in the United States of America using a time step of one day. The effect of insulating the solar collecting surfaces at night was also calculated.

Fuel savings in this paper are not expressed as the amount of solar heat absorbed in the solar kiln because one needs to account for the greater heat loss of the solar kiln through the transparent surfaces (which have lower insulation values than conventional kiln walls, as discussed below). The percentage of fuel saved refers to the reduction of the heat load of a conventional kiln by substitution with a solar kiln;

$$\text{Fuel savings} = \frac{Q_{sn}}{Q_c - Q_f} = \frac{Q_{sg} - (Q_s - Q_c)}{Q_c - Q_f} \times 100 \qquad (6)$$

where Q_c = conventional heat load including Q_f
Q_f = electric fan power
Q_s = solar kiln heat load (i.e. for wood drying and heat losses)
Q_{sg} = solar gain (i.e. amount of energy absorbed from solar radiation)
Q_{sn} = net solar gain (or loss) = $Q_{sg} - (Q_s - Q_c)$

The theoretical kiln considered was a conventional rectangular prism shape with solar collecting surfaces incorporated into the structure of the kiln on the roof, north (i.e. converted for southern hemisphere), east and west walls (Fig. 1).

The thermal resistance (R value) of the opaque slab, opaque walls and the night-time insulated transparent walls or roof was assumed to be 1.76 m^2.K/W (0.1 Btu/(ft^2.h.°F)) and similarly an R value of 0.23 m^2.K/W (0.75 Btu/(ft^2.h.°F)) for the uninsulated, transparent surfaces. The transparent surfaces were assumed to have a solar transmission of 85 per cent. The actual construction details were left to the kiln builder to decide.

Although the collectors in this study have been referred to as passive, they are better described as a hybrid type because air is blown across the absorber surface by fans, but the size and orientation of the absorbers is determined by the kiln's shape. Thus the system does not have the design freedom, nor performance, of a kiln with external collectors (an active system).

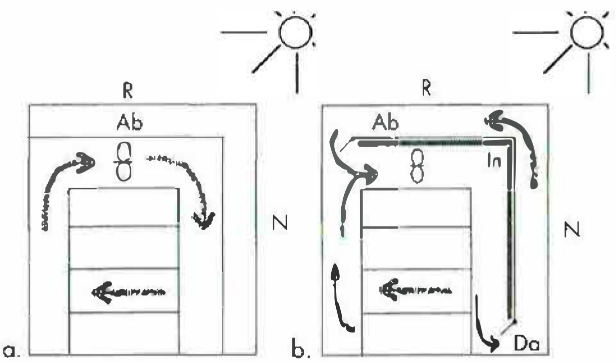
From the nine locations Tschernitz (1986) developed regressions relating fuel savings to the ambient conditions (temperature, humidity and solar radiation) and kiln characteristics (size and use or not of night-time insulation). Thus it is now possible to

TABLE 1

Comparison of estimated mean relative humidity with calculated mean relative humidity (per cent) for two sites.

BELMONT AMO (PERTH)													
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
MEAN	53	53	56	64	72	78	78	75	72	67	61	58	66
EST.	50	50	53	61	66	71	71	68	65	61	56	53	60
ERROR	-3	-3	-3	-3	-6	-7	-7	-7	-7	-6	-5	-5	-6
SYDNEY													
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
MEAN	71	73	73	71	71	71	67	64	64	65	67	69	69
EST.	69	72	71	70	71	71	65	63	61	63	64	66	67
ERROR	-2	-1	-2	-1	0	0	-2	-1	-3	-2	-3	-3	-2

Mean = arithmetic mean of the eight (3-hourly) values of RH from the Bureau of Meteorology (%).
Est. = weighted mean from 9 a.m. and 3 p.m. values of RH from the Bureau of Meteorology (%) using the technique from Erbs *et al.* (1985).



Where R = roof
Ab = absorber surface for solar radiation
In = insulation material
N = north wall (in southern hemisphere)
Da = damper

Figure 1. Theoretical kiln designs comparing the effects of (a) no night-time insulation and (b) with extra night-time insulation. After Tschernitz (1986).

predict the amount of fuel saved by using a solar kiln if the mean monthly values of temperature, absolute humidity and solar radiation and the latitude are known. The form of Tschernitz's equation is:

$$\text{Fuel savings} = a_0 + a_1T + a_2S + a_3H + a_4L \quad (7)$$

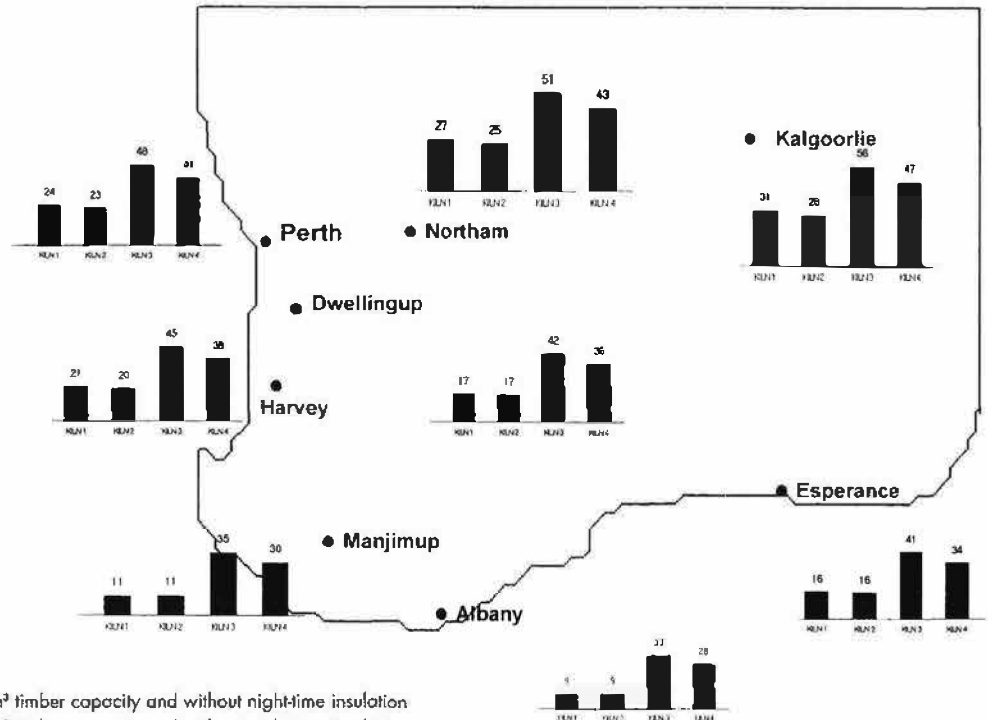
where $a_0 - a_4$ = coefficients for each kiln size, insulation and month
T = mean monthly temperature (°F)
S = mean monthly solar radiation on a horizontal surface (Btu/ft².day)
H = mean absolute humidity (lb water/lb air)
L = latitude (degrees)

These regressions were used in this study to estimate the fuel savings for kilns with timber capacities of 22 m³ or 84 m³, with or without night-time insulation for thirty locations in Australia using Equation (7). The mean monthly climatic values were obtained or estimated as described above, and the fuel savings calculated for each month for each of the four kiln size/types[1], using the coefficients derived by Tschernitz (1986) (included here as Appendix 2).

Estimated Fuel Savings

The estimated average annual fuel savings for the four kiln types are presented for the south-west of Western Australia (Fig. 2) and for eastern Australia (Fig. 3). For kiln type 1 (22 m³, no extra night-time insulation) the annual fuel savings varied from a low of 2 per cent at Hobart to a high of 38 per cent at Darwin. For kiln type 3 (22 m³, with extra night-time insulation) the fuel savings varied from 28 per cent at Hobart to 56 per cent at Darwin. The fuel savings of kiln types 2 and 4 (84 m³ kilns, with and without extra night-time insulation) have similar values. The full set of climatic data and fuel savings are given in Appendix 3 for all thirty sites. Thus, the fuel savings of a solar assisted kiln without extra night-time insulation is insignificant in the lower southern parts of Australia (such as southern Victoria and Tasmania) while all other kiln types and locations represent fuel savings of practical significance.

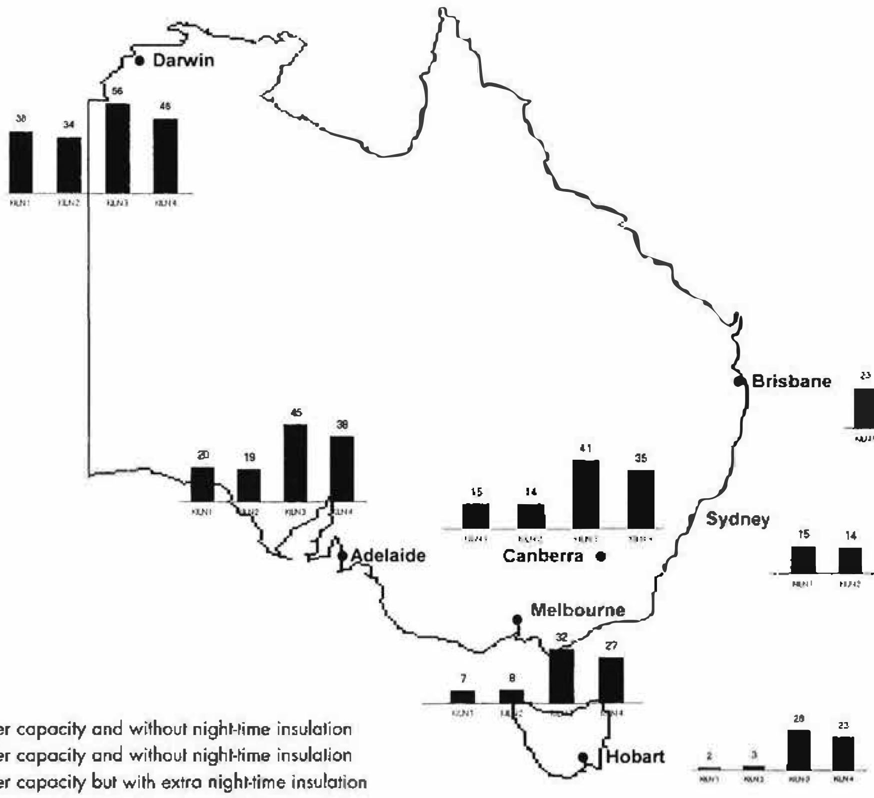
[1] From here on referred to simply as a kiln type.



Where

Kiln 1 is 22 m³ timber capacity and without night-time insulation
Kiln 2 is 84 m³ timber capacity and without night-time insulation
Kiln 3 is 22 m³ timber capacity but with extra night-time insulation
Kiln 4 is 84 m³ timber capacity but with extra night-time insulation

Figure 2. Performance of solar assisted kilns in south-western Australia—per cent fuel savings when compared with non-solar kilns.



Where

Kiln 1 is 22 m³ timber capacity and without night-time insulation
Kiln 2 is 84 m³ timber capacity and without night-time insulation
Kiln 3 is 22 m³ timber capacity but with extra night-time insulation
Kiln 4 is 84 m³ timber capacity but with extra night-time insulation

Figure 3. Performance of solar assisted kilns in eastern Australia—per cent fuel savings when compared with non-solar kilns.

From Figures 2 or 3, it can be clearly seen that extra night-time insulation provides a marked improvement upon fuel savings. As an example, night-time insulation for a 22 m^3 kiln in Perth improves fuel savings from 24 per cent to 48 per cent.

The monthly variation of fuel savings for kiln type 1 is less for the northern site of Brisbane compared with the southern site of Perth (Fig. 4) owing to the less variable climate of Brisbane. Similar annual patterns are revealed for kiln type 3, although the annual variation is less and the fuel savings of higher value (Fig. 5). Figure 4 shows the fuel savings for Perth drop to a negative value (–1 per cent) for June – a situation in which more supplementary heat is required for a solar assisted kiln than a conventional kiln. This situation occurs for other southern sites in winter months for kiln types 1 and 2 (i.e. no extra night-time insulation) (Appendix 3). The larger the annual variation the greater the required capacity of the supplementary heater.

How to Use these Estimates

Because the estimates in this study are based upon theoretical principles without verification from actual kilns, caution must be exercised in their usage. As the calculation method is the same for all sites, consideration of the differences between sites is likely to be of greater accuracy than the accuracy of the actual, or absolute, performance values. This inference will be of great benefit when data on performance of actual kilns in Australia become available.

For now, the estimates can be used to assess the general feasibility of a solar style of kiln. Fuel savings in dollars can be estimated by:

Annual saving (\$) = Per cent fuel savings x annual heat load x fuel price

As an example, the annual heat load for a conventional 84 m^3 kiln running the lower temperature solar schedule in Perth is 1.43×10^6 MJ (1420 MJ m^{-3} of timber, derived from Tschernitz (1986)). The annual fuel savings for a solar kiln with insulation would be \$26 050[1] when using electric heating elements or \$10 357[2] when using a direct-fired gas burner. This is equivalent to a reduction in CO_2 emissions of 176 t or 41 t[3] for electrical or gas heating, respectively.

Strictly speaking, the estimates provided and the feasibility assessment should only be applied to timber which dries in a similar manner to the 'commercial red oak' evaluated by Tschernitz (1986) and of the same thickness (25 mm). One may, with fair confidence, apply the above feasibility assessment to the drying of 25 mm boards of other species with a similar basic density to 'commercial red oak' (0.56 kg m^{-3} (Tschernitz and Simpson 1979)). It is logical to assume that even greater fuel savings are possible for thicker boards because the solar heat will provide a greater proportion of the lower heat load (owing to the slower drying).

Implications for other Kiln Designs

In designing a solar kiln, one needs to consider how the advantageous features of the Tschernitz (1986) generalized designs can be implemented. To obtain a similar performance to that estimated in this paper one requires an approximately equal area of absorber, and similar insulation values. The roof plus northern wall absorber area for the 22 and 84 m^3 kilns were 60 and 160 m^2, respectively. The thermal resistance (R) of the opaque walls and slab referred to in this paper was 1.76 $m^2.K.W^{-1}$, and 0.23 for the transparent roof and walls. The opaque wall insulation value can easily be achieved by 50 mm of fibreglass batts (R = 1.27 (ASHRAE 1989)) with an inflated twin plastic skin (R = 0.48 (Wong 1977[4])). Achieving the night-time insulation value of 1.76 $m^2.K.W^{-1}$ chosen by Tschernitz (1986) for the transparent surfaces with extra insulation can be difficult. If the insulation is stationary as shown in Figure 1, common insulation materials (batt or loose fill) can easily achieve the required value. However, if one needs to use a movable thermal screen due to the absorber being draped over the timber (as in the CALM Solar Assisted Kiln) the insulation value given above may not be achievable. An R value of approximately 0.5 can be expected from the thermal screen (Cotton and Bailey 1983). The total insulation value of the twin skin plus thermal screen (R=1.0) falls well short of that assumed in the calculations (R=1.76). Thus, the performance of kilns similar to the CALM Solar Assisted Kiln will be approximately midway between the night-time insulated and no night-time insulated kiln values calculated here.

CONCLUSIONS

This study has shown that heat load calculations can reveal much about the performance of a solar kiln. Assuming the method to be fairly accurate, the estimates of solar contributions in kilns at most of the Australian sites considered in this study, indicated considerable fuel savings by using a solar kiln. This is particularly so when using extra night-time insulation of a high insulation value, although achievement of such high values of insulation can be difficult in some kiln designs.

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1 397 600 kWh @ \$0.1598 x 41% fuel savings. SECWA 1992 tariffs.

2 1.43×10^6 MJ ÷ 3.6 MJ/unit ÷ 75% burning efficiency x \$0.0477/unit x 41%. SECWA 1992 tariffs.

3 Using conversions of 0.3 and 0.07 tonnes of CO_2/GJ of end use energy, for electricity and gas respectively. (Western Australian Greenhouse Co-ordination Council 1991)

4 Calculated for an air gap of 13 mm, effective emittance of IR modified polyethylene of 0.6, internal kiln temperature of 60°C and external temperature of 30°C.

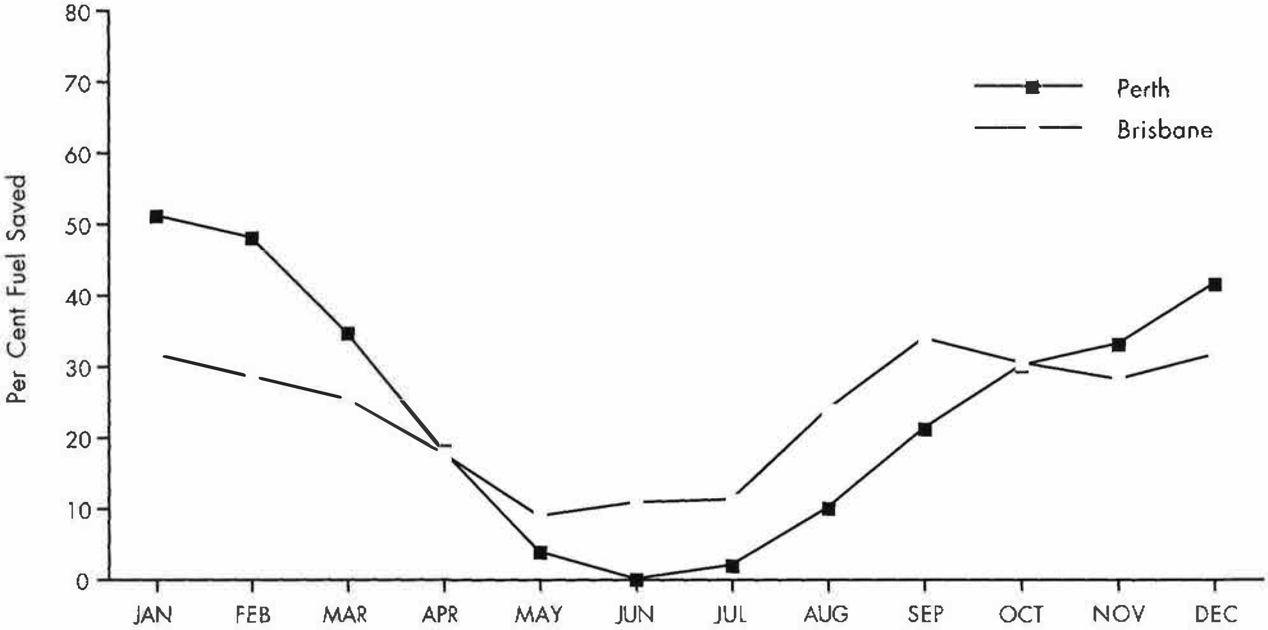

Figure 4. Estimated monthly variation of fuel savings in kiln type 1 (22 m³ and no night-time insulation) for Perth and Brisbane.

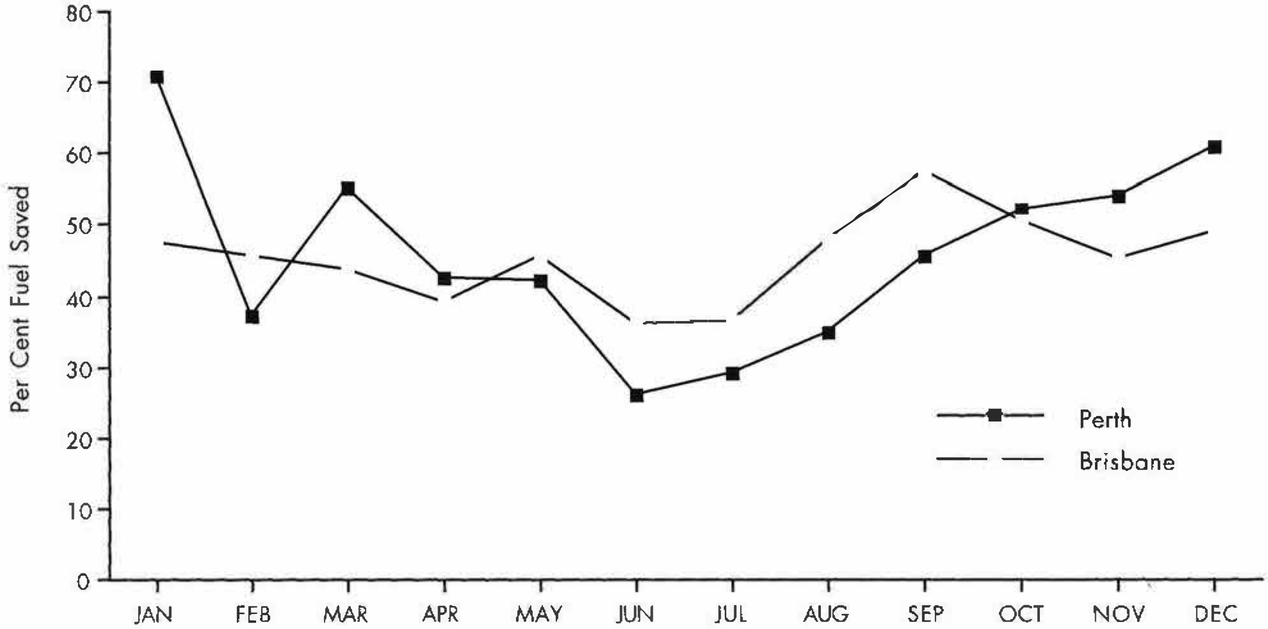

Figure 5. Estimated monthly variation of fuel savings in kiln type 3 (22 m³ but with extra night-time insulation) for Perth and Brisbane.

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APPENDIX 1

Source of climatic data and solar time adjustment for the thirty sites.

SITE	CLIMATIC DATA SOURCE	TIME ADJUSTMENT (hours)
W.A.		
Perth AMO	F	-0.25
Albany AMO	F	0
Kalgoorlie	F	0
Esperance	B	0
Manjimup	E	-0.25
Dwellingup	E	-0.25
Harvey	E*	-0.25
Northam	E	-0.25
N.T.		
Darwin	F	-0.73
QLD.		
Brisbane	F	0
Townsville	B	-0.25
Innisfail	B	-0.25
Rockhampton	F	0
Theodore	E	0
Warwick	E	0
N.S.W.		
Sydney	F	0
Wagga Wagga	F	0
Orange	E	0
Inverell	E	0

SITE	CLIMATIC DATA SOURCE	TIME ADJUSTMENT (hours)
A.C.T.		
Canberra	F	0
S.A.		
Adelaide	F	-0.25
Mt Gambier	F	0
Kyancutta	E	-0.50
VIC.		
Melbourne	F	-0.33
Mildura	F	-0.50
Kyabram	E	-0.33
Sale East	E	0
TAS.		
Hobart	F	0
Launceston	E	0
Swansea	E	0

F = All climatic data from Frick *et al.* (1988).

B = All climatic data from the Bureau of Meteorology.

E = Temperature and relative humidity direct from the Bureau of Meteorology, solar radiation estimated from bright sunshine hours (Bureau of Meteorology) using the Hounam (1969) equation.

* = Relative humidity values from Bunbury (40 km SW of Harvey).

APPENDIX 2

Coefficients used for fuel savings estimates (Equation 7) – extracted from Tschernitz (1986). Six month adjustment made for the southern hemisphere.

KILN 1 22 m³ Without night-time insulation

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
a0	−194.05	−186.48	−196.36	−140.90	−115.06	−75.76	−69.15	−73.90	−71.25	−84.80	−129.44	−157.15
a1	1.9259	1.8534	1.5451	1.1706	0.6970	0.4720	0.4139	0.4907	0.6904	1.0375	1.2783	1.5786
a2	0.0352	0.0366	0.0445	0.0450	0.0529	0.0534	0.0527	0.0491	0.0413	0.0306	0.0314	0.0314
a3	−1274.6	−1514.1	−393.2	−715.9	38.7	−13.2	20.8	−186.5	−1163.1	−1685.2	−1159.3	−1203.6
a4	0.6832	0.8009	1.2326	0.8585	0.8445	0.2183	0.1251	0.1457	0.0007	0.1435	0.5695	0.6210

KILN 2 84 m³ Without night-time insulation

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
a0	−152.35	−143.06	−147.57	−107.46	−87.52	−59.21	−55.26	−58.49	−52.66	−55.58	−98.39	−120.46
a1	1.5918	1.4851	1.2238	0.9346	0.5730	0.4133	0.3673	0.4196	0.5558	0.8174	1.0339	1.2889
a2	0.0317	0.0327	0.0372	0.0364	0.0408	0.0401	0.0399	0.0380	0.0332	0.0252	0.0280	0.0282
a3	−1270.8	−1437.7	−492.2	−619.1	−14.0	−21.2	19.8	−124.6	−945.5	−1550.3	−1073.7	−1196.0
a4	0.4485	0.5225	0.8177	0.5549	0.5400	0.0892	0.0409	0.0508	−0.1334	−0.1328	0.3117	0.3748

KILN 3 22 m³ With extra night-time insulation

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
a0	−176.82	−170.08	−198.28	−95.33	−79.84	−61.46	−58.63	−65.47	−49.41	−65.76	−117.46	−140.11
a1	1.8459	1.7242	1.4543	0.9804	0.5161	0.4001	0.3837	0.4727	0.6300	0.9610	1.1965	1.5009
a2	0.0392	0.0420	0.0524	0.0464	0.0572	0.0598	0.0579	0.0535	0.0445	0.0339	0.0364	0.0353
a3	−1636.3	−1799.6	−339.9	−1560.4	724.4	−571.6	−460.7	−546.9	−1736.4	−2053.4	−1323.8	−1508.7
a4	0.7428	0.9449	1.6765	0.7612	0.9498	0.7164	0.6723	0.6378	0.1605	0.2713	0.6891	0.6522

KILN 4 84 m³ With extra night-time insulation

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
a0	−137.48	−128.88	−148.77	−69.04	−59.99	−47.37	−46.18	−51.14	−35.51	−38.95	−88.31	−105.69
a1	1.4949	1.3574	1.1247	0.7469	0.3998	0.3206	0.3117	0.3376	0.4840	0.7239	0.9408	1.2004
a2	0.0350	0.0371	0.0439	0.0379	0.0451	0.0462	0.0448	0.0422	0.0363	0.0282	0.0324	0.0316
a3	−1569.7	−1674.0	−443.9	−1321.9	−621.1	−478.4	−382.2	−418.9	−1398.0	−1854.8	−1192.3	−1443.2
a4	0.4984	0.6402	1.1854	0.4739	0.6680	0.5138	0.4957	0.4636	0.0176	0.0000	0.4127	0.3996

APPENDIX 3

Climatic values and percentage fuel savings of a passive solar kiln based on Tschernitz regressions.

SOL RAD = total solar radiation (kJ m^{-2})
ABS HUM = absolute humidity ((kg water/kg dry air) x 10 000)
RH = relative humidity (%)
TEMP = average temperature (°C)

Kiln type 1 is 22 m^3 timber capacity and without extra night-time insulation
Kiln type 2 is 84 m^3 timber capacity and without extra night-time insulation
Kiln type 3 is 22 m^3 timber capacity and with extra night-time insulation
Kiln type 4 is 84 m^3 timber capacity and without extra night-time insulation

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
LOCATION 1	PERTH	LATITUDE	31.93										
SOL RAD	29200	25500	21300	15200	10800	8800	9500	12300	16800	21900	25300	28300	18742
ABS HUM	95	99	94	87	78	74	69	68	70	73	79	88	81.2
RH	50	50.5	53.2	60.7	66.5	71	71	68.5	65	60.5	55.5	53	60.5
TEMP	24.1	24.5	22.5	18.9	15.8	13.9	12.9	13.2	14.3	16.3	18.9	21.5	18.1
KILN 1	51	47	35	18	4	-1	2	18	21	30	34	42	24
KILN 2	51	45	32	15	3	-2	-0	7	17	27	34	42	23
KILN 3	71	67	55	42	42	26	29	35	45	52	54	61	48
KILN 4	66	61	48	34	23	19	22	25	37	46	49	58	41
LOCATION 2	ALBANY	LATITUDE	34.95										
SOL RAD	24700	20600	16400	11500	8800	7600	8300	10800	14400	18600	21100	24600	15617
ABS HUM	84	93	88	87	79	73	69	67	68	71	76	79	77.8
RH	59.2	63.8	64.8	73.6	77.6	80.8	80.2	78	74.6	70.6	67.8	61	71.0
TEMP	19.5	19.8	18.7	16.5	14.1	12.4	11.7	11.7	12.5	14	15.8	18	15.4
KILN 1	25	19	9	0	-4	-7	-4	2	11	18	17	24	9
KILN 2	25	21	11	1	-4	-7	-5	1	8	17	19	27	9
KILN 3	44	39	28	25	33	21	24	29	35	39	36	44	33
KILN 4	43	37	26	20	16	15	18	20	28	35	34	42	28
LOCATION 3	ESPERANCE	LATITUDE	33.83										
SOL RAD	25870	24990	18430	13080	9180	7910	8580	11670	16400	20610	24880	26610	17351
ABS HUM	101	104	99	91	80	71	66	67	72	76	84	92	83.6
RH	65	66	67.6	69.8	71.8	72.8	72.4	70.6	69.6	67.4	65.8	64.2	68.6
TEMP	20.8	21.1	20	18	15.5	13.5	12.6	13.1	14.4	15.7	17.8	19.6	16.8
KILN 1	30	35	19	9	-2	-5	-3	7	20	25	30	32	16
KILN 2	32	35	19	8	-2	-5	-4	5	16	23	31	34	16
KILN 3	49	56	39	33	35	23	26	34	44	47	51	51	41
KILN 4	47	52	34	27	18	17	19	24	35	42	47	49	34
LOCATION 4	MANJIMUP	LATITUDE	34.25										
SOL RAD	23771	21458	18016	12046	9097	7395	8709	11385	14364	19308	22683	24672	16075
ABS HUM	82	89	87	82	75	70	65	64	64	64	69	75	73.8
RH	54.2	58.5	64	72.7	78.5	83	82.7	78.7	73.2	65.2	60.2	55.5	68.9
TEMP	20.5	20.6	18.7	15.7	13.3	11.4	10.4	10.7	11.9	13.7	16.1	18.7	15.1
KILN 1	25	24	14	1	-5	-9	-4	4	10	20	22	27	11
KILN 2	28	26	15	1	-5	-9	-5	2	8	19	24	29	11
KILN 3	44	44	35	26	33	19	25	31	35	42	42	46	35
KILN 4	43	42	31	21	17	14	18	22	28	38	39	44	30
LOCATION 5	DWELLINGUP	LATITUDE	32.72										
SOL RAD	26665	23772	19793	13505	10565	7928	9387	12192	15146	20806	24628	27688	17673
ABS HUM	82	89	85	83	76	71	65	63	65	64	69	74	73.8
RH	48.7	53	58.2	72.2	79.7	84.2	83.2	80	74.5	63	56.7	50	67.0
TEMP	22.2	22.2	20	16.1	13.1	11.3	10.3	10.4	11.8	14.2	17	20.2	15.7
KILN 1	39	36	23	6	1	-7	-1	7	13	25	29	38	17
KILN 2	41	36	23	6	-0	-7	-2	4	10	23	30	40	17
KILN 3	59	56	44	31	38	20	27	33	37	47	49	58	42
KILN 4	55	52	39	26	21	15	20	24	30	42	46	55	36

Appendix 3 Continued

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
LOCATION 6	HARVEY	LATITUDE	33.13										
SOL RAD	26788	24146	20657	13860	10754	8174	9471	12640	16182	21180	24446	27516	17985
ABS HUM	90	93	98	98	90	82	78	74	70	69	72	78	83
RH	50	51	60	73	82	85	86	81	72	62	55	50	67
TEMP	23.3	23.55	21.6	18.4	15.4	13.35	12.5	12.5	13.55	15.6	18	21.1	17.4
KILN 1	42.2	41.4	30.9	11.5	4.8	-3.9	1.5	10.7	18.2	27.6	30.8	40.2	21
KILN 2	43.3	40.5	28.8	9.9	3.0	-4.5	-0.6	7.3	14.7	25.3	30.9	40.9	20
KILN 3	61.6	61.6	52.0	34.9	42.9	22.9	29.1	36.7	42.4	49.9	51.0	59.9	45
KILN 4	57.8	56.2	45.5	28.4	22.9	16.8	21.5	26.4	34.0	44.2	46.9	56.4	38
LOCATION 7	NORTHAM	LATITUDE	31.75										
SOL RAD	27760	24464	21078	14529	11940	9137	10721	13663	17089	23114	27166	30073	19228
ABS HUM	82	92	85	82	71	71	66	64	64	64	63	69	72.8
RH	40.5	46.2	49.2	62.5	70.7	81.5	82.2	77.5	70.2	56.7	44	38.2	60.0
TEMP	25.3	25	22.6	18.1	14.1	11.8	10.7	11	12.6	15.9	19.7	23.4	17.5
KILN 1	52	46	34	13	7	-1	6	14	21	34	42	54	27
KILN 2	52	45	32	12	5	-2	3	16	17	31	41	53	25
KILN 3	72	66	55	39	45	26	34	40	46	57	63	75	51
KILN 4	67	60	48	32	27	20	25	29	37	50	58	69	43
LOCATION 8	KALGOORLIE	LATITUDE	30.78										
SOL RAD	29600	25200	20900	16800	12000	10600	11400	14300	19800	24000	26000	28900	19958
ABS HUM	86	92	85	75	65	60	56	54	52	57	64	75	68.4
RH	40.9	46.7	48.7	55.5	63.1	69.1	69.7	61.7	49.7	43.9	40.3	39.3	52.4
TEMP	26	24.9	22.8	18.7	14.4	11.8	10.7	11.9	14.9	18.2	21.4	24.4	18.3
KILN 1	59	48	33	23	7	6	9	17	35	42	42	52	31
KILN 2	58	46	31	20	5	3	5	12	29	38	41	51	28
KILN 3	79	68	53	49	44	34	37	44	61	65	63	72	56
KILN 4	73	62	47	40	27	26	28	32	49	57	57	67	47
LOCATION 9	ADELAIDE	LATITUDE	35										
SOL RAD	29600	26200	19600	13700	9700	8300	8000	11200	16000	21800	24900	27100	18008
ABS HUM	77	80	76	70	68	64	61	60	58	61	65	70	67.5
RH	47.2	49	52.2	58	68.2	74	75	70.2	61.5	55	50.5	48	59.1
TEMP	21.7	21.8	19.8	16.9	13.9	11.7	10.9	11.7	13.2	15.7	17.9	19.8	16.3
KILN 1	48	46	25	11	-0	-4	-6	4	19	31	34	38	20
KILN 2	49	45	24	16	-1	-5	-7	2	15	28	33	39	19
KILN 3	70	68	46	37	36	25	23	31	44	54	54	58	45
KILN 4	65	62	41	30	20	18	16	22	35	47	50	54	38
LOCATION 10	MT GAMBIER	LATITUDE	37.75										
SOL RAD	24500	22200	16100	10900	7700	6400	7000	9600	13300	18000	20800	23600	15008
ABS HUM	74	81	78	73	69	64	61	60	60	61	65	68	67.8
RH	57.3	61.7	65.9	73.7	81.4	85.8	85.6	80.6	74	68.4	64.4	59	71.5
TEMP	17.9	18.1	16.6	13.8	11.5	9.6	9	9.6	10.8	12.3	14.1	16.2	13.3
KILN 1	22	23	6	-4	-10	-14	-12	-4	6	15	15	20	5
KILN 2	26	25	8	-3	-9	-13	-11	-5	4	14	17	23	6
KILN 3	42	44	26	22	27	15	18	24	31	38	35	39	30
KILN 4	41	42	24	18	12	11	13	16	24	34	33	38	25
LOCATION 11	KYANCUTTA	LATITUDE	33.13										
SOL RAD	25901	22868	19712	13972	10853	8947	10139	12640	15564	20749	24907	26112	17697
ABS HUM	67	74	80	74	72	65	63	61	60	56	53	59	65.3
RH	36.5	41	51.5	59.5	71.7	76.2	77.5	70.7	61.7	47	37.2	36.7	55.6
TEMP	23.7	23.4	20.8	17.4	14	11.5	10.8	11.8	13.7	16.7	19.6	21.6	17.1
KILN 1	44	40	26	12	3	-2	3	10	17	31	38	40	22
KILN 2	45	39	25	10	2	-3	1	7	14	28	37	41	20
KILN 3	64	60	46	37	41	27	32	37	42	53	58	60	46
KILN 4	60	55	41	31	23	20	24	26	34	47	53	56	39

Appendix 3 Continued

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
LOCATION 12	MELBOURNE	LATITUDE	37.83										
SOL RAD	24200	21600	16000	11000	7400	5900	6700	9100	12600	17400	21000	23700	14717
ABS HUM	81	87	81	74	67	61	57	57	58	61	68	74	68.8
RH	55.5	59	61	67.2	73.5	77.5	76.2	70.5	64.3	59.3	58.1	55.8	64.8
TEMP	19.9	20	18.4	15.4	12.5	10.3	9.5	10.7	12.4	14.4	16.4	18.4	14.9
KILN 1	27	26	10	-0	-11	-16	-13	-5	5	17	21	25	7
KILN 2	30	27	11	-0	-9	-14	-12	-5	4	16	21	27	8
KILN 3	46	47	31	25	26	13	17	22	30	39	40	45	32
KILN 4	44	43	27	20	12	9	12	15	23	35	37	43	27
LOCATION 13	MILDURA	LATITUDE	34.25										
SOL RAD	28300	25300	20700	15100	10500	8800	9600	12600	16900	21700	26000	28900	18700
ABS HUM	82	89	81	73	69	62	58	58	58	60	65	70	68.8
RH	42.9	47.6	51.3	61.1	72.5	78.5	76.5	69.5	58.7	50.2	45.2	41.5	58.0
TEMP	24.3	23.9	21.1	16.8	13.2	10.5	9.8	11.3	13.7	16.7	19.7	22.3	16.9
KILN 1	52	48	32	16	2	-3	0	19	22	33	40	49	25
KILN 2	52	46	30	13	0	-4	-2	6	18	29	39	48	23
KILN 3	72	69	53	42	39	26	30	37	48	55	61	69	50
KILN 4	67	62	47	34	22	19	22	27	38	49	55	64	42
LOCATION 14	KYABRAM	LATITUDE	36.33										
SOL RAD	25528	23412	19693	13931	9784	7609	8526	11287	15266	20553	24940	27193	17310
ABS HUM	67	74	76	71	66	58	53	56	58	59	55	57	62.5
RH	41.3	43.8	54.4	66.4	78.6	83.9	82.1	76.9	70.4	58.7	45.3	39.5	61.8
TEMP	21.7	22.4	19.3	14.9	11.4	8.4	7.6	9.2	10.9	14	17.1	19.9	14.7
KILN 1	38	41	25	9	-2	-10	-6	3	13	25	34	40	17
KILN 2	40	40	24	8	-3	-18	-7	1	10	23	33	41	17
KILN 3	58	62	48	36	36	20	24	31	38	48	55	61	43
KILN 4	55	56	42	29	20	14	18	22	31	42	50	57	36
LOCATION 15	SALE EAST	LATITUDE	38.1										
SOL RAD	23357	20535	16987	12319	8940	6998	8466	11126	14645	19020	22371	23870	15719
ABS HUM	88	92	88	75	66	59	53	56	60	68	73	81	71.6
RH	63.8	66	70.1	73.3	78.4	81.4	77.4	75.9	72.4	70.8	67.2	65.2	71.8
TEMP	18.9	19.2	17.5	14.4	11.4	9.1	8.4	9.5	11.2	13.3	15.2	17.3	13.8
KILN 1	20	19	12	3	-5	-12	-6	3	11	18	21	22	9
KILN 2	24	21	12	2	-5	-11	-7	0	8	17	22	25	9
KILN 3	39	40	33	29	33	19	26	31	36	41	42	41	34
KILN 4	38	37	29	23	18	13	19	22	29	36	38	40	29
LOCATION 16	SYDNEY	LATITUDE	33.93										
SOL RAD	24300	20000	17600	13100	9800	8400	8800	12500	16000	19300	21200	24800	16317
ABS HUM	117	123	113	93	77	65	56	58	65	79	92	107	87.1
RH	69	71.8	71.4	70	70.6	70.6	65.4	62.6	61.2	63	64.4	66.4	67.2
TEMP	22.2	22.4	21.2	18.3	15	12.8	11.7	12.8	14.9	17.4	19.5	21.4	17.5
KILN 1	28	20	18	9	0	-3	-2	11	20	24	23	31	15
KILN 2	30	22	18	8	-0	-4	-3	7	16	22	24	32	14
KILN 3	46	38	38	33	38	25	27	38	44	46	42	49	38
KILN 4	43	35	33	27	20	19	20	27	35	40	38	46	32
LOCATION 17	CANBERRA	LATITUDE	35.32										
SOL RAD	27600	24300	19400	13900	10000	8900	8600	11500	16300	20800	25100	26700	17758
ABS HUM	82	89	79	65	55	48	45	45	50	56	62	70	62.2
RH	54.9	60.7	62.7	69.3	75.9	79.3	78.9	73.1	67.5	61.4	56.1	52.5	66.0
TEMP	20.3	19.9	17.6	13.1	8.9	6.4	5.6	6.8	9.4	12.6	15.4	18.6	12.9
KILN 1	37	32	18	5	-5	-6	-7	2	16	23	29	33	15
KILN 2	39	33	19	4	-5	-7	-8	-0	13	22	29	35	14
KILN 3	57	54	40	33	33	25	23	29	42	47	50	53	41
KILN 4	55	50	36	27	19	19	17	21	34	42	46	51	35

Appendix 3 Continued

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
LOCATION 18	WAGGAWAGGA	LATITUDE	35.25										
SOL RAD	27300	24800	20000	14600	9800	7900	8600	11300	16000	20900	25700	28100	17917
ABS HUM	86	94	84	73	66	58	54	56	60	65	69	74	69.9
RH	46.7	51.5	55.3	65.9	77.9	83.3	83.5	78.3	71.5	63.1	53.7	45.9	64.7
TEMP	23.5	23.5	20.5	15.6	11.4	8.6	7.5	9	11.2	14.5	17.9	21.5	15.4
KILN 1	46	45	28	12	-3	-9	-6	2	16	26	36	45	20
KILN 2	47	43	27	10	-3	-9	-7	0	13	23	35	45	19
KILN 3	66	66	50	38	35	21	24	30	41	49	57	65	45
KILN 4	62	59	44	31	19	15	17	21	33	43	51	60	38
LOCATION 19	ORANGE	LATITUDE	33.32										
SOL RAD	25299	23554	19539	14711	11097	8725	9991	13137	16637	22014	25660	27352	18143
ABS HUM	76	82	74	64	55	47	43	45	49	49	62	69	59.7
RH	56.2	61.6	65.1	73.1	79.4	83.6	81.0	78.4	73.0	68.6	62.6	56.6	70.0
TEMP	18.8	18.4	15.9	12.1	8.6	5.6	4.6	5.9	8.1	9.0	13.7	17.0	11.4
KILN 1	24	24	12	4	-2	-8	-2	8	15	21	26	29	13
KILN 2	28	27	14	4	-3	-8	-4	4	12	20	27	32	13
KILN 3	44	46	33	33	36	22	28	35	42	45	47	50	38
KILN 4	43	44	31	27	22	16	21	25	34	41	44	48	33
LOCATION 20	INVERELL	LATITUDE	29.78										
SOL RAD	24109	23531	21603	16051	12704	10856	12093	15682	19026	22800	25577	26029	19172
ABS HUM	97	95	89	73	63	54	48	49	51	62	68	83	69
RH	53.1	54.9	58.7	61.7	69.9	73.7	71.3	66.9	58.1	54.7	48.9	50.4	60
TEMP	23.5	22.7	20.4	16.7	12.4	9.4	8.0	9.2	12.2	16.0	19.2	21.8	15.9
KILN 1	34	36	32	18	10	5	10	21	29	34	37	38	25
KILN 2	36	36	30	16	7	2	6	15	23	30	36	38	23
KILN 3	52	56	54	45	48	36	41	50	55	57	58	57	51
KILN 4	49	52	47	37	30	27	31	37	44	50	53	53	42
LOCATION 21	BRISBANE	LATITUDE	27.42										
SOL RAD	24200	22200	19700	14900	11800	11100	11300	15100	19000	20300	21900	24100	17967
ABS HUM	130	135	130	112	89	75	67	67	75	88	102	118	99.0
RH	64.6	67.2	68.6	67.8	66.4	65.1	62.9	59.1	57.2	57.6	58.2	61.2	63.0
TEMP	25	24.9	24	21.8	18.5	16.1	15	15.9	18.2	20.6	22.8	24.3	20.6
KILN 1	31	29	25	17	9	11	11	24	34	31	28	32	23
KILN 2	33	30	25	15	7	7	7	18	28	28	29	33	22
KILN 3	48	46	43	39	46	37	37	48	57	50	45	48	45
KILN 4	45	43	38	32	26	28	28	35	46	45	42	46	38
LOCATION 22	TOWNSVILLE	LATITUDE	19.25										
SOL RAD	21290	20020	19820	17200	15220	14670	15720	18270	21970	24310	24610	23440	19712
ABS HUM	163	174	162	138	117	94	91	97	109	128	150	163	132.2
RH	68.2	74.5	73	69.7	68	64.5	65.2	64.5	64	64.7	66.7	68.2	67.6
TEMP	27.8	27.5	26.6	24.7	22.4	19.9	19.2	20.3	22.3	24.8	26.8	27.9	24.2
KILN 1	22	18	22	23	23	29	34	39	46	41	34	29	30
KILN 2	25	20	23	21	19	22	25	31	38	38	35	31	27
KILN 3	35	31	36	43	61	51	56	60	66	59	50	44	49
KILN 4	35	30	33	36	35	39	42	45	54	53	47	42	41
LOCATION 23	INNISFAIL	LATITUDE	17.53										
SOL RAD	18780	17300	16290	13840	11920	16010	13040	15560	16030	19960	20690	19770	16599
ABS HUM	169	179	168	152	139	119	112	117	115	121	139	152	140.2
RH	75.5	81.2	79	80	82	80	78.2	75.7	69.2	65.2	65.7	69	75.1
TEMP	26.7	26.5	25.9	24	22.2	20.1	19.5	20.7	21.9	23.8	25.9	26.5	23.6
KILN 1	9	4	4	6	6	35	21	27	23	29	22	16	17
KILN 2	14	8	8	7	6	27	16	22	20	29	24	20	17
KILN 3	21	15	15	24	44	56	40	45	41	45	36	29	34
KILN 4	22	17	16	21	19	43	30	33	34	42	35	30	29

Appendix 3 Continued

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
LOCATION 24	**ROCKHAMPTON**	**LATITUDE**	**23.38**										
SOL RAD	22200	20700	20000	17400	14000	13700	14200	17000	19900	22200	23500	24300	19092
ABS HUM	151	155	145	120	97	82	77	80	90	104	121	137	113.3
RH	67.4	70.6	70.3	67.5	67.1	67.7	67.9	63.3	60.9	58.9	59.4	62.4	65.3
TEMP	26.8	26.4	25.5	23.1	19.8	16.9	16	17.6	20.2	23	25.3	26.5	22.3
KILN 1	26	23	25	25	17	23	25	32	38	37	34	34	28
KILN 2	28	24	25	22	14	17	18	25	32	34	34	35	26
KILN 3	40	37	41	47	55	47	49	55	59	56	50	49	49
KILN 4	39	35	37	39	32	36	37	41	49	50	47	47	41
LOCATION 25	**THEODORE**	**LATITUDE**	**24.83**										
SOL RAD	22033	20679	19561	16692	14051	12638	14411	16756	19728	22746	24465	24230	18999
ABS HUM	134	133	123	98	83	69	64	66	71	88	103	122	96
RH	58.9	60.3	60.9	58.9	63.1	65.9	64.3	59.5	53.1	52.3	51.9	55.5	59
TEMP	27.2	26.6	25.1	22.0	18.2	14.7	14.0	15.5	18.6	22.1	24.9	26.6	21.3
KILN 1	35	35	36	30	24	18	25	31	37	41	43	42	33
KILN 2	36	33	32	25	18	12	18	23	30	35	40	40	29
KILN 3	51	51	56	53	62	48	56	59	62	62	62	58	57
KILN 4	47	46	47	43	39	36	42	44	50	53	55	53	46
LOCATION 26	**WARWICK**	**LATITUDE**	**28.2**										
SOL RAD	23240	21635	19916	16791	13362	11590	13403	16355	19483	22548	25019	24767	19009
ABS HUM	114	116	108	88	73	62	55	54	61	74	89	100	83
RH	62	65	67	67	71	74	70	63	59	58	59	58	64
TEMP	23.5	22.95	21.55	18.2	14.4	11.3	10.2	11.55	14.45	17.8	20.5	22.65	17.4
KILN 1	26	24	21	19	11	9	17	26	32	34	33	31	24
KILN 2	29	26	22	17	9	6	11	19	27	31	34	33	22
KILN 3	43	42	40	44	49	37	45	51	57	55	52	49	47
KILN 4	41	40	36	37	30	28	34	38	47	50	49	47	40
LOCATION 27	**DARWIN**	**LATITUDE**	**12.42**										
SOL RAD	20100	20200	20100	22300	20400	19700	20500	22100	23600	24700	24100	22700	21708
ABS HUM	188	188	184	159	130	107	104	118	141	162	177	186	153.7
RH	76.3	77.3	75.3	64.6	57	52.6	52.3	55.6	59.3	63.3	68	72.6	64.5
TEMP	28.2	28	28.1	28.3	26.9	25.1	24.8	25.9	27.7	29	29.2	28.9	27.5
KILN 1	12	13	18	43	47	55	59	59	54	43	32	23	38
KILN 2	17	17	20	38	38	43	45	47	47	41	33	26	34
KILN 3	24	24	29	61	85	76	79	77	72	59	46	36	56
KILN 4	25	25	28	52	53	58	61	58	60	53	44	36	46
LOCATION 28	**HOBART**	**LATITUDE**	**42.83**										
SOL RAD	22600	19600	14300	10100	6400	5100	6000	8600	12600	17100	20100	21800	13691
ABS HUM	75	76	72	66	59	53	50	52	54	58	63	68	62.2
RH	60.8	62	65	68	73.2	75.2	74.6	73	67.4	64.6	63	62.2	67.4
TEMP	17	17	15.7	13.3	10.6	8.6	8	8.8	10.4	12.2	13.9	15.4	12.6
KILN 1	16	15	3	-4	-13	-20	-17	-8	3	14	16	16	2
KILN 2	20	17	4	-3	-12	-18	-15	-8	1	12	17	18	3
KILN 3	36	37	24	23	24	12	16	22	29	37	36	35	28
KILN 4	35	35	22	18	11	8	11	15	22	32	33	34	23
LOCATION 29	**LAUNCESTON**	**LATITUDE**	**41.55**										
SOL RAD	24159	21599	17092	11912	7914	6106	7329	9998	13966	19629	23465	24966	15677
ABS HUM	69	72	72	65	59	53	50	52	55	58	61	67	61.1
RH	58.4	60.4	66.9	73.9	80.6	83.8	83.2	80.3	75.3	71.3	65.8	62.8	71.9
TEMP	16.6	16.7	15	12	9.3	7.1	6.5	7.5	9.2	10.9	12.9	14.9	11.6
KILN 1	19	20	19	-0	-9	-17	-12	-3	7	18	22	22	6
KILN 2	23	22	11	-0	-9	-16	-12	-5	4	16	23	25	7
KILN 3	40	43	33	27	29	15	21	27	33	42	44	42	33
KILN 4	39	40	29	22	15	11	15	18	25	36	40	41	28

Appendix 3 Continued

LOCATION 30 SWANSEA LATITUDE 42.13

SOL RAD	22415	19390	15504	11087	7598	5890	7164	9929	13610	18594	21367	23133	14640
ABS HUM	73	76	73	68	61	55	52	52	53	56	64	68	62.6
RH	60.6	63	65.4	70.6	75.2	76.2	75.8	72.4	66.2	62.2	64.2	62.8	67.9
TEMP	16.8	16.8	15.6	13.4	10.9	9.1	8.2	9.1	10.7	12.3	14	15.2	12.7
KILN 1	15	13	6	-0	-8	-16	-11	-2	7	18	19	18	5
KILN 2	19	16	7	-0	-8	-15	-11	-4	5	16	20	21	5
KILN 3	34	35	29	26	29	16	22	28	34	42	40	38	31
KILN 4	34	33	25	21	15	11	15	19	26	36	36	37	26

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Review of the ecology and control of the introduced bark beetle *Ips grandicollis* (Eichhoff) (Coleoptera: Scolytidae) in Western Australia, 1952–1990

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SUMMARY

This paper reviews and collates historical material, previously unpublished, relating to *Ips grandicollis*, hereafter called *Ips*, in pine plantations in Western Australia. Within 10 years of being discovered, *Ips* was distributed in nearly all plantations. *Ips* initially caused concern to foresters because it introduces blue stain fungi to felled logs. Attack of felled logs by *Ips* is retarded by cool weather. Low temperatures also increase the length of the larval phase of the life cycle. Available data indicate that logs of radiata pine are more attractive to *Ips* than those of pinaster pine.

By 1970 the coincidence of a severe drought and canopy closure of many hectares of radiata pine plantations in the Blackwood Valley led to outbreaks of *Ips*, resulting in some feeding attacks. Subsequent droughts in 1972, 1979 and 1987, combined in some instances with inadequate disposal of thinning slash, led to further outbreaks. The balance of local evidence available indicates that *Ips* is a secondary pest of the pine.

From 1984 to 1990, Western Australia participated in a national scheme to establish biological control agents (insect predators and parasitoids) to help minimize future *Ips* outbreaks. Only the parasitoid *Roptrocerus xylophagorum* (Hymenoptera, Pteromalidae) has established in Western Australian plantations, where an average rate of parasitization of *Ips* of *c.* 5 per cent was recorded in 1990.

INTRODUCTION

Ips grandicollis (Eichhoff) (hereafter *Ips*) was first recorded in Western Australia in September 1952. Western Australia and South Australia are the only parts of Australia where *Ips* and pines have coexisted for more than three decades.

Although research into *Ips* commenced in Western Australia in 1955, the amount of effort allocated has been limited and only one scientific paper has been published (Rimes 1959). During 1966–1979 S.J. Curry[1] carried out surveys, none of which were published. A search of files of the Department of Agriculture and of the Forests Department revealed existing records of data collected to be fragmentary. Nonetheless, studies of *Ips* in South Australia (Morgan 1967, 1989) and Victoria (Neumann and Morey 1984) complement this information.

This review organizes existing facts and information into two time frames. The period 1952 to 1982 included the important necessary steps of documenting the spread of *Ips* through the south-west of Western Australia, elucidating its life history, and devising operational techniques for limiting the damage that outbreaks may cause to the pinewood resource. The second phase, 1984 to 1990, involved a biocontrol program carried out in conjunction with the *Ips* Project Management Committee (Australian Forestry Council), and the formulation of a prescription for the introduction of biocontrol agents into pine plantations managed by the Department of Conservation and Land Management (CALM).

THE INSECT: DISTRIBUTION, HABITAT AND SEASONAL ACTIVITY

Description

See Wood (1982: pp 699–701) for a full diagnosis.

Distribution in Northern Hemisphere

According to Wood (1982), *Ips* ranges over most of the eastern half of North America, from southern Manitoba and Quebec to Florida, and Mexico and Central America.

[1] Forest Entomologist, Department of Agriculture, Western Australia from 1964 to 1984.

Introduction to Australia

The species was first recorded in Australia, at Wirrabara in South Australia, in 1943 (Morgan 1967).

Distribution in Western Australia

In 1952 *Ips* was recorded only in Collier and Somerville plantations near Perth. The species is presumed to have reached Western Australia through shipment of infested material to Fremantle. It is not known whether such material came from South Australia or directly from North America.

By 1954 *Ips* was found in the Gnangara, Scaddan, Mudros and Greystone plantations near Perth as well as in metropolitan timber yards, but not in plantations further south. In 1962 *Ips* was present in all plantations except Boranup. By 1968, Curry recorded it in all plantations except two comparatively isolated ones south and east of Pemberton and Manjimup respectively. It has since reached these and has been recorded further east at Albany (see map in Abbott 1985).

Habitat

The main breeding habitat of *Ips* is fresh slash material (either from felled or wind blown material) and recently felled logs (Rimes 1959). Standing trees damaged by fire, lightning or weakened by drought are also attacked (see also below). In Western Australia attack has been recorded on eight species of pine. Neumann (1987) records attack on 10 species of pine in Australia and Wood (1982) lists 16 *Pinus* species which are attacked in North America. Both adults and larvae feed on the inner bark tissues of conifers. Wood felled for more than one year becomes too dry to sustain *Ips*.

Life cycle

The following account is condensed from Rimes (1959), Morgan (1967), and Neumann and Morey (1984). Two types of attack on trees may be found. Only males can initiate the breeding attack, whereas either sex can initiate the feeding attack.

In the *breeding* attack, the male enters the inner bark (cambium) and constructs a nuptial chamber. Both the initial attraction of females and the aggregation of the population are mediated through the production of pheromones. A female later enters and constructs an egg gallery from the chamber. Mating occurs, after which the female constructs lateral galleries into which eggs are laid. Eggs hatch in 7–12 days, depending on temperature. There are three[1] larval instars, each lasting 5–9, 6–10, and 6–10 days. Each larva produces a mine more or less perpendicular to the brood gallery. (If the bark is removed, the overall pattern of tunnels resembles an engraving in the sapwood.) Upon maturation a pupal chamber is formed and metamorphosis occurs. The freshly hatched adults bore to the outside of the wood, making an exit hole. Bark thickness influences larval survival, as thicker bark ensures a higher moisture content of cambium and this promotes survival. The fastest period from oviposition to emergence is *c.* 45 days in South Australia, in contrast to 60 days in Victoria. In South Australia 4–5 generations per year are recorded, whereas only 4 occur in Victoria.

In the *feeding* attack no nuptial chamber or brood galleries are constructed. Instead, the phloem, cambium and outer sapwood of live trees, recently killed trees and freshly felled logs are damaged. Such an attack is often found in the branches and upper bole during February and March.

SEASONAL ACTIVITY

Aims and Methods

A detailed study of seasonal activity in four plantations close to Perth was carried out by S.J. Curry during 1966 and 1967. Pinaster pine (*Pinus pinaster*) was studied at Collier in compartments 12 (planted 1932), 21 (1933) and 23 (1934), Somerville 51 (1940) and 57 (1945), Greystones 11 (1950) and Beraking 1 (1955). Radiata pine (*P. radiata*) was also studied at Greystones and Beraking. Collier and Somerville plantations no longer exist, having been replaced by the suburbs of Bentley and Murdoch to the south of Perth. Greystones and Beraking are on the Darling Plateau 30–45 km east of Perth.

The stated objective of this study was to relate seasonal variation in attack of pine logs by *Ips* to rainfall and humidity, and in particular to establish whether *Ips* is dormant during winter. Two trees were felled in each compartment each month for one year from May 1966. Each tree was cross cut into two 3 m (10 feet) logs and any lateral branches were removed though the crown was left intact. The two logs were placed on old logs so that they were off the ground and could easily be rolled over for inspection.

Logs in Collier compartment 12 were interfered with by firewood collectors; subsequently observations were transferred in July 1966 to compartment 21. Logs were examined within one week of felling and thereafter at fortnightly intervals (Collier, Somerville) or monthly intervals (Greystones, Beraking) for one year. Entry and exit holes were counted and marked with a cork borer and crayon at each inspection. Unfortunately, the diameter of the logs is not recorded in the files, nor is the sampling unit specified unequivocally. Therefore it is not possible to express these parameters in absolute terms. Comparisons between plantations are consequently not possible.

The period between felling and first recorded attacks, and the period between felling and first recorded emergences at the Collier and Greystones

[1] Morgan (1967) recorded four instars. This is now known to be in error, based on head capsule widths of some 'giant' larvae. There are only three moults to the pupa from hatching (F. D. Morgan, personal communication).

compartments has been examined in relation to mean maximum temperature during these periods. Weather data from Perth and Kalamunda, the nearest temperature recording centres, were used.

RESULTS AND DISCUSSION

Dormancy

Ips beetles were inactive from May until late August in all plantations. Dormant beetles were found in old galleries beneath the bark of logs (produced by the last autumn generation in logs then freshly felled) and dead standing trees. *Ips* may also overwinter as larvae or pupae.

Onset of Attack

Attack was recorded as soon as two days after felling, or as late as 64 days after felling (Table 1). A significant inverse relationship was found between mean maximum temperature and the number of days after felling before attack began (Fig. 1).

Emergence of New Generation of Beetles

This took place from November to January for the logs felled in May (autumn), whereas the process took only 15–30 days from logs felled during summer. It is possible that some of the records of <30 days represent re-emergence of attacking adults and not emergence of their brood. There is a strong inverse relationship between number of days from felling to emergence of adults and mean maximum temperature for that period (Fig. 2). Even if the six lowest points are omitted (for the reason just discussed), the strong inverse relationship remains (Fig. 2).

A 15-day generation length in February and March is twice as fast as recorded by Rimes (1959), and implies that a maximum of nine generations between May and April of the following year is possible. However, Rimes (1959) suggested that there could be 6–8 generations per year. This large number of generations per year explains why, under suitable conditions, *Ips* can reach outbreak levels rapidly.

The total number of adult *Ips* emerging from the felled logs shows no uniform seasonal pattern (Table 2): large numbers can emerge during the subsequent 1–15 months from logs felled in any month. Presumably this variability reflects differences in the numbers of *Ips* available to attack freshly felled logs (perhaps related to differences in silvicultural treatment such as thinning, slash management and stand basal area), as well as differences in the frequency of attack, ambient temperature and bark thickness.

A noticeable implication from the data pertaining to the two plantations containing both pine species (Table 2) is that many more *Ips* emerged from the logs of radiata pine. This may indicate that this species is a more attractive host than pinaster. Confirmation of any host preference would require specifically designed controlled field and laboratory studies.

Some anecdotal data available on file indicate that although greatest activity occurs from September to May, unseasonal conditions can extend or inhibit this. For example, *Ips* was still active in June 1967 north of Perth but not so near Mundaring which is wetter and cooler. In November 1968 unseasonal cool weather reduced activity near Perth. Curry considered that activity was usually much less in the south of Western Australia where winters are cooler and wetter. These anecdotes agree with the inverse relationship demonstrated in Figure 1 between time from attack and temperature.

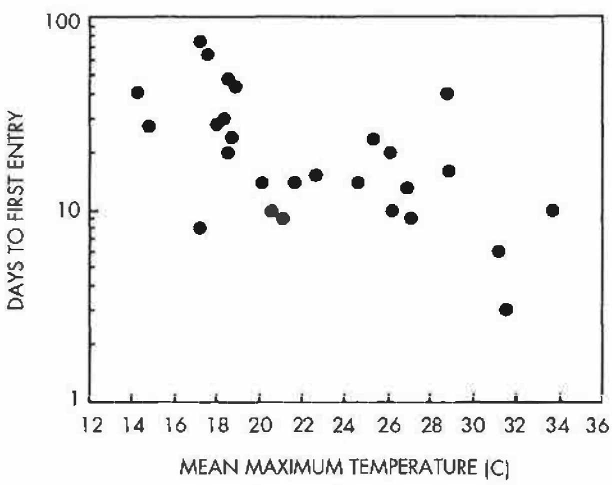

Figure 1. Relationship between number of days before adult Ips *attack freshly-felled logs of pinaster pine and mean maximum air temperature. Data pertain to Collier and Greystones plantations. Least squares best-fit regression: log $Y = 2.08 - 0.0366\,X$ ($r^2 = 0.36$, $P = 0.001$).*

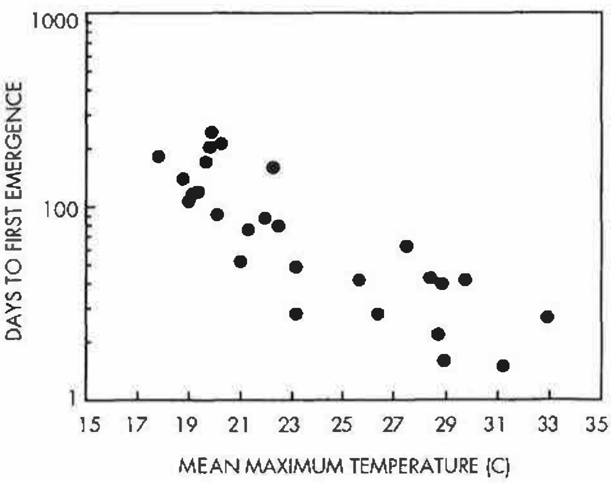

Figure 2. Relationship between number of days before adult Ips *emerge from freshly-felled logs of pinaster pine and mean maximum air temperature. Data pertain to Collier and Greystones plantations. Least squares best-fit regression: log $Y = 3.42 - 0.0647\,X$ ($r^2 = 0.71$, $P = 0.001$).*

TABLE 1

Periods between felling of test logs and first emergence of adult *Ips* in 1966–67, based on dates of felling, first recorded attack by beetles and first emergences of progeny.

GREYSTONES

Date of felling (day/month)	18/5	16/6	14/7	10/8	15/9	13/10	8/11	1/12	10/1	6/2	7/3	4/4	2/5
PINASTER													
Attack first recorded	27/5	27/7	10/8	13/10	13/10	27/10	1/12	10/1	16/1	9/2	20/3	19/4	1/6
(days)	9	41	27	64	28	14	20	40	6	3	13	15	30
Emergence first recorded	16/1	16/1	1/12	16/1	1/12	1/12	10/1	10/1	6/2	21/2	4/4	2/5	2/11
(days)	243	214	140	159	77	49	63	40	27	15	28	28	184
RADIATA													
Attack first recorded	27/5	10/8	27/7	13/10	13/10	27/10	10/1	10/1	16/1	21/2	20/3	19/4	1/6
(days)	9	55	13	64	28	14	63	40	6	15	13	15	30
Emergence first recorded	1/12	1/12	16/1	16/1	16/1	16/1	10/1	10/1	6/2	7/3	2/5	16/5	3/10
(days)	197	168	186	159	123	95	63	40	27	29	56	43	154

BERAKING

Date of felling (day/month)	17/5	16/6	14/7	10/8	15/9	13/10	8/11	1/12	10/1	6/2	7/3	4/4	2/5
PINASTER													
Attack first recorded	7/6	27/7	30/8	15/9	13/10	27/10	1/12	10/1	6/2	21/2	20/3	19/4	16/5
(days)	21	41	47	36	28	14	23	40	27	15	13	15	14
Emergence first recorded	1/12	1/12	1/12	8/11	8/11	1/12	1/12	10/1	6/2	7/3	4/4	5/7	1/10
(days)	198	168	140	90	54	49	23	40	27	29	28	31	154
RADIATA													
Attack first recorded	30/5	10/8	15/9	27/10	13/10	1/12	1/12	10/1	6/2	21/2	20/3	19/4	4/7
(days)	13	55	63	78	28	49	23	40	27	15	13	15	64
Emergence first recorded	1/12	8/11	1/12	10/1	10/1	10/1	1/12	10/1	6/2	21/2	4/4	5/9	3/10
(days)	198	145	140	153	117	89	23	40	27	15	28	154	154

COLLIER (all pinaster)

Date of felling (day/month)	13/5	15/6	12/7	9/8	13/9	11/10	9/11	6/12	3/1	7/2	7/3	4/4	2/5	6/6
COMPT 12/21														
Attack first recorded	23/5	–	29/8	29/8	21/9	25/10	2/12	22/12	25/1	13/2	9/3	8/4	–	–
(days)	10	–	48	20	8	14	23	16	22	6	2	4	–	–
Emergence first recorded	–	–	9/11	9/11	9/11	2/12	22/12	12/1	9/2	9/3	6/4	18/5	–	–
(days)	–	–	120	92	57	52	43	37	37	30	30	44	–	–
COMPT 23														
Attack first recorded	23/5	29/8	29/8	29/8	21/9	25/10	2/12	22/12	12/1	17/2	17/3	18/4	15/6	30/6
(days)	10	75	48	20	8	14	23	16	9	10	10	14	44	24
Emergence first recorded	2/12	2/12	9/11	9/11	2/12	2/12	22/12	22/12	25/1	21/3	18/4	30/6	28/8	22/9
(days)	203	170	120	92	80	52	43	16	22	42	42	87	118	108

SOMERVILLE (all pinaster)

Date of felling (day/month)	16/5	14/6	12/7	9/8	6/9	12/10	9/11	7/12	11/1	7/2	7/3	4/4	2/5	20/6
COMPT 51														
Attack first recorded	26/5	12/7	25/8	25/8	13/9	26/10	29/11	30/12	24/1	13/2	15/3	6/4	31/5	8/9
(days)	10	28	44	16	7	14	20	23	13	6	8	2	29	80
Emergence first recorded	10/11	10/11	10/11	10/11	10/11	29/11	30/12	11/1	8/2	8/3	22/3	4/5	13/7	22/9
(days)	178	149	121	93	65	48	51	35	28	29	15	30	72	94
COMPT 57														
Attack first recorded	26/5	24/8	13/9	24/8	12/10	26/10	24/11	30/12	24/1	13/2	15/3	20/4	4/5	–
(days)	10	71	63	15	36	14	15	23	13	6	8	16	2	–
Emergence first recorded	10/11	10/11	10/11	10/11	10/11	24/11	30/12	30/12	8/2	8/3	30/3	4/5	31/5	–
(days)	178	149	121	93	65	43	51	23	28	29	23	30	29	–

– not recorded or no data

TABLE 2

Number of adult beetles emerging from logs felled at different dates 1966–7.

GREYSTONES													
Date of felling (day/month)	18/5	16/6	14/7	10/8	15/9	13/10	8/11	1/12	10/1	6/2	7/3	4/4	2/5
Pinaster (up to 3 Aug 1967)	480	472	320	524	516	668	733	815	3007	2300	2710	1078	0
Radiata (up to 3 Aug 1967)	1451	1707	2402	1463	989	1522	2198	869	1492	3433	51	1022	0
BERAKING													
Date of felling (day/month)	17/5	16/6	14/7	10/8	15/9	13/10	8/11	1/12	10/1	6/2	7/3	4/4	2/5
Pinaster (up to 14 June 1967)	876	1335	593	884	566	971	787	1014	1020	1119	2100	0	0
Radiata (up to 14 June1967)	4244	1770	1990	2319	2219	1940	1733	1766	3039	3619	1596	0	0
COLLIER (all pinaster)													
Date of felling (day/month)	13/5	15/6	12/7	9/8	13/9	11/10	9/11	6/12	3/1	7/2	7/3	4/4	
compt 12/21 (up to 18 May 1967)	–	–	2116	1984	2270	847	665	358	192	223	142	2	
compt 23 (up to 4 May1967)	682	1224	1695	1964	1612	582	804	1519	1715	94	159	0	
SOMERVILLE (all pinaster)													
Date of felling (day/month)	16/5	14/6	12/7	9/8	6/9	12/10	9/11	7/12	11/1	7/2	7/3	4/4	
compt 51 (up to 31 May 1967)	3303	2539	3039	2126	3085	1981	2991	3936	2571	5306	1478	143	
compt 57 (up to 18 May 1967)	1816	1298	2520	1249	3082	1729	2560	2647	2476	5212	2739	515	

THE HOST TREE: PINES AND THEIR SILVICULTURE IN WESTERN AUSTRALIA

At the end of 1990, the area of Government-owned pine plantations in Western Australia was 68 408 ha, comprising radiata pine (57 per cent), pinaster pine (42 per cent) and other species (<1 per cent). Radiata pine is grown in the cooler and wetter parts of the south-west and pinaster pine is grown on the sandy soils of the Swan Coastal Plain. Radiata pine therefore tends to be grown where topography is relatively steep and on relatively fertile soils tending to be shallow and stony.

A regular annual planting program began in 1922 at Ludlow and Mundaring, although little was achieved during 1939 to 1945 (Foresters' Manual 1964). The area planted increased rapidly from about 7 000 ha in 1953 (Fig. 3). Initially pinaster pine was the preferred species for planting (Table 3).

The silvicultural systems applied to pine plantations have been explained in detail in the various editions of the Foresters' Manual (1927, 1952, 1964, 1973, 1981) and in the Pine Management Guide (CALM 1985). For both species, early management of plantations (up to 1970) was extremely conservative, mainly because there was no market for early thinnings. Up to then, the closing of the canopy was achieved at 6–7 years after planting depending on the site (Foresters' Manual 1954). In 1970 a new prescription was implemented, in order to produce high quality timber on a short rotation by heavy, early thinning and high pruning of crop trees. The stand was reduced to its final crop stocking early in the rotation. For radiata pine the first thinning was to be carried out before the stand reached 20 m (*c.* 10 years after planting) to ensure wind stability.

Delayed thinning and subsequent overstocking causes instability and susceptibility to windthrow, reduced diameter growth rates and, in extreme cases, death from drought (Hopkins 1971; McKinnell 1971; Butcher and Havel 1976; McGrath *et al.* 1990).

THE INTERACTION: *IPS*, BLUE STAIN FUNGI, DROUGHT AND PINE DEATHS

Pinaster Pine

Prior to 1970 *Ips* was considered a problem in the metropolitan plantations in its role as a vector of blue stain fungi, particularly *Ophiostoma* (syn. *Ceratocystis*) *ips* (Rumb.) Nannf., into logs stored on the ground (E. Hopkins[1], personal communication; see also Rimes 1959 and Stone and Simpson 1987). This infection discolours sapwood, thereby degrading wood and depreciating its market value.

Extensive drought deaths of pinaster pine on sands of the Swan Coastal Plain occurred after severe droughts in 1949–50 and 1976–77. During 1950–51 there were many investigations at Gnangara into the causes but there was no mention of insects or *Ips* in

[1] Dr E. Hopkins, formerly of Forests Department and Department of Conservation and Land Management, Western Australia.

TABLE 3

Planting history of the two major pine species in state plantations in South-Western Australia, to 1990.

	PERCENTAGE OF HECTARES PLANTED BY YEAR SHOWN					
SPECIES	1939	1964	1970	1980	1990	TOTAL AREA PLANTED (ha)
			ha			
RADIATA PINE	3.6	15.1	27.1	62.1	100.0	39 062
PINASTER PINE	10.8	32.0	53.2	81.8	100.0	29 346

Compiled from Annual Reports of the Forests Department of Western Australia and CALM.

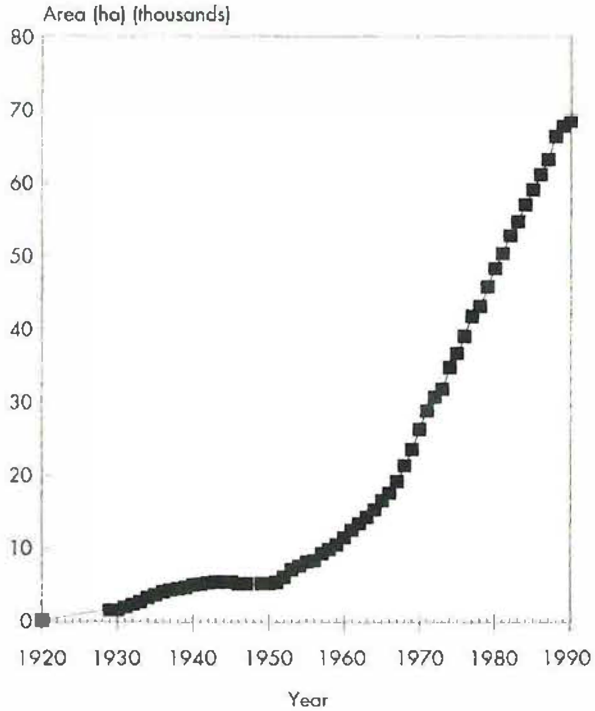

Figure 3. Area under pine plantation (Government-owned) in South-west Western Australia, 1920–1990.

particular. Deaths in Somerville plantation in February 1961 were thought to have been caused by moisture limitations in the shallow, limestone soils (yellow sands). However, for the first time *Ips* was suspected to have contributed. This plantation had suffered tree mortality in fertile (though shallow) sites over limestone at about 7–10 years of age. This corresponded with canopy closure and full utilization of the site. The disorder was known as Autumn Brown Top and was common until thinning was introduced in the late 1960s (Hopkins, personal communication).

In June 1976, 4 per cent of 9-year-old pinaster in a recently (April–May) thinned plantation at Yanchep experienced heavy attack by *Ips*. During 1977–78 there was wholesale collapse of older, dense, healthy plantations; *Ips* was present on most of these trees as well as on less healthy ones (Butcher[1], personal communication). Trees started dying from late May 1977. All of these instances involved drought in overstocked stands. Also relevant is that pinaster pine, by virtue of its mode of branching, is vulnerable when first pruned at age 6–7 years. This pruning may nearly ring-bark the tree, and if done in summer may result in its death.

Thus, in conclusion, no evidence was found on file to support the speculation that *Ips* infestation resulted in mortality of pinaster pine. However, the blue stain fungi associated with *Ips* are primary pathogens of pine as they disrupt the movement of water to the crown.

Radiata Pine

Significant mortality of radiata pine and feeding attacks by *Ips* were first recorded in 1970, and then in 1973, 1980 and 1987–88. These events occurred primarily in overstocked stands and/or on sites susceptible to drought. Most of these stands and sites occur in the Blackwood Valley. Bridgetown, situated in this valley, has a long term (1887-1990) average annual rainfall of 837mm. In the period 1929-1990 yearly rainfall has been below average 33 times, with the five driest years being 1940 (509 mm), 1969 (547 mm), 1972 (586 mm), 1979 (596 mm) and 1987 (555 mm): 1940 may be disregarded because there was no plantation then in the Blackwood Valley, only isolated trees. In addition, *Ips* was probably not present then. In 1969 well below average rainfall coincided with canopy closure in many of these plantations (Butcher and Havel 1976).

The 1970 and 1973 summers each followed a dry winter. Up to three-quarters of the 13 to 14-year-old trees in overstocked plantations near Nannup died, mostly from the top down. *Ips* attack of these usually followed the dying tissue down the tree. A small,

[1] T. Butcher, Research Scientist, Department of Conservation and Land Management, Como.

unspecified, proportion of trees was attacked at the base, and these died more quickly due to *Ips* attack. Curry (unpublished reports) doubted these would have survived even in the absence of this attack. The worst affected stands were recorded on north-facing slopes.

In April 1970, 1900 radiata trees were examined in three plantations near Nannup. It was found that 12 per cent were attacked by *Ips* in the lower 3 m (10 feet) of stem visible above ground level. Of the 30 per cent of the 1900 trees which were green and as yet not noticeably affected by drought, fewer than 1 per cent were attacked by *Ips*.

In the summer of 1973 *Ips* attack of green, apparently healthy, trees was recorded following thinning of 8 to 9-year-old plantations at Lewana. In the youngest plantation, thinned in the dry spring of 1972, 11 per cent of the standing trees were attacked by *Ips* during summer following their breeding in the slash. These trees generally died from the base up after *Ips* ring-barked them. In the older plantations, thinned and pruned over summer, more than 30 per cent of the standing trees died over the following year, after *Ips* attack in early autumn. Similar observations were made in Mungalup (planted 1957) and Wellington (1961–62) plantations near Collie during the summers of 1970–71 and 1971–72 (Shedley[1], personal communication).

Attack of living trees was also reported in plantations at Mundaring and Harvey. In March 1973 *Ips* was recorded attacking live trees in plantations near Collie, Nannup and Mundaring. These were either recently thinned 5 to 9-year-old stands or (at Collie) an unthinned 9-year-old stand. In February 1980 a feeding attack by *Ips* was recorded on 8-year-old trees in Murray plantation near Dwellingup. This plantation is on steep, rocky slopes and had been progressively thinned and pruned since November 1979.

In May 1988 Morgan[2] inspected a 17-year-old stand in Ferndale plantation which had experienced drought and wind damage in December 1987. Large populations of *Ips* were present; some trees had dead tops with *Ips* breeding in the lower bole and others still with green tips had *Ips* attack in their boles. One tree was felled and revealed that a feeding attack had occurred to the mid-crown level and all branches had been attacked by *Ips*. Breeding had then progressed further down with the most recent breeding in the lower bole.

During 1988 a broadscale survey of Blackwood Valley radiata pine plantations was carried out by McGrath *et al.* (1990), following dry winters of 1986 and 1987. The presence/absence of *Ips* exit holes at breast height was recorded on each tree sampled. The percentage of trees with evidence of *Ips* presence was 0.4 per cent (live trees), 3.3 per cent (trees showing tip death) and 70.9 per cent (dead standing trees). A graph of the proportion of basal area in each plot infested by *Ips* plotted against the proportion of basal area showing drought stress symptoms (tip death or dead) clearly indicates that the proportion of trees infested with *Ips* does not exceed the proportion of the basal area showing drought stress symptoms. This relationship supports the widely held view that *Ips* is not generally a cause of crown dieback or death of pines.

The mechanism of the interaction between the adult beetle and the host tree was investigated by Witanachchi and Morgan (1981) in South Australia. Resistant trees prevent continued boring of beetles through the bark by exuding resin in the phloem. In contrast, susceptible trees do not respond (this also explains why felled logs or recently dead trees are readily infested). During drought, particularly on sites with shallow soils, on upper slopes and ridges and facing north-east (McGrath *et al.* 1990), presumably the resin defence system of trees is insufficient to repel *Ips*, as are subsequent hypersensitive reactions of host tissues (see Fernandes 1990).

CONTROL OF *IPS* 1952–1982

Early research evaluated the efficacy of insecticides such as BHC, DDT, Chlordane, Dieldrin, Aldrin and NaPCP (Pirrett *et al.* 1953). Strips of pinaster pine stands at Gnangara were sprayed in May 1953 to examine whether *Ips* beetles could be killed and if further attack could be prevented. A complementary study of logs sprayed with insecticide was also conducted. Both studies concluded in December 1953. Neither study was successful because of faulty experimental design and non-quantitative recording of infestation. However, the authors' impression was that the sprayed strips were less heavily infested than the untreated slash. They concluded:

> It appears abundantly clear that spraying other than of logs is impracticable and it would definitely be desirable to remove slash from the Plantation floor. It is realised that this is much too costly an operation, therefore the risk of a large reservoir of beetles in this slash turning to live trees on exhaustion of slash feeding stocks must be taken for the present. However, close watch should be kept, particularly on unthrifty trees and should attack occur, these and several other trees should be felled to attract the beetles and gradually reduce their numbers by exhaustion as is done in some parts of Europe.

These authors also suggested that trucks working unaffected plantations should not be allowed into affected plantation or timber yards or conversely, vehicles operating in infested areas should be kept out of unaffected plantations or thoroughly cleaned before entering them.

In 1957–58, a further experimental study was made

[1] P. Shedley, formerly of Forests Department and Department of Conservation and Land Management, Western Australia.

[2] F. D. Morgan, Department of Entomology, Waite Institute of Agricultural Research, Adelaide.

of protecting logs with insecticide (Rimes 1959). Such protection was not implemented in plantation management. About the same time it was realized that appropriate silvicultural techniques would minimize damage to plantations. Rimes (1959 and unpublished) recorded that *Ips* is not a primary pest of pines in Western Australia, i.e. healthy trees are not susceptible to attack, though if damaged by fire or other means entry could be made and reproduction could occur. Dead branches of healthy trees provide suitable breeding sites. The prompt removal of felled trees, within 12 to 24 hours, was recommended. Bark removal at the time of felling would make the log unattractive to *Ips*, but this was considered uneconomic. In practice, the policy adopted was to remove the logs from thinning within a few weeks in the summer and autumn months.

Curry reported that prescribed low intensity fire could kill *Ips* living in slash, but only where the bark was charred. Removal of slash was probably more effective in the long term as it removed the habitat required by *Ips*. Unfortunately, fire is of limited use as a silvicultural technique because of the sensitivity of pine trees to fire. The policy in Western Australia is generally to exclude fire from radiata pine plantations and surround them with fuel-reduced buffers. However, in pinaster pine plantations older than 20 years, fuel reduction is easily carried out, and appears to reduce *Ips* populations (McKinnell[1], personal communication).

The findings of the early 1970s showed that either the combination of a dry winter with the presence of recent prunings and thinnings on the plantation floor or of a dry winter with overstocked plantations resulted in heavy infestation of trees with *Ips*. The risk of drought and ensuing tree mortality is particularly great on shallow soils on steep, rocky slopes, shallow soils and on north-facing slopes.

Because *Ips* is active from September to May, pruning and thinning of stands during this period should ideally be avoided unless the slash can be promptly removed or mulched. Any non-commercial thinning should be restricted to the period April to August. Chemical thinning is not recommended, as it results in large numbers of dead standing trees which serve as suitable breeding habitats for *Ips*.

In summary, chemical insecticides are successful but are expensive and must be applied quickly after felling. Good silvicultural management (thinning followed by slash removal through burning or maceration) reduces the availability of breeding substrate for *Ips* and promotes healthy, vigorous trees (Neumann 1987; Morgan 1989). In Western Australia no burning is carried out in radiata pine plantations, and no maceration is carried out in pine plantations.

CONTROL OF *IPS* 1984–1990

Although the importance of thinning stands on schedule and the prompt disposal of slash is recognized as fundamental to the successful management of *Ips*, provision of biological control agents was thought to provide extra resource security (Morgan 1989). In 1981 he gained permission for the Waite Insititute of Agricultural Research to import several species of *Ips* parasitoid and predators for laboratory studies. The breeding in the laboratory of large numbers of these biocontrol agents for release was funded by the State forest services and private plantation owners. Laboratory studies showed, however, that one of these agents, the parasitoid *Roptrocerus xylophagorum*, rarely parasitized more than 5 per cent of the *Ips* population (Samson and Smibert 1986).

Roptrocerus was released under permit into several South Australian plantations in 1982, and was clearly established there by 1988 (Morgan 1989).

In Western Australia, the first releases of biocontrol agents (Table 4) took place at Gnangara in November 1984. In 1988 a prescription for release of predators and parasitoids of *Ips* in Western Australia was written, based largely on a field manual prepared by F.D. Morgan and S.A. Lawson in South Australia. Releases terminated in May 1990. *Roptrocerus* had clearly established in Gnangara by March 1985 when two adult *Roptrocerus* wasps emerged from caged billets. In 1988 *Roptrocerus* adults were detected in Gnangara and Ferndale plantations and also in a privately owned plantation (Loc. 8476) *c.* 2 km north of Dalgarup Brook between Greenbushes and Bridgetown (Morgan, personal communication). *Roptrocerus* had never been released in the latter two plantations. To provide extra genetic diversity, more *Roptrocerus* were introduced in 1989–90 (Tables 5, 6).

In May 1990 two U.S. entomologists, W. Berisford and D. Dahlsten, visited several release sites in Ferndale plantation. They found evidence only of *Roptrocerus* having established. Furthermore, studies of caged radiata pine billets collected from Ferndale (D2) and Pinjar (compartment 27) plantations have conclusively proven that only *Roptrocerus* has established. Billets were collected from recently thinned stands in May 1990 and caged until November 1990. *Roptrocerus* was found to have parasitized on average only about 5–6 per cent of the *Ips* population (Table 7), with considerable variation between the 19 caged samples evident.

ACKNOWLEDGEMENTS

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[1] Dr F. McKinnell, Department of Conservation and Land Mangement, Western Australia.

TABLE 4

Biocontrol agents released in Western Australian pine plantations 1984-1990.

SPECIES	ORDER	FAMILY	FUNCTION ROLE
Dendrosoter sulcatus Mues.	Hymenoptera	Braconidae	North American parasitoid of *Ips* larvae
Roptrocerus xylophagorum (Ratz.)	Hymenoptera	Pteromalidae	North American parasitoid of *Ips* larvae
Thanasimus dubius (Fab.)	Coleoptera	Cleridae	North American predator of *Ips* larvae and adults
Temnochila virescens (Fab.)	Coleoptera	Trogossitidae	North American predator of *Ips* larvae and adults

TABLE 5

Numbers of biocontrol agents sent to, and released in, Western Australia (adult males, females, larvae, eggs).

YEAR	*Dendrosoter*		*Roptrocerus*		*Thanasimus*				*Temnochila*			
	M	F	M	F	M	F	LARVAE	EGGS	M	F	LARVAE	EGGS
1984/5	120	329	194	325	150	150						
1987/8								60	60			
1988/9			153	1425			414		84	111	3620	500
1989/90	40	428	878	1223	137	150	8	3137	70	100	4	12005
TOTAL NO. SENT	169	757	1225	2973	287	300	422	3137	214	271	3624	12505
TOTAL NO. RELEASED	147	663	933	1985	139	146	414	2791	?	?	2020	48104

TABLE 6

Sites where biocontrol agents were released in Western Australia, together with dates of releases and numbers released.

SPECIES	RELEASE DATES	PLANTATION	NUMBERS RELEASED	
Dendrosoter	09.01.85 – 10.04.85	Gnangara	Adults	98M, 235F
	25.04.90 – 10.05.90	Ferndale D	"	49M, 428F
Roptrocerus	28.11.84 – 10.04.85	Gnangara	"	158M, 325F
	27.01.89	Ferndale C	"	38M, 500F
	08.04.89	Balingup	"	40M, 150F
	1989	Dalgarup	Not recorded	
	28.03.90	Ferndale B	Adults	55M, 94F
	20.04.90 – 03.05.90	Ferndale D	"	567M, 625F
Thanasimus	24.09.84 – 30.04.85	Gnangara	"	132M, 132F
	11.01.89	Ferndale C	Larvae	140 1st instar
	27.01.89 – 17.03.89	Southampton	"	274 " "
	10.01.90 – 25.04.90	Ferndale B	Eggs	3806
			Adults	5M, 6F
	28.03.90 – 03.05.90	Ferndale D	Eggs	785 1st Instar
			Adults	2M, 8F
Temnochila	21.12.88 – 08.04.89	Ferndale C	Larvae	1460 1st Instar
				100 mature
			Adults	69M, 91F
			Eggs	300
	1988	Pinjar	Adults	50M, 60F
	03.03.89	Balingup	Larvae	300 1st Instar
			Adults	10M, 20F
	17.03.89	Southampton	Larvae	160 1st Instar
	1989	Dalgarup	Eggs	Not recorded
	05.01.90 – 25.04.90	Ferndale B	Eggs	4068
		Ferndale D	Adults	7
			Eggs	442+

TABLE 7

Abundance of *Ips* beetles and *Roptrocerus* wasps emerging from caged billets of pine (U, M and L refer to billets taken from upper, middle or lower bole).

PLANTATION	SPECIES	TYPE AND NO. OF BILLETS PER CAGE	NO. *Ips* PER 10^3 cm² OF BARK	NO. *Roptrocerus* PER 10^3 cm² OF BARK	% PARASITIZATION
PINJAR	Pinaster	U4	89.8	7.5	8.4
		U7	27.3	1.9	7.0
		U7	89.8	8.3	9.2
		U8	27.7	1.3	4.7
		U7	28.6	2.1	7.3
		U6	25.9	2.9	11.2
		M4	55.6	1.3	2.3
		Means	43.2	3.2	6.3
FERNDALE	Radiata	U4	10.3	0	0
		U6	5.5	0.9	16.4
		U3	12.6	1.7	13.5
		U5	29.2	0.3	1.0
		U4	35.7	0.7	2.0
		U4	11.6	0.1	0.9
		U4	13.5	0.4	3.0
		U/M 5/1	10.7	1.6	15.0
		M5	9.4	0.1	1.1
		M3	14.6	0.6	4.1
		M3	18.[illegible]	0.4	2.2
		L2	7.4	0.2	2.7
		Means	14.9	0.6	5.2

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Growth of *Populus deltoides* and some related clones in the south-west of Western Australia

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ABSTRACT

In 1972, an unreplicated trial of seven selected clones of poplar, (*Populus deltoides* Bartr.ex Marsh and *Populus euramericana* (Dode) Guinier) was planted near Balingup in the south-west of Western Australia.

The trial aimed to demonstrate the growth performance and timber potential of the clones on a site previously used for grazing, and was considered to be excellent for timber growing in W.A. Clones planted were:

'I-214'
'I-154'
'I-488' (1-year-old sets)
'I-488' (2-year-old sets)
'G-48'
'Canberra'
'Bassendean'
'Angulata' planted 1973

Trees were planted at 5 m by 5 m spacing (400 stem ha^{-1}) in 1972 and were thinned to approximately 235 stems ha^{-1} in 1984 at 12 years. Final pruning was carried out at 11 years to a height averaging 9.8 m.

By age 19.2 years, 'I-488' (1-year-old set) produced the largest volume (136 m^3 ha^{-1}) in the pruned section of the tree and 'Angulata', the smallest (59 m^3 ha^{-1}). At this age, 'I-488' also attained the best height of 20 m and was ranked third in diameter (28.4 cm).

A visual assessment of tree form showed that the clones, 'G-48', 'I-488', 'Canberra', 'I-154' and 'I-214' had acceptable log straightness and therefore were utilizable for millable timber.

Milling of two logs from trees at 13.5 years gave recovery rates of 31 per cent of high grade timber (furniture and select).

Overall, the poplar clones that showed the most potential in terms of growth and log quality were 'I-488' and 'G-48'.

INTRODUCTION

World-wide, poplars (*Populus* spp.) have been grown extensively in plantations and as ornamental, amenity or shelterbelt plantings. They have been used to stabilize hillsides and river banks in New Zealand (Pryor 1969). Shelterbelts of poplars have been shown to increase productivity in beef cattle by 20 per cent because of higher protein and mineral levels when poplar leaves were used as fodder (Reid and Wilson 1985). Treeby (1978) also found that poplar leaves are a useful fodder crop supplement for livestock. In Australia, most poplar agroforestry has been aimed at combining wood production with grazing beef and dairy cattle (Reid and Wilson 1985). Timber from poplar is used for match splints or woodwool and skillets, pulp, peelers, furniture or general purpose sawlogs (Pryor 1969).

In 1972 an unreplicated demonstration trial was planted with seven clones of hybrid *P. deltoides* near Balingup in the south-west of Western Australia, with the aim of demonstrating the growth potential of commercial clones of *P. deltoides*.

METHODS

Establishment

The trial area was located on brownish fine sandy loams over yellowish-brown sandy loams at 50 to 60 cm depth, adjacent to the Balingup Brook. The site was ploughed prior to planting in 1972. Spacing was 5 m by 5 m (400 stems ha^{-1}) in a grid pattern of 7 by 7 trees (for most plots) in an area of 1.2 ha.

Clones planted were:

'I-214'
'I-154'
'I-488' (1-year-old sets)
'I-488' (2-year-old sets)
'G-48'
'Canberra'
'Bassendean'
'Angulata' (planted 1973)

The clones 'I-214', 'I-154' and 'I-488' are hybrids derived from crossing the two black poplar species, *Populus deltoides* and *P. nigra*. *P. deltoides* is native to northern America while *P. nigra* is from Europe. These clones are generally known as *P. 'euramericana'* (Pryor and Willing 1983) and have the International Poplar Commission registration numbers. The clone, 'Angulata', is *P. deltoides* subsp. *angulata*. 'G-48' is based on a seedling of *P.deltoides* from Texas (Pryor[1], personal communication) and was produced by the Federal Match Company in eastern Australia.

'Canberra' and 'Bassendean' are local Australian clones of unknown origin. All clones planted in the trial were deciduous.

Cutting material was obtained by the Seed Store of the then W.A. Forests Department, and the origin of the material is uncertain (Dalton[2], personal communication). The cutting material was set into nurseries at West Manjimup and Nannup prior to planting out in 1972 or 1973 as bare-rooted cuttings (barbatelles). Owing to poor initial survival in 1972, it was decided to replace a plot of 'I-488' (1-year-old sets) with 'Angulata' cuttings the following year. Another plot of 'I-488' (1-year-old sets) was retained and most other plots were also infilled in 1973.

Prior to replanting in 1973, the site was reploughed and an attempt was made to control weeds (wild oats, *Avena* spp.; kikuyu grass, *Pennistum clandestinum;* couch, *Cynodon dactylon;* and paspalum, *Paspalum dilatatum*) by boom spraying 'Vorox AA' (320 g L^{-1} amitrole and 320 g L^{-1} atrazine) at 9 kg ha^{-1}. However, only the western half of the plot was sprayed because the other was too wet for tractor access.

Fertilizing

Two months after infilling in 1973, all trees received a spot application of Agras 18:18 (17.5 per cent N, 7.6 per cent P, 600 ppm Zn, 16 per cent S) at 500 g/tree. The trial also received the following broadcast applications:

(1) age 11.8 years[3] (1983) - superphosphate (9.1 per cent P, 10.5 per cent S) at 100 kg ha^{-1}.

(2) age 13.2 years (1985) - Agran 34-0 (34 per cent N) at 440 kg ha^{-1}.

Further applications of fertilizer may have occurred because the area was leased for sheep grazing from 1978 to 1990.

Previous fertilizer history is unknown, however, the site probably received some fertilizer during its period as a grazing property.

Tending

Four months after planting in 1972, pruning of side branches was carried out to encourage a dominant leader and remove potential defects.

At 3.1 and 6.2 years, pruning to half tree height was carried out. Tree height at the latter age was 7 to 10 m.

At 11.1 years, trees were pruned to a 10 cm stem diameter, or to a point at which multi-leaders or malformations occurred. Epicormic shoots were also removed at this stage. A further pruning to 10 m occurred at 12.3 years using a 'Squirrel', a mobile hydraulic pruning platform, and epicormic shoots were again removed from the bole section. Pruning to 10 m was aimed at producing a high quality knot-free sawlog. Above this height, the tree was considered to be non-merchantable, owing to malformations, kinks, large branches or general crown development. To maintain the knot-free sawlog objective, it was necessary to remove epicormic shoots thereafter at 11.1, 12.3, 13.5, 14.5, 15.5 and 18.2 years. The 'Squirrel' was used in all instances, except at age 15.5 years when a 7.5 m polesaw was used.

Thinning was carried out at 12.8 years, reducing overall stocking by 27 per cent (see Table 1). Poplar stumps were sprayed with a 10 per cent solution of 'Roundup' herbicide (glyphosate 360 g L^{-1}) to prevent coppicing. *Eucalyptus rudis* regrowth was also felled at this time and stumps treated the same as those of poplars. Stocking rates before and after thinning are shown on Table 1, and survival percentage at this age is also presented.

Mensuration

In November 1978 (6.3 years) five trees were randomly selected within each plot, and total height and diameter at breast height over bark (d.b.h.o.b.) were measured. These parameters were measured again three years later at 9.3 years. Measurement plots were established in 1984 (12.3 years). Plots 1 to 6 and 9 were 24 m x 24 m (0.06 ha), Plot 7 was 19 m x 19 m (0.04 ha), and plot 8 was 22 m x 14 m (0.03 ha). Measurement plots had a one-row, one-tree buffer between plots. D.b.h.o.b. was measured at 12.3, 13.3, 15.2, 17.2 and 19.2 years and tree height was measured at 12.3, 15.2 and 19.2 years. Volume of the pruned section of trees was estimated at 19.2 years, using Smalian's method (Carron 1968) where d.b.h.o.b. was used as the butt measurement. Crown diameter over bark was measured at the top end of the pruned bole average height at 9.8 m.

Form Assessment

A visual assessment of tree form was carried out when the stand was 19.2 years old, to determine whether there were any differences between clones that would downgrade their commercial timber potential. Form was defined as the degree of straightness within: (a) Butt section – from ground level to 2.5 m height; and

[1] Emeritus Professor L. Pryor, C/- Australian National University, Canberra.

[2] Mr M Dalton, Department of CALM, Manjimup.

[3] Ages used in the text are based on initial plantings in 1972.

TABLE 1

Survival percentage and stocking rates before and after thinning of 12.8-year-old *P. deltoides* clones.

CLONE	OVERALL SURVIVAL (%) BY 12.8 YEARS	STOCKING (stems ha^{-1}) PRE-THIN	POST-THIN
I-488 (1-YEAR-OLD SETS)	96	382	260
I-488 (2-YEAR-OLD SETS)	84	330	243
BASSENDEAN	96	382	243
I-514 (1)[a]	74	295	243
I-514 (2)[a]	83	332	249
G-48	87	349	222
I-214	87	347	260
ANGULATA	87	347	243
CANBERRA	39	156	156
MEAN	81	324	235

[a] Replicates

(b) stem section – from 2.5 m to crown height. Trees had been pruned previously from 8 m to 11 m in height (as discussed in 'Tending').

The butt and stem sections were assessed on a 1 to 4 scale where: 1 = perfectly straight log section; 2 = slight – some minor log sweep or deviation; 3 = moderate – some kinks, stem sweep or malformation; 4 = severe – considerable number of kinks, some wobble or sweep and numerous malformations (including twist, bends, bumps). The amount of sweep or unacceptable stem malformation (based on visual appraisal) is directly related to sawlog potential of logs. Classes 1 and 2 would therefore produce ideal long length sawlogs, but class 3 would be confined to short length sawlogs. Most trees in Class 4 would be unmerchantable owing to unacceptable sweep or malformations.

Mill Study

Two 2.6 m logs from 13.5-year-old trees from 'I-488' (plot 9) were sent to the Department's Wood Utilization Research Centre at Harvey for a sawmill study. Small end diameter under bark was 17 and 18 cm and large end diameter under bark was 19 and 22 cm respectively.

The logs were cut 'heart-in' using the twin edger, band-saw and circular re-saw into 25 mm thick boards with 75 mm, 100 mm or 120 mm width. Following cutting, the boards were placed in a low temperature tunnel kiln and dried at ambient temperatures for 11 weeks to below fibre saturation point. Following initial pre-drying, the boards were combined with a regrowth jarrah (***Eucalyptus marginata***) bundle and seasoned to equilibrium moisture content in the laboratory high temperature kiln using a conventional drying schedule. Board bow and spring were measured after sawing, after tunnel kiln drying and after high temperature kiln drying. The boards were graded using the Western Australian Industry Standard for furniture timber (Forest Products Association(W.A.))1985 and Australian Standard 2796 – 1985 (Standards Association of Australia 1985).

Analysis

D.b.h.o.b. and tree height data were analysed using analysis of variance, and comparisons between clones were made using least significant differences (L.S.D.). Analysis of these parameters was done on a single tree basis owing to the lack of replication of clones and the fact that the data were normally distributed. The basal area per ha data were not analysed owing to lack of replication.

RESULTS AND DISCUSSION

By 6.3 years diameter growth trends of 'I-48 8' (both sets), 'Bassendean' and 'I-514'(Plot 5) clones were better than others, averaging 12.6 to 11.1 cm (Table 2). This trend also continued to 9.3 years. The best diameter increment over this period was achieved by 'I-488' (1-year-old set)(6.7 cm).

Height growth trends were also similar by 9.3 years with 'I-488' (1-year-old set) (13.8 m), 'I-488'(2-year-old set) (13.2 m) and 'Bassendean' (12.0 m).

By 12.3 years, the mean diameters of 'G-48','I-488' (both plots, 'I-154' (Plot 5) and 'Bassendean' were significantly larger ($P<0.05$) than other clones (Table 3). This diameter trend continued at 15.2 years except that 'Canberra' and the above clones were significantly larger ($P<0.05$) than 'I-154', 'I-214' and 'Angulata'. By 19.2 years, the mean diameters of 'Canberra', 'G-48', 'I-488' (both plots), 'I-154' (Plot 5) clones were significantly larger ($P<0.05$) than 'I-154' (Plot 7), 'I-214' and 'Angulata' clones (Table 3). At this age (19.2 years), 'Canberra' had the largest mean diameter at 29.9 cm, and 'Angulata' the smallest at 21.3 cm. Basal area trends also followed this growth pattern over the same period (12.2 to 19.2 years) (Table 4).

The basal area mean annual increment (M.A.I.) of 'I-488' (1-year-old set) at 19.3 years was the best clone with 0.89 m^2 ha^{-1} per year and 'Angulata' the worst with 0.45 m^2 ha^{-1} per year. Although the tree stocking was low (156 stems ha^{-1}) for the 'Canberra' clone, compared with others, its basal area increment at 19.3 years was similar to 'I-488'(2-year-old set), 'Bassendean', 'I-214' and 'I-514'(one replicate).

Tree height of 'I-488' (1-year-old set) at 19.2 years was significantly larger ($P<0.05$) than 'Canberra',

TABLE 2

D.b.h.o.b. and height of *P. deltoides* increments from 6.3 and 9.3-years-old (based on 5 trees per plot).

CLONE	D.B.H.O.B. (cm)			HEIGHT (m)		
	6.3YRS	9.3YRS	INCREMENT	6.3YRS	9.3YRS	INCREMENT
I-488 (1-YEAR-OLD SETS)	11.1	17.8	6.7	9.3	13.8	4.5
I-488 (2-YEAR-OLD SETS)	12.6	18.2	5.6	9.9	13.2	3.3
BASSENDEAN	11.8	16.4	4.6	9.1	12.0	2.9
I-154[a]	11.5	16.7	5.2	8.0	11.8	3.8
CANBERRA	9.2	15.3	6.1	7.6	11.7	4.1
G-48	9.8	15.0	5.2	8.1	11.5	3.4
I-214	8.9	13.9	5.0	6.8	10.8	4.0
ANGULATA	8.8	12.6	3.8	7.1	10.8	3.7
I-154[a]	9.0	13.3	4.3	7.0	9.9	2.9

[a] Replicates

TABLE 3

Tree D.b.h.o.b. increments of *P. deltoides* clones from 12.3, 15.2 and 19.2 years (based on plots).

CLONE	D.B.H.O.B. (cm)[a] AGE (YRS)[b]			INCREMENT (cm)	
	12.3	15.2	19.2	1ST	2ND
CANBERRA	18.3AB	23.0A	29.9A	4.7	6.9
G-48	19.7A	24.0A	28.6A	4.3	4.6
I-488 (1-YEAR-OLD SET)	20.0A	24.1A	28.4A	4.1	4.3
I-154[c]	18.8A	22.1A	27.3A	3.3	5.2
I-488 (2-YEAR-OLD SET)	19.6A	23.5A	26.8A	3.9	3.3
BASSENDEAN	19.7A	22.7A	26.0A	3.0	3.3
I-154[c]	15.5BC	19.3B	22.9B	3.8	3.6
I-214	15.8BC	19.0B	22.5C	3.2	3.5
ANGULATA	15.3C	18.3B	21.3C	3.0	3.0

[a] Common capital letters indicate non-significant differences at P<0.05 level. [b] Since initial planting in 1972. [c] Replicates.

'Bassendean', 'I-154' (both plots), 'Angulata' and 'I-214'. 'Angulata' tree height was significantly larger (P<0.05) than 'I-214' and 'I-154' (Plot 7). By 19.2 years, 'I-488' (1-year-old set) attained the largest mean height at 20.1 m and 'I-154' the smallest mean height of 15.4 m (Table 5).

The clone 'I-488' (1-year-old set) produced the largest over bark volume (135.9 m^3 ha^{-1}) in the pruned section of the tree and 'Angulata' the smallest (59.1 m^3 ha^{-1}) by 19.2 years (Table 6).

Assessment of external form characteristics showed that for the butt sections, of clones 'G-48', 'I-488' (both sets)','Canberra' and 'I-154' (both reps) all trees were in the straight and slightly affected classes (Table 7).

TABLE 4

Basal area increments, M.A.I. and stocking of *P. deltoides* clones from 12.3 to 15.2 and 19.2 years.

CLONE	BASAL AREA (m^2 ha^{-1}) AGE (YRS)			INCREMENT		M.A.I. (19.2 YRS)	TREE STOCKING (19.2 YRS)	
	12.3	15.2	19.2	1ST	2ND	(m^2 ha^{-1}/yr)	PER HECTARE	PER PLOT
I-488 (1-YEAR-OLD SET)	8.6	12.3	17.1	3.7	4.8	0.89	260	15
I-154[a]	6.9	10.4	14.4	3.5	4.0	0.75	243	14
G-48	6.8	10.1	14.2	3.3	4.1	0.74	222	7
I-488 (2-YEAR-OLD SET)	7.5	10.7	13.9	3.2	3.2	0.72	243	14
BASSENDEAN	7.6	10.0	13.2	2.4	3.2	0.69	243	14
I-214	5.3	7.7	10.8	2.4	3.1	0.56	260	15
I-154[a]	5.0	7.6	10.8	2.6	3.2	0.56	249	9
CANBERRA	4.5	7.6	10.8	3.1	3.2	0.56	156	9
ANGULATA	4.5	6.4	8.7	1.9	2.3	0.45	243	14

[a] Replicates

TABLE 5

Tree height of *P. deltoides* clones at 12.3,15.2 and 19.2 years.

CLONE	PLOT NO.	HEIGHT (m)[a]		
		12.3 YRS	15.2 YRS	19.2 YRS
I-488	1	14.2A	17.5AB	20.1A
G-48	8	14.3ABC	18.1A	19.7AB
I-488	9	13.7A	17.4AB	19.6AB
BASSENDEAN	3	14.3AB	16.7ABC	18.7B
I-154	5	13.5ABCD	16.1CD	18.6B
CANBERRA	6	13.0BCD	16.2BCD	18.6B
ANGULATA	2	12.8CD	14.9DE	16.9C
I-214	4	11.6DE	14.2E	15.5D
I-154	7	10.1E	14.1E	15.4D

[a] Common capital letters indicate non-significant differences at $p<0.05$ level.

However, 57 per cent of the butt sections of 'Angulata' trees were in the moderate and severely affected class. The percentage of trees in the stem section of the following clones were in the straight and slightly affected classes: 'G-48' (100 per cent), 'I-488' (2-year-old set) (93 per cent), 'I-488' (1-year-old set) (80 per cent) and 'I-214' (93 per cent).

Green sawn recoveries for the two logs milled were 59.2 and 56.6 per cent respectively. The graded recovery rates of board grades in the study were: Furniture, 30 per cent; Select, 1 per cent; Standard, 30 per cent; Utility, 29 per cent. Reasons for downgrading of boards included the following faults:

Grade	faults in board
Select	heart and knots
Standard	heart and knots, sapwood and wane
Utility	heart and knots, wane, undersize

In terms of diameter growth by 19.2 years (Table 3), 'I-488', 'Canberra', 'I-154', 'G-48' grew significantly larger than other clones, ranging from 26.80 cm ('I-488' Plot 1) to 29.90 cm ('Canberra'). The 'I-488' (Plot 1) clone also grew the tallest, reaching a height of 20.1 m. By contrast, 'I-488' (Plot 9) clone produced the largest over bark volume in the pruned section (136 m^3 ha^{-1}), followed by the same clone (Plot 1) which produced 117 m^3 ha^{-1}.

Although the analysis of diameter and height showed significant differences between the clones, this is probably an unfair estimate on the performance of them due to lack of replication, low numbers of trees analysed (Table 4), and site variation.

Based on external characteristics (within the butt section of the tree), all clones had greater than 86 per cent of utilizable timber, except for 'Angulata' which had only 43 per cent of the butt log utilizable (form rating 1 and 2). Within the pruned stem section of the tree, 'Angulata' and 'Bassendean' were considered to have unacceptable sweep with 50 per cent and 64 per cent respectively.

TABLE 6

Overbark volumes[a] (m^3 ha^{-1}) of pruned log sections and pruned bole lengths of 19.2-year-old *P. deltoides* clones.

	PLOT NO.	VOLUME (pruned log) (m^3)	(m^3 ha^{-1})	STOCKING[a] (stems ha^{-1})	M.A.I. PRUNED LOG (m^3 ha^{-1} yr^{-1})	PRUNED BOLE LENGTH (m)
I-488	9	7.83	135.8	260	7.04	11.0
I-488	1	6.76	117.39	243	6.08	11.0
G-48	8	3.37	107.09	222	5.65	9.8
I-154	5	5.90	102.36	243	5.30	10.0
BASSENDEAN	3	5.35	92.95	243	4.82	9.6
CANBERRA	6	4.61	80.02	156	4.15	10.0
I-214	4	4.26	73.99	260	3.13	8.1
I-154	7	2.63	72.77	209	3.77	9.3
ANGULATA	2	3.41	59.13	243	3.06	9.7

[a] Volumes calculated by Smalian's method.

TABLE 7

Stem form within butt and stem sections of 19.2-year-old *P. deltoides* clones.

CLONE	FORM CLASS[a] P/N	BUTT SECTION % OF TREES 1	2	3	4	STEM SECTION % OF TREE 1	2	3	4	NO. OF STEMS ASSESSED
G-48	8	71	29			57	43			7
I-488	1	93	7			33	60	7		15
I-214	4	13	73	7	7	33	60	7		15
I-488	9	87	13			33	47	13	7	14
CANBERRA	6	56	44				67	22	11	9
I-154	7	44	56				67	11	22	9
I-154	5	64	36			7	57	22	14	14
ANGULATA	2	7	36	36	21		50	29	21	14
BASSENDEAN	3	29	64		7		36	57	7	14

[a] Form Class: Butt section – ground level to 2.5 m } Pruned
Stem section – 2.5 metres to crown (10 m) } Log

1 = perfectly straight log section.
2 = slight – some minor log sweep or malformation.
3 = moderate – some kinks, stem wobble or malformation.
4 = severe – considerable number of kinks, stem wobble or sweep, or numerous malformations.

Utilization of the two clones would therefore be limited to short, rather than long log sections owing to downgrade.

Overall, the 'I-488' clone produced the best growth and potential of all clones tested. Pruned volumes from trees in the 2 plots were 136 (Plot 9) and 117 m³ ha⁻¹. The 'I-488' clone also had some moderate and severe stem sweep or malformations, which was mostly the result of the earlier removal of part of a fork during pruning.

The fact that the 'Canberra' clone grew best in terms of diameter is probably the result of the low stocking of the plot, which had been growing at 156 stems ha⁻¹ from an early age following poor initial survival. Basal area by 19.2 years was low at 10.8 m² ha⁻¹. Its volume production by this age was average, attaining 80 m³ ha⁻¹ within the pruned section. The butt section was fully utilizable, while the stem section was 67 per cent utilizable, based on external visual assessment.

The two plots of the 'I-154' clone had similar tree form but growth parameters varied. This was probably owing to site variation between the plots and the heights reflect this: Plot 5 was 18.6 m by 19.2 years, whereas Plot 7 was significantly lower ($P<0.05$) at 15.4 m. Only 9 trees were measured in Plot 7 compared with 14 in Plot 5.

The 'G-48' clone produced one of the best volumes (107 m³ ha⁻¹) and had 100 per cent utilizable timber in the butt and stem sections of the pruned bole. The stocking rate of 222 stems ha⁻¹ for the 'G-48' plot is deceiving, however, as there were only seven trees measured, owing to small plot size. This is probably too low to fairly assess the potential of the clone. By 19.2 years, this clone ranked third in basal area (14.2 m² ha⁻¹) and second in d.b.h.o.b. (28.6 cm).

As well as demonstrating poor tree form, 'Angulata' grew the slowest, and by 19.2 years had produced a volume in the pruned section of 59 m³ ha⁻¹, and grown to a height of 16.9 m. Basal area was the lowest of the clones tested at 8.7 m² ha⁻¹.

Although 'I-214' demonstrated slower diameter and height growth than most other clones except 'Angulata', it has potential for commercial timber production as it has straight butt and stem sections. By 19.2 years, it had grown to 15.6 m and produced a volume of 74 m³ ha⁻¹ in the pruned section.

Epicormic shoots have been a constant problem over the life of the trial and constituted the largest tending expense. As one of the objectives of the trial was to produce a knot-free log section to 10 m, shoots were removed at 11.1, 12.3, 13.5, 14.5, 15.5 and 18.2 years. Attempts were made to vary the seasonal timing of pruning to reduce epicormic development, but this had no effect. It is possible that previous pruning operations damaged cambial tissue which led to shoot development. However, at age 19 years, it was observed that epicormic shoots and buds were developing from areas of the bark that had not previously been disturbed by pruning. This indicates that the clones tested are highly vulnerable to the production of epicormics when subjected to heavy pruning (to 10 m).

Sun scorch caused some damage to trees in the 'I-214' and 'I-514' plots. This may reflect the poorer growth rates of these clones compared with others. Sun scorch occurred only on the western side of the butt section of affected stems, and these two plots were located on the western side of the trial, adjacent to an open paddock. This damage to the butts made them non-merchantable for timber use.

Timber utilized from the mill study can be used for panelling or furniture. The major reasons for downgrading the boards to a lower grade were: heart wood, knots, amount of sapwood, wane and undersizing. Other log defects were small bumps and some rot associated with the bumps. All bow and spring measurements were within the specified limits in the grading standards (Forest Products Association (WA) 1985; Standards Association of Australia 1985). Green sawn recovery rates for the two logs were 59.2 per cent and 56.6 per cent respectively, and the study showed that good sawlog recoveries and useful utilization of boards can be produced by a thinning at 13 years. However, the timber would not have much potential for structural uses because of its low strength properties (Bootle 1983).

In summary, *Populus deltoides* clones that showed most potential in this trial were 'I-488' and 'G-48'. Better growth rates would be expected from regular applications of fertilizer, and perhaps irrigation. Pryor (1969) reported that good growth rates have been achieved in Chile and South Africa by flood irrigation or irrigation by town sewerage. Similar sites without irrigation produced approximately one quarter of the volume. The best sites in South Africa can reach 29.4 m³ ha⁻¹ M.A.I. over 20 years. The trial site, which has an annual rainfall of 950 mm, is considered to be excellent for tree growing in Western Australia. The site also dries out over the summer months and this may have inhibited poplar growth to some extent. I would suggest that better overall growth rates could have been achieved in the trial if summer irrigation were present, or that a better moisture relationship had occurred during the drier months. The soils were brownish fine sandy loams over yellowish-brown sandy loams at 50 to 60 cm depth. Pryor and Willing (1983) believe that good growth rates can be achieved on light textured soils where irrigation or rainfall from 750 mm to 1000 mm per annum is present. They also indicate that poplars grow best on moist, fertile agricultural grade land which is generally associated with alluvial soils on river systems. These sites, which attract premium land prices and are generally used for horticultural or orchard production, are limited in area in Western Australia.

In recent years, tree improvement programs have led to a wider range of poplar clones showing superior qualities of tree growth, stem and branch form and increased resistance to poplar rust (*Melampsora medusae* and *M. larici-populina*). The clones 'I-488', 'I-154', 'G-48' and 'Angulata' are extremely sensitive to

Melampsora (Pryor and Willing 1983). This may limit their potential in W.A. In fact, some of these clones have been withdrawn from cultivation in eastern Australia (Pryor and Willing 1983) because of this.

Shivas (1989) reported *Melampsora larici-populina* in W.A. in 1974 and also recorded a case of yellow leaf blister (*Taphrina populina*) at Dale River in 1982. There is little other evidence of poplar rust in W.A., but we should be cautious about large-scale plantings of these clones here.

Further testing of newer, improved clones could be tried on a range of suitable soil types and rainfall zones in the south-west of Western Australia. Trial plantings could be incorporated with systems associated with sewerage or irrigation dispersal and (as previously discussed) growth rates would be greatly improved. Recent local interest may justify these trials.

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Provenance comparisons of *Pinus pinaster* Ait. in Western Australia

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SUMMARY

Results from field trials established during the period 1964 to 1974, support earlier research in confirming that Leiria, in Portugal, is the most vigorous provenance of *Pinus pinaster* when grown under Western Australian conditions. Relative to other provenances tested, it also has superior drought resistance but low resistance to frost.

The Corsican race has outstanding qualities in stem straightness and apical dominance. Differences between provenances in branch angle and branch size were not as significant as expected. Selection within the Leirian provenance, or any provenance, is probably the best procedure for improving branching in the species.

Leirian populations are very defective in apical dominance and a high percentage of trees exhibit forks or ramicorns. Improvement in this character with selection in Leirian populations has been limited. Inter-provenance crossings with the Corsican origin may have to be considered in future but current results indicate that such a cross would lead to significant losses in volume production.

Fecundity varies with provenance from high production of cones within four years of planting for trees of Tunisian origin to a general sparseness of cones throughout the life of Corsican trees. In Western Australia, Leirian trees produced cones at a younger age than those from Landes or Corsica. Genetic control of time of flowering was confirmed. Flowers in trees of Leirian origin ripened earliest, followed by flowering in the French Landes, Tunisian, Italian and Corsican provenances, in sequence as spring proceeded. A wide variation in flowering time was shown for clones within any one geographic group.

Limited comparisons of wood properties between provenances indicated that the Leirian provenance, with relatively high basic density and low grain deviation, was the best suited for production of sawn timber. Therefore, breeding with this provenance would not compromise the future quality of the wood produced.

Trials with inter-provenance crosses between plus trees of Leirian, Landes and Corsican origin demonstrated the inheritance and dominance of such racial characters as vigour in the Leirian and stem straightness and apical dominance in the Corsican provenance. Crosses between Landes and Leiria may provide a hybrid of vigour approaching that of Leirian trees. Similarly, the combination of straightness and apical dominance was achieved in Leiria by Corsican crosses but vigour was low.

Over the range of sites tested in Western Australia for provenance variation, crosses between clones of the Leirian provenance were significantly superior in diameter and height growth to those of Leiria by Landes and Leiria by Corsica. There was, however, a tendency for the advantage in diameter growth of the Leirian provenance to decrease as plantings were extended to the south where conditions were cooler and wetter.

Geographic similarity and the distinctiveness of provenances were clearly demonstrated by canonical discriminant analysis of attributes measured in the trials. Improvement appears to be obtainable by concentrating on the Landes provenance for cooler, frost-prone areas and on the Leirian provenance for warmer and drought-prone sites.

For Western Australia, all improvement required within the range of variation of the species is being obtained from selection and crossing within the Leirian population.

THE PROBLEM AND APPROACH

This paper reviews the knowledge of variation in *Pinus pinaster* Ait. of value to the commercial future of the species in Western Australia and presents previously unreported results from field trials begun in the period 1964–1967. The objective is to document these local investigations and indicate areas which could be of importance to the local improvement program for the species.

The presentation is in four sections. The first section introduces the history of the species in Western Australia, outlines the nature of investigations and provides a brief literature review of racial variation in the species. The second section describes eleven field trials and is intended for only those concerned with the details of *P. pinaster* provenance testing. Differences in flowering time and fruitfulness of several provenances considered in the local crossing program are covered briefly in a third section. The final section considers the relevance of provenance variation to tree improvement in the State and the validity of the investigation.

Introduction

Pinus pinaster, the maritime pine (also formerly known as cluster pine), and its varied forms have been of interest to forestry in the south-west corner of Western Australia since early colonial days. European colonizers of the similar climatic provinces in both South Africa and south-west Australia noted the paucity of natural softwoods for the local economy, and extensive tracts of low quality forest on sandy soils, and treeless areas. Outstanding examples of afforestation on similar sands and in similar climates in Gascony, France, during the period 1787 to 1864 (Harle 1920; Guinaudeau 1964) were conducive to early afforestation attempts in Cape Province (Duff 1928) and later, in Western Australia.

The relevance of *P. pinaster*, and the possible significance of its geographic variation, to forestry in Western Australia was assessed in 1916. Hutchins, a forester with experience in India, South Africa and East Africa and professional training in Europe was invited to comment on the forestry situation in the State. He reported (Hutchins 1916)

> 'The climate of the Western Australian jarrah forest is sufficiently similar to southern France but more favourable to cluster pine (*Pinus pinaster*). It is in fact the exact climate of Leiria in Portugal, where I saw cluster pine at its best...'.

Hutchins took pains to distinguish between the different growth forms of the species in France and Portugal and recommended the use of seed from the forest of Leiria in Portugal.

Variation in this species and the importance of seed origin to its forestry potential in the southern hemisphere was first described by Duff (1928) and elaborated, from experience with field trials in South Africa, by Rycroft and Wicht (1947). Duff's report of the species in both its natural range and in the developing plantations in South Africa was well received in Western Australia. Reports of expressions of racial differences in the species observed in local plantation trials were published by Perry (1940, 1949). Quantitative evidence for early provenance evaluations in the State was collated by Hopkins (1960) who also argued the value of a tree improvement program based on Portuguese seed.

Figure 1. Representative samples of the Leirian (left) and Landes (right) provenances at age 21 years in trial YS08, Gnangara plantation.

Research in evaluating the status of geographic races and provenance variation for *P. pinaster* (Figs 1 and 2) has been carried out at various locations in both the northern and southern hemispheres (Destremau *et al.* 1982). Major aspects of geographic variation in the species are now well understood. In France and Western Australia in particular, knowledge of variation and heritability of characters is being used to improve the plantation tree in such attributes as volume production, stem straightness, branch angle and size, drought tolerance, frost resistance, and wood density, fibre length, grain deviation and resin content.

Geographic Races

The most recent and comprehensive article reviewing provenance variation in *P. pinaster* is by Destremau *et al.* (1982). They associated variation within the species with dispersion and isolation following past changes of climate. During the Quaternary period the distribution of the species in western and southern Europe, under glaciation, was discrete within mid-elevations on the continental massif. As a result of geographic barriers, isolated populations tended to develop differences in characteristics. Remnants of the original domain of the

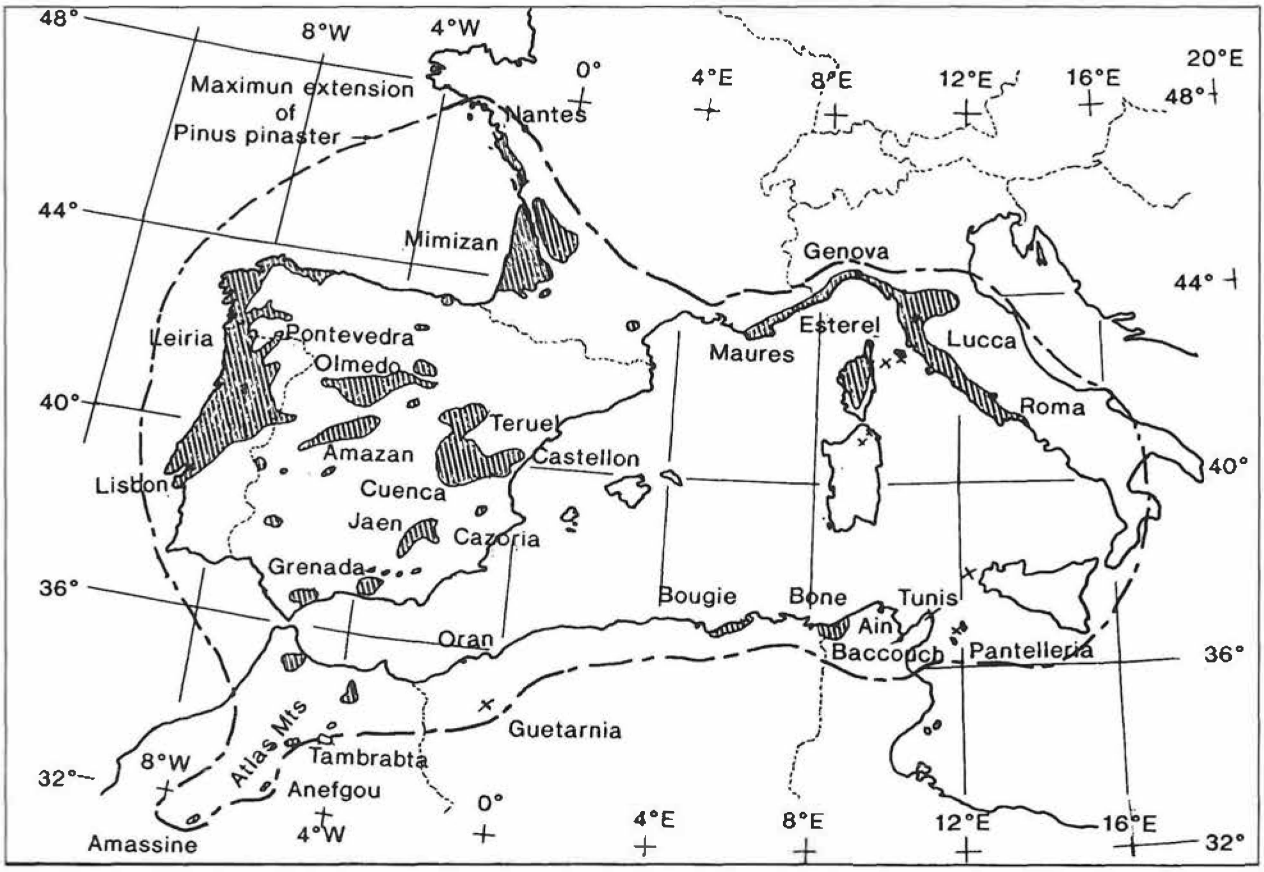


Figure 2. Map showing the natural distribution of Pinus pinaster. *The shaded sections and crosses mark the concentrations of the species (After Destremau* et al. *1982).*

pine in the western Mediterranean area are on the massifs of Maures, Esterel, Corsica, Sardinia, Edough, Ain Draham, Rif, Grand Atlas, Sierra Nevada, the Iberian mountains, the piedmont of the Pyrenees and the sandy coastal plains along the Atlantic (Fig. 2).

Some authorities believe that maritime pine also occurred naturally on islands of the Adriatic sea along the Yugoslav coast and down to Greece. Recent indications are, however, that all maritime pine present in Yugoslavia was introduced within recent historical times.

Destremau *et al.* (1982) suggested that the centre of dissemination of the species was the mid-altitudinal areas of the Iberian Peninsula, at the junction of the Mediterranean and Atlantic climatic currents. According to palaeo-botanical studies, colonization of the lower Gascogne plains was accomplished recently either from mountain refuges of Galicia or from isolated sites in Catalogne. For palynologists there is little doubt that the Gascogne extension can only be dated to the recent post-glaciation period.

Destremau *et al.* (1982) agreed with Resch (1974) that the species consists of five major races geographically separated by physical barriers or sharply contrasting microclimates. These races are:

1. The Atlantic group, which occupies the coastal plains and seaboard of the Atlantic Ocean from south of Lisbon in Portugal to the mouth of the river Loire (Nantes) in France.
2. The provincial Mediterranean group, which is localized to the coastal sites along the northern coast of the Mediterranean Sea from Tarragona in Spain to Tivoli, just east of Rome, in Italy.
3. The Corsican group, restricted to the islands of Corsica and Sardinia.
4. The Continental group, of the Iberian mountain regions, to which are attributed a large variety of Spanish, Moroccan and Portuguese ecotypes. These ecotypes occupy very special ecological niches which are the local provenances of the divides of the natural surfaces of the quaternary glacial periods.
5. The North African coastal group, restricted to coastal areas from Bougie in Algeria to Pantelleria off north eastern Tunisia.

The grouping is based on consistent expressions of tree vigour and phenotypic appearance recorded by many observers and detailed comparative trials (Duff 1928; Rycroft and Wicht 1947; Perry 1949; Hopkins 1960; Sweet and Thulin 1962; Illy 1966; Rodriguez 1966; Resch 1974; Alazard 1982; Matziris 1982). Recently, effective replication of provenances within trials and comparisons of a wide range of provenances and controlled crosses (Alazard 1982) have provided quantitative results which relate to genetic control of racial attributes.

Bernard-Dagan *et al.* (1971) have provided a consistent identification procedure for genetic separation of provenances on the basis of monoterpene contents of the wood and cortical tissues of mature trees. Their studies and recent work (Baradat *et al.* 1979) have identified distinctive chemical compositions for the racial groupings 1, 2, 3 and 4 described above but did not sample Italian (group 2) and the north African (group 5) provenances. They were also able to distinguish clearly between Portuguese and Landes provenances on the basis of the amount of D3-carene contained in the cortical tissues.

Perry (1949) differentiated between Portuguese and Landes groups on the basis of genetic control of flowering times and Destremau *et al.* (1982) also recorded these differences in flowering times for comparative conditions in Europe.

Evaluation in Western Australia

Early plantings of *P. pinaster* in Western Australia clearly demonstrated the superiority of trees derived from the forests of Leiria, in Portugal, for commercial plantations (Perry 1940; Hopkins 1960). Since 1942 all Western Australian plantations have had a Portuguese seed origin.

A genetic improvement program for *P. pinaster* in Western Australia was begun in 1957 (Hopkins 1960; Perry and Hopkins 1967; Hopkins 1969; Hopkins and Butcher 1993). The program concentrated on the Portuguese provenance with the aim of improving stem straightness, branching characteristics and uniformity of the commercial tree. Renewed interest in other provenances was also focused on quantitative aspects of provenance testing and species variation, as no statistically controlled trial or useful gene bank for the species was available in Australia. The possible contribution of genes from other provenances to improvement in stem straightness, hybrid vigour, branch size, spiral grain, wood density and drought resistance required consideration.

A series of provenance tests and inter-provenance crossings was undertaken during the early phase of the *P. pinaster* breeding program (Fig. 3). This compared growth under a range of conditions in the field and evaluated wood properties. Wherever possible the trials included seed from trees of superior phenotype (plus-trees), selected by international agencies. Seedling studies of provenances were used to evaluate drought resistance (Hopkins 1971b).

Details of the time of flower receptivity for three provenances were recorded as part of the controlled pollination phase of the species improvement program.

Comparisons of major wood properties of provenances, from trees sampled in Western Australia or Portugal, were carried out in arrangement with the Commonwealth Scientific and Industrial Research Organisation (Nicholls *et al.* 1963; Nicholls 1967; Nicholls 1968).

The original trial nomenclature has been used in this report because it is relevant to the local workers in the field. The original designation for Portuguese (Leirian provenance) plus-trees of E (elite) followed by a number has been retained. Similarly, plus-trees of Landes origin are designated with an L and those of Corsican origin with a C.

FIELD TRIALS

Introduction

This chapter describes in detail the procedure and results of eleven field trials established from 1964 to 1967 to demonstrate the performance of provenance groups under a range of field conditions (Table 1). Four of these trials (3/65, XS09, XS12, XR1) were designed to show differences between bulked collections of major provenance groups. The remaining seven included half-sib (open pollinated) or full-sib (control pollinated) material, particularly of Portuguese and French origins which are most favourable to Western Australian conditions, to demonstrate the range of variation within these two provenances. They were also intended to provide material in which future selection for controlled crossing might be undertaken. Three of these seven trials included inter-provenance crossings together with improved stock from a recently established seed orchard to indicate the potential of hybrids within the improvement program.

Field trials were replicated in either Latin Square or randomized block designs. Most were established with seedlings raised in tubes to obtain high survival on planting out and remove effects of nursery treatment and refilling from the results. The initial trials with bulked provenance groups employed square plots of 36 or more plants as the unit of comparison. Later trials with half-sib or full-sib families and tubed stock used line plots with 5 or 10 trees, but with increased replication.

In all trials a commercial seed batch imported from the Portuguese forests of Leiria for general plantation establishment, was included. This is referred to as the routine seed batch and provided a control to link provenance comparisons between trials.

Assessments for characteristics of form were on the basis of standard scores as depicted in Table 2. Results were expressed either as the percentage of stems in the population with average or better stem straightness (i.e. percentage in classes 1, 2, 3) or the mean score (arithmetic mean of points awarded). The percentage of population is more acceptable to field workers as a stand parameter and is used here. For analysis all percentages were transformed to angle arcsin (the angle whose sine is the square root of the percentage).

The trials were conducted over the period 1964–1985. With over 20 years elapsed since the last trial was established results are conclusive and can be confidently interpreted to apply to mature stands.

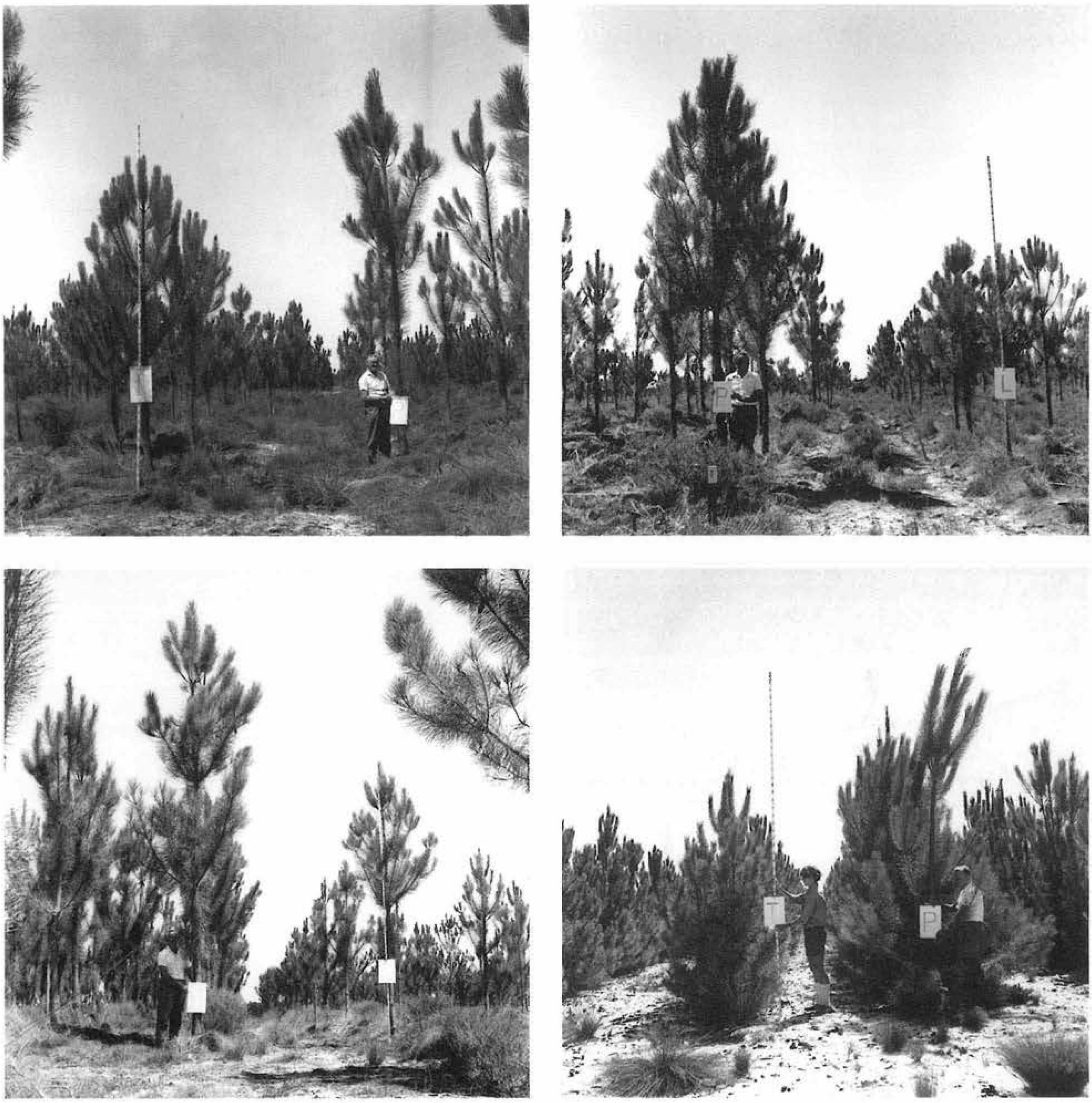


Figure 3. Early growth of provenances at Gnangara plantation. The comparisons are Italian-Portuguese (top left), Portuguese-Landes (top right), Portuguese-Corsican (bottom left), and Tunisian-Portuguese (bottom right). The first three comparisons are in trial 3/65 at age 5 years; the fourth is in trial XS09 at age 4 years.

General Comparisons

Trial 3/65 – Comparison of Commercial Seed Lots from Portugal, France, Corsica and Italy

Establishment

Trial 3/65 was established in 1964 with seedlings from five bulk provenance seed lots to statistically evaluate differences between the growth of provenances in Western Australia. Earlier trials had suffered from lack of replication within sites and from thinning. A fire in the main demonstration area in compartment 19, at Gnangara plantation further limited the use of existing plots.

Provenances – The five bulked seed lots were from Portugal (Leiria), France, Corsica, and Italy as follows:

Leiria R. Seed lot number S2866. One kilogram was received from Portugal in 1962, reputed to be collected from the Forest of Leiria.

Leiria 2. Source unknown. Mistakenly used as the provenance from Lucca (Italy). Probably part of the commercial Leiria batch used for plantation establishment in 1964.

TABLE 1

Description and location of *Pinus pinaster* provenance tests established in Western Australia since 1960.

TRIAL NO.	LOCATION	YEAR PLANTED	PROVENANCE					REPLICATION	MEASUREMENT			
			LEIRIA	LANDES	CORSICAN	TUNISIAN	OTHER	TREES/PLOT IN BRACKETS	HT.	DIAM.	FORM	DROUGHT
3/65	Gnangara	1964	2 B	1 B	1 B		Italian 1 B	(128) x 5	1969 1973 1975 1977 1985	 1973 1975 1977 1985	1969 1975	
XS09	Gnangara	1966	1 FS 1 B 12 HS			24 HS	Spanish 2 B	(10) x 8	1970 1976	 1976		
XS11	Gnangara	1967	4 FS 1 B	14 HS				(10) x 10	1971 1976	1976		1977
XS12	Yanchep	1967	2 FS 1 B 1 HS	2 HS	4 B			(36) x 5	1971 1975 1977 1987	 1975 1977 1987	 1975	 1977
YS08	Gnangara	1967	14 FS 1 B 1 HS	3 HS 1 FS				(10) x 10	1971 1975	 1975 1980	 1975	
YS09	Yanchep	1967	9 FS 1 B 1 HS	8 HS 1 FS				(10) x 10	1971 1975	 1975 1980		 1977
YS10	Mundaring	1967	8 FS 1 B 1 HS	10 HS				(5) x 20	1971	 1976		
XR1	Yanchep	1966	1 FS 7 HS 2 B	4 FS		18 HS	Italian Lucca N Spain W Spain	None	1979 (Part)	1979 (Part)	1979 (Part)	1979
YS51	Gnangara	1974	10 FS 2 B	10 FS	8 FS			(5) x 10	1983	1983	1983	
YS52	Yanchep	1974	9 FS 2 B	9 FS	8 FS			(5) x 10	1978 1983	 1983	 1983	
YS53	Busselton	1974	9 FS 2 B	9 FS	8 FS			(5) x 10	1978 1983	 1983	 1984	

Seed lots: B bulk HS half-sib; FS full-sib.

TABLE 2

Scoring scales used for assessment of tree form characteristics in early provenance trials.

STEM FORM:	Normal	1
	Malform	2
	Fork	3
STRAIGHTNESS:	Perfect Tree	1
	Nearly straight but not perfect	2
	Average (slight deviation but no wastage)	3
	Crooked (waste part of log)	4
	Extremely crooked, large sweep and kinks	5
BRANCHING:		
Type	Uninodal	1
	Binodal	2
	Multinodal	3
Angle	Low angled, approx. 90°	1
	Intermediate—average	2
	High angled, steep	3
Thickness	Small	1
	Medium	2
	Heavy, thick	3
CROWN:	Well balanced, vigorous	1
	Well balanced, dormant	2
	Unbalanced, vigorous	3
	Unbalanced, dormant	4
BUTT SWEEP, LEAN, BEND:	Present 1	Absent 2
RAMICORN:	Present 1	Absent 2
CONES:	Present 1	Absent 2
LEADER:	Present 1	Absent 2

Landes. Seed lot number S2865. The batch was received in 1962 as being typical of the Landes forests.

Corsica. Seed lot number S2897. Received in December 1962. It was collected in the Antisanti region. Elevation 750 m. Latitude 42°9'. Longitude 9°21'E. Annual rainfall 880 mm. Annual average air temperature 12°C.

Italian. Seed lot number S2864. Origin Italy.

Design – The provenances were established in a 5 x 5 Latin Square design with square plots of 128 trees (8 rows with 16 trees in each row) planted at the rate of 2240 stems per hectare (stems ha^{-1}).

Procedure – The trial was planted in June 1964 with 1-0 nursery stock on a high quality site in Walton Block, Gnangara plantation. The site was wet at time of planting owing to extensive clearing and an exceptionally wet winter. Some refilling was carried out in 1965.

The plants were thinned in 1970 to 735 stems ha^{-1} (from 128 to 42 in each plot) and in 1977 to 368 stems ha^{-1} (from 42 to 21 in each plot). Fertilizer was added as a spot application of superphosphate at planting, 500 kg ha^{-1} of superphosphate was broadcast in 1973 and 500 kg ha^{-1} of Agras (NP) was broadcast in 1978.

TABLE 3

Seedling mortality of provenances in trial 3/65 in the two years after planting in June 1964. Refilling to original numbers was carried out in June 1965.

PROVENANCE	NUMBER PLANTED JUNE 1984	PERCENTAGE MORTALITY 1965	1966
LeiriaR	640	14.7	11.6
Leiria2	640	13.4	11.1
Landes	640	5.3	7.0
Corsican	640	4.4	5.9
Italian	640	4.2	5.2

Pruning was carried out in 1970 (to 2 m), 1974 (to 3 m) and 1977 (to 4 m).

Measurement – Tree height and diameter at breast height (d.b.h.) were measured in 1969, 1973, 1975, 1977 and 1984. Branch angle, number of whorls and flowering characteristics were assessed in 1969 and a major assessment of form and branching was carried out in 1975. The scoring system in Table 2 was used in assessing tree form.

Results

Seedling survival – Results for seedling deaths in each of the two years following planting are set out in Table 3.

Height and diameter – Means for height, diameter and volume measurements are presented in Table 4. The provenances have separated into two distinct groups – the faster growing Leiria R and Leiria 2 and the slower growing Landes, Corsican and Italian provenances. The superiority of the former two is highly significant under the trial conditions.

Form – Results for form and flowering characteristics for trial 3/65 at ages 5.5 and 10.5 years are listed in Tables 5 and 6, respectively.

The counts of trees with or without cones or pollen development were expressed in Table 5 as a percentage of the total in each plot and transformed to angle arcsins for analysis. Differences between provenances for height growth and percentage of trees with cones or pollen were highly significant (.01 level), but those for branch angle and number of branches per whorl were not. In Table 6 variation in frequency of normal crowns, fine branches and butt sweep was not significant while that of binodal branching was significant at the .05 level. Differences in all other traits were highly significant (.01 level).

Portuguese provenances developed cone and pollen crops earlier than the others (Table 5).

TABLE 4

Growth of height, diameter and volume of provenances in trial 3/65.

PROVENANCE	10.5 YEARS			20.5 YEARS		
	HEIGHT (m)	DBHOB (cm)	VOLUME (m^3)	HEIGHT (m)	DBHOB (cm)	VOLUME (m^3)
LeiriaR	8.7a	13.1a	31.2a	15.0a	26.9a	116.3a
Leiria2	8.3a	12.7ab	28.9a	14.8a	25.7a	102.6a
Corsican	6.0b	10.4bc	14.4b	11.1b	21.8b	55.2b
Landes	6.0b	10.1c	14.3b	10.6b	20.9b	50.6b
Italian	5.5b	9.8c	11.8b	9.5c	19.9b	40.6b
LSD .05	0.4	1.0	10.0	0.9	2.9	22.5

[a] Measurements with similar alphabetic letters are not significantly different.

TABLE 5

Branching and flowering traits of provenances in trial 3/65 at 5.5 years of age.

PROVENANCE	MEAN HEIGHT (m)	PERCENTAGE (ARCSIN TRANSFORMATION) TREES WITH		BRANCH ANGLE IN WHORL AT 1.3 m		NUMBER OF BRANCHES /WHORL
		CONES	POLLEN	LARGEST	SMALLEST	
LeiriaR	3.7	37.6a	81.5a	66.0	44.2	4.9
Leiria2	3.8	38.7a	81.2a	66.4	43.8	4.9
Landes	2.6	2.3c	12.1c	62.3	40.8	5.4
Corsican	2.7	1.1c	20.4c	61.7	40.6	5.5
Italian	2.5	16.7b	45.9b	63.5	44.0	5.1

TABLE 6

Form and branching traits of provenances in trial 3/65 at age 10.5 years.

PROVENANCE	MEAN HEIGHT (m)	PERCENTAGE (ARCSIN TRANSFORMATION) OF TREES WITH								
		CONES	LEAN	BUTT SWEEP	RAMI-CORN	FINE BRANCH	STEEP BRANCH	BI-NODAL BRANCH	STRGT STEMS	NORMAL CROWN
LeiriaR	8.7a	51a	51a	29	34a	27	34a	80a	35b	68
Leiria2	8.3a	38b	52a	36	29ab	27	30a	80a	35b	70
Landes	6.0b	18c	25b	36	20b	27	15b	47b	49a	76
Corsican	6.0b	20c	32b	28	7c	27	18b	69ab	47a	72
Italian	5.5c	48a	44a	39	22b	25	20b	80a	17c	62
LSD .05	0.4	10	12	NS	10	NS	6	24	10	NS

Discussion

The relatively high seedling mortality of the Portuguese provenances (Table 3) is normal to Western Australian experience under these conditions. It has always been the most difficult of provenances to germinate and hand plant in the field. Under operational conditions good nursery practice, proper and extensive site preparation and machine planting have resulted in survival values consistently over the 90 per cent mark. Whenever hand planting is required, however, the project may be subject to high losses. For this reason tubed stock, which provided near to 100 per cent survival, was used in all other important trials within the improvement program.

Poor seedling survival of the Atlantic provenances was reported by Sweet and Thulin (1962) in New Zealand trials. Matzyris (1982) recorded failure of Portuguese seedlings owing to frost at one trial site in Greece but the provenance appeared to have similar early survival to three others compared at six further locations. Difficulty in seed handling and obtaining good seedling survival was considered to be an important attribute of the Portuguese provenance and was given major attention (Hopkins 1971a) in the local improvement program.

The results for height, diameter and volume growth and the general aspects of stem form support previous findings in Western Australia (Hopkins 1960). The Italian provenance is the slowest growing and the one of poorest form from the commercial viewpoint. The Landes and Corsican provenances have similar height and diameter growth rates but generally are superior in stem form and crown characteristics. The Corsican is outstanding in stem straightness and crown and branch symmetry. The Portuguese provenances are the most vigorous, significantly so, but defective in the percentage of ramicorns, high branch angle and upper stem straightness.

The form assessment separated the Portuguese and Italian from the Landes and Corsican provenances. The first pair have the poorest form with a relatively large percentage of ramicorns (large branches competing with the leader), leaning stems, high-angled branching and a lower percentage of straight stems. The Landes and Corsican groups have a high percentage of straight stems, well-shaped crowns and flat branching characteristics. However, the Corsican differed from the Landes through its lower frequency of ramicorns.

The Portuguese provenances were the earliest to produce cone and pollen crops under local conditions (Tables 5 and 6). The Landes and Corsican provenances were significantly later in this respect. The results indicate that precocity of flowering is genetically controlled and the characteristic has developed differently throughout the natural distribution of the species.

The Landes provenance had a lower proportion of binodal trees. This is not in accord with previous experience with the two provenances in Western Australia where the reverse situation was considered to be more probable. Differences in interpretation in assessment are possible and it should be noted that in the current data no multinodal stems (Class 3) were recorded in the assessment. All were classed as uninodal or binodal. Later it will be shown that the Landes seedlot in this trial had a close affinity with the Corsican provenances.

Trial XS12 – Intra- and Inter-Provenance Variation within Seed lots from Portugal, France and Corsica at Yanchep

Establishment

In 1967, availability of seed of reliable and selected sources in the Portuguese, Landes and Corsican races allowed for a trial design to compare variation both within and between provenance groups. The trial was also designed for establishment on limestone sands of the Spearwood dunes system (McArthur and Bettenay 1960) which represented much of the future planting area for the species. These limestone sites, with lower rainfall and less accessible ground water, are more drought prone. Prior to this, trials had been conducted mainly on deep grey sands with an accessible water table on the better sites.

Provenances – The trial incorporated 4 Portuguese seed lots, 2 Landes lots and 4 Corsican lots as follows:

1. Leiria E5xE40 – a controlled crossing of two plus parents selected in W.A. plantations.
2. Leiria E19xE40 – a controlled crossing of two plus parents selected in W.A. plantations.
3. Leiria MPDL – a mixture of seed from plus trees selected in Portugal.
4. Leiria routine – an unimproved bulk collection from Portugal (seed lot number S3697).
5. Landes 64445 – seed collected from plus tree 38.27 in France.
6. Landes 64435 – seed collected from plus tree 71.05 in France.
7. Corsica 3749 – seed collected from good trees in a stand at Vivario; altitude 800 m.
8. Corsica 3750 – seed collected from good trees in a stand at Porto Vecchia; altitude 900 m.
9. Corsica 3751 – seed collected from good trees in a stand at Zonza; altitude 700 m.
10. Corsica 3752 – seed collected from straight, vigorous trees in a stand at Chisoni; altitude 800 m.

Design – The trial was planted as a complete, randomized block design with 5 replications of the 10 seed sources. Square plots of 36 trees, at 2.4 m x 2.4 m spacing, were planted with tubed seedlings in June 1967.

Procedure – Seedlings received a spot application of 100 g of zinc superphosphate (zinc and copper additions) at planting and 500 kg of super plus 200 kg of urea broadcast per hectare in 1976.

The stand was thinned from the original

1680 stems ha^{-1} to 560 stems ha^{-1} (36 to 12 trees per plot) in September 1977.

Pruning of plots of Leirian origin was carried out in 1972 (to 2 m), 1977 (to 4 m) and 1979 (to 7 m). The other provenances were pruned later, always leaving at least 30 per cent of the green crown intact.

Measurement – Height was measured in 1971, 1975, 1977 and 1986. D.b.h. was measured at the last three dates.

In 1975, an assessment of form and branching was carried out using the categories in Table 2.

Results

Volume growth – Measurements up to age 19.5 years (Table 7) revealed a general superiority of the four Portuguese groups of which the routine was the poorest.

For stem diameter and total volume growth the full-sib (crossed) Leiria families and the half-sib (open pollinated) Leiria family (MPDL) were superior (.05 level) to the routine Portuguese imported seed batch which is significantly (.01 level) superior to the Landes and Corsican groups. These latter were not significantly different from each other in diameter but some variation existed between the better Landes family (64445) and the poorer Corsican groups (3749, 3752) in volume comparisons.

For height development to 19.5 years of age, all the Portuguese groups were significantly superior (.01 level). The Landes families were also significantly superior (.01 level) to the Corsican lots which showed some variation amongst themselves.

Form – Results of the stem form assessment at age 7.5 years (Table 7) reveal that for the percentage of ideal stems (those scored as 1 and 2) the Corsican provenances were markedly superior to the other two. One Landes family had superior form to the Portuguese routine and the other was equivalent to it.

Results for acceptable stems (categories 1, 2 and 3 which would involve little or no waste in processing owing to defect), were reasonably similar in ranking and emphasize the poor stem form often found in stands from commercial routine Portuguese seed. The proportion of stems of acceptable straightness in the three Leirian lots of selected origin was significantly higher than that of the routine lot.

Drought Resistance – In November 1977, prior to thinning, dead and severely damaged trees were distributed over all the treatment blocks but were concentrated within the Landes and Corsican provenance cells (Table 8).

Discussion

Trial XS12 is an efficient provenance test for evaluating differences between the major geographic groups considered for commercial plantation development in Western Australia. General results clearly confirmed observations of previous trials for growth and form characteristics. Knowledge of the extent of the variation between families within a provenance group has provided confidence in the interpretation of results for variation between groups.

Within this series of provenance trials, XS12 is particularly important in that it is the only trial with a good representation of the Corsican sources. They have consistently proved to be significantly straighter than other provenances.

There is a strong indication from trial results that selection and breeding within the Portuguese provenance would result in useful improvement in stem straightness. For example, the family E19xE40 approached the level of form in the Corsican race which has long been considered the best formed provenance (Hopkins 1960).

The years 1976 to 1977 were the driest on record in the region and resulted in considerable crown damage and pine deaths throughout the plantation. The trial provided an ideal field basis to assess the drought resistance of different provenances.

It was fortunate that the stands were suitably developed to clearly describe provenance response to the 1976–77 drought. This has not been demonstrated previously in mature trees. Clearly the Leirian provenance is the most drought-resistant of the provenances compared.

There was conjecture whether plus tree selection for form and vigour in the improvement program would be favourable to species' drought resistance. Results for controlled crosses in Table 8 indicate that they are at least as resistant as the parent population, which suggests that selection within the local breeding program will at least maintain the high drought resistance displayed by the race.

The Leirian families with significantly greater biomass (height and basal area) were superior in drought resistance (0.8 per cent mortality) to the Landes (9.7 per cent) and Corsican (10.1 per cent) groups. The latter groups were similar in sensitivity to drought with some variation between families. Results from other trials subject to the same drought (XS11, XS09, XR1) have supported these conclusions.

The results of this trial on a limestone soil are essentially similar to those obtained from trials on the deep grey Bassendean sands (McArthur and Bettenay 1960), thus indicating an adaptability of provenance to different soil types. The trial is also helpful in indicating the value of half-sib (MPDL) and full-sib (E19xE40, E5xE40) selections in improving commercial production of the species.

The advantage of the Portuguese provenance for volume production in Western Australia is obvious.

TABLE 7

Results for stem straightness at age 7.5 years and diameter, height and volume at age 19.5 years for trial XS12.

PROVENANCE GROUP	STAND AGE 7.5 YEARS				STAND AGE 19.5 YEARS					
	STEM STRAIGHTNESS ACCEPTABLE		IDEAL		VOLUME (m^3 ha^{-1})		DIAMETER (cm)		HEIGHT (m)	
	RANK	%	RANK	%	RANK	MEAN	RANK	MEAN	RANK	MEAN
Leiria E5xE40	5	67	8*	16	2	147.2	2	23.9	1	16.5
Leiria E19xE40	7	65	6*	23	1	149.4	1	24.1	2	16.3
Leiria MPDL	9*	60	7*	19	3*	138.6	3	23.7	3*	15.8
Leiria Routine	10*	51	9*	15	4*	118.9	4*	22.3	4*	15.4
Landes 64445	6	67	5	25	6	65.5	6	17.9	5	12.6
Landes 64435	8*	60	10*	13	10	49.1	10	17.0	6	12.2
Corsica 3749	1	72	3	32	9	49.6	9	17.5	9	10.6
Corsica 3750	3	70	2	32	8	53.4	8	17.6	7	11.1
Corsica 3751	2	72	1	33	5	61.5	5	18.1	8	11.0
Corsica 3752	4	68	4	30	7	53.7	7	17.6	10	10.3
LSD .05		9		8		11.3		1.2		0.6
LSD .01						15.1		1.7		0.8

* Not significantly different to the Routine control.

TABLE 8

Distribution of damage in trial XS12 resulting from the 1976–1977 drought. The trial was planted in 1967.

FAMILY AND PROVENANCE	TOTAL TREES PER FAMILY	NUMBER OF DEAD AND SEVERELY DAMAGED TREES BLOCK						DAMAGE %
		I	II	III	IV	V	TOTAL	
E5xE40	180	0	0	0	0	0	0	0.0
E19xE40	180	0	0	1	0	0	1	0.6
MPDL	180	0	1	0	1	0	2	1.1
Routine	180	0	0	0	3	0	3	1.7
LEIRIA							6	0.8
64435	180	5	1	3	2	1	12	6.7
64445	180	3	7	2	2	9	23	12.8
LANDES							35	9.7
3749	180	10	1	1	6	5	23	12.8
3750	180	4	3	1	2	6	16	8.9
3751	180	0	1	2	5	2	10	5.6
3752	180	4	4	2	4	10	24	13.3
CORSICAN							73	10.1
Total	1800	26	18	12	25	33	114	6.3

Trial XS09 – Tunisian and Spanish Provenances at Gnangara

Establishment

There is no record of trials of seed sources from North Africa or Spain in early introductions of *P. pinaster* into Western Australia. Reports of comparisons in South Africa (Rycroft and Wicht 1947) gave little promise that the Moroccan could be of commercial advantage in South Africa. It was, however, desirable to test provenances from North Africa in Western Australia to provide future gene sources for the breeding program. In particular, the status of the drought resistance of the Portuguese improved race was questionable and African provenances might have had some advantage in this attribute. The availability of half-sib seed collected in Tunisia provided an opportunity to compare the characteristics of this North African source with Portuguese and Spanish sources in trials at Gnangara and Yanchep in 1966 and 1967.

Provenances – The following provenance groups were compared (Table 9):

1. Leirian full-sib – one seed lot, the standard cross E40xE2 used as a tester in the improvement program.
2. Leirian half-sib – eight separate seed lots from trees E104, E110, E115, E121, E131, E152, E173 and E181 selected as plus trees in the forest of Leiria.
3. Leirian Routine – one commercial seed lot imported from the forest of Leiria.
4. North Spain – one pooled seed lot collected from 5 trees in a plantation at Barreiros by Perry (Perry and Hopkins 1967) on the north coast of Spain. The trees were of good form and vigour with dense, dark green crowns.
5. West Spain – one pooled seed lot collected by Perry near La Toja west of Pontevedra on the west coast of Spain, from about 20 fast growing trees of good form.
6. Tunisian half-sib – 24 half-sib seed lots from plus trees at Ain Baccouch in north-west Tunisia.

Trial Design – Ten-tree line plots with 8 replications were used in randomized blocks.

Procedure – Plants were raised in tubes and planted out with superphosphate fertilizer spot application in June 1966. The initial spacing of 2150 stems ha^{-1} was thinned to 1080 stems ha^{-1} (10 plants reduced to 5 in each line plot) in 1971, to 430 stems ha^{-1} (5 to 2 in each line plot) in 1977 and to 215 stems ha^{-1} (2 to 1 in each line plot) in September 1980.

Superphosphate was broadcast at the rate of 500 kg ha^{-1} in October 1972 and 500 kg ha^{-1} of Agras (NP) fertilizer was broadcast in September 1981.

Pruning was carried out in 1971 (to 2 m), 1975 (to 4 m) and 1980 (to 7 m).

Measurement – Heights were measured in June 1970 (age 4 years) and both heights and diameters were measured in December 1976 (age 10.4 years).

Results

Height and diameter means from the 1976 measurement (Table 9) show a clear separation of the Atlantic and Tunisian provenance groups. All Tunisian families were significantly less than the Spanish and Leirian provenances in height growth and significantly inferior (.01 level) in diameter growth, except for the North Spain and E138 and E173 Leirian batches. Generally the Portuguese and Tunisian families showed uniform and continuous variation within groups.

Only four of the Atlantic coast families (E152, E40xE2, E131, E104) grew significantly faster (.05 level) than the routine source for height growth while none, within the Atlantic group, differed significantly from this control for diameter.

Discussion

The mean heights and diameters of the Spanish provenances and the commercial Portuguese routine source did not differ significantly from each other. Field descriptions (Perry and Hopkins 1967) had indicated phenotypic similarity between these groups.

Seedlings of the Tunisian provenance were distinctively different in appearance from those of other *Pinus pinaster* provenances in the nursery. The bud has a whitish edge to the scale that is like that of *P. canariensis* in the nursery stage. The experimental site is adjacent to a swampy area and in the early stages of the trial all the Tunisian trees were covered with the woolly aphid (*Pineus pini*). Only occasional trees of Portuguese origin were affected by the insect.

The Tunisian trees were the most precocious in flowering of all provenances tested in Western Australia. Abundant pollen and cone development was apparent within four years of planting.

Stem form of the Tunisian families was inferior to that of the better Leirian groups but this was not quantitatively assessed (see Trial XR1 for an assessment of this trait).

No significant mortalities occurred in any family in trial XS09 during the 1976 drought. Some adjacent trials were severely affected and good survival in trial XS09 could have been owing to its wetter locality and its well thinned condition. The comparison for drought resistance was better made in trial XR1 which was established on a very drought-prone site.

Trial XR1 – Strip Comparisons

Establishment

Trial XR1 differs from all other provenance comparisons in this series in that it does not follow a normal statistically controlled design. The objectives were to:

1 Establish on a similar site a wide range of provenances, some with limited plant numbers. The large numbers of provenances available for

TABLE 9

Mean height and diameter of Portuguese and Spanish provenances and half-sib Tunisian families in trial XS09 at age 10 years.

RANK	HEIGHT (m)		DIAMETER OVER BARK (cm)	
	FAMILY	MEAN	FAMILY	MEAN
1	P E152	8.7	P E40xE2	13.5*
2	P E40xE2	8.7	P E131	13.3*
3	P E131	8.5	P E152	13.1*
4	P E104	8.5	P E104	13.1*
5	P E110	8.3*	P E110	13.1*
6	P E118	8.1*	P E181	13.0*
7	P E145	8.1*	P E118	12.9*
8	P E121	8.1*	P E115	12.5*
9	P E115	8.1*	P E145	12.5*
10	Spain West	8.1*	P E121	12.4*
11	P E181	7.8*	P Routine	12.3*
12	P E156	7.8*	Spain West	12.1*
13	P Routine	7.8*	P E156	11.9*
14	P E138	7.7*	P E173	11.9*
15	P E173	7.7*	P E138	11.7*
16	Spain North	7.6*	Spain North	11.3*
17	T 3539	6.2	T 3539	10.7
18	T 3524	6.1	T 3543	10.2
19	T 3529	5.9	T 3524	10.1
20	T 3547	5.8	T 3528	10.0
21	T 3528	5.7	T 3527	10.0
22	T 3541	5.6	T 3529	10.0
23	T 3532	5.6	T 3541	9.9
24	T 3527	5.6	T 3547	9.7
25	T 3535	5.6	T 3545	9.6
26	T 3537	5.5	T 3530	9.6
27	T 3533	5.5	T 3535	9.5
28	T 3526	5.5	T 3544	9.5
29	T 3545	5.5	T 3534	9.4
30	T 3543	5.4	T 3546	9.4
31	T 3530	5.4	T 3532	9.3
32	T 3546	5.4	T 3537	9.2
33	T 3534	5.3	T 3526	9.2
34	T 3544	5.3	T 3533	9.1
35	T 3525	5.2	T 3538	9.1
36	T 3542	5.1	T 3525	8.7
37	T 3540	5.1	T 3531	8.6
38	T 3538	5.1	T 3542	8.6
39	T 3531	5.0	T 3540	8.3
40	T 3536	4.8	T 3536	8.1
	LSD .05 =	0.62	LSD .05 =	1.10
	LSD .01 =	0.81	LSD .01 =	1.45

P Portuguese T Tunisian families.
* Not significantly different (.05 level) to the Routine Control.

comparison, the varying importance of the provenance groups to the local program and the small numbers of seeds available in some groups either precluded replication within a standard experimental design or did not warrant the work involved in establishing and measuring such a trial.

2 Use an interplanted control seed source as a standard or covariant on which to rate the performance of each provenance and to overcome problems caused by site variation within the test area.

3 Evaluate Spanish, Italian and Tunisian provenances under drought-prone conditions and on the yellow limestone sands of the Spearwood Dune Series (McArthur and Bettenay 1960).

Provenances – Provenances tested included:

1 Routine – imported Portuguese seed (S3352) used as the control.

2 Leiria S2 – a full-sib family with plus parents (E40xE2), used as a standard in all progeny trials.

3 PDL4 – half-sib seed from a plus tree selected in Portugal (E104).

4 Portugal – a batch of seed collected from an isolated stand near Lamego in north Portugal.

5 Landes 1 and 2 – two half-sib families from plus trees in the Landes forest (S2860, S2865).

6 Tunisia 1 to 6 – six batches of seed mixed from eighteen half-sib collections from Tunisian plus trees.

7 Lucca – an Italian provenance from Lucca in Tuscany (S2855).

8 Italy – a general Italian provenance (S2864).

9 Spain – seed collected at Barreiros on the north-west coast of Spain.

Design – The trial was established in a rectangular block with 130 rows of trees aligned in a north-south direction. Each row was 120 m long and included approximately 60 trees at 1.8 m spacing. Spacing between rows was 2.4 m (i.e. a stocking of 2243 stems ha^{-1}). Each provenance or family (or mixture of families in the case of some Tunisian groups) was planted in a strip of four rows with four rows of the routine Portuguese stock on either side as a control. Sufficient stock was available for the Spanish and Leirian S2 seed lots to be planted twice to provide some replication within the trial. The outer three trees at the end of each row were regarded as a buffer and omitted from measurement.

The trial was established in two sections and only the section in Compartment 48A is considered in this report.

Procedure – The trial was planted at Yanchep in 1966 on yellow coastal sands. The site is flat with a slight increase in elevation from west to east.

The control and most other stock was open rooted and planted by machine; the tubed stock (Leiria S2) was planted by hand.

Trees were low pruned in November 1976 and thinned to approximately 450 stems ha^{-1} in May 1980.

Measurement – The trial was evaluated in 1979 by students from the Western Australian Institute of Technology. Fifteen trees in each of the two inner rows of each four-row bay were measured to allow a mean of 30 trees of each provenance to be compared by 't' tests with that of the adjacent controls. Form was subjectively assessed on the basis of the standards presented in Table 2.

Results

Results are presented in Tables 10 and 11. In Figure 4 the impact of topography on site index is depicted by the dotted line for height of the routine Leiria control in the height graphs.

Height and Diameter – At age 13 years, the full-sib and half-sib Leiria (S2, PDL4) and one of the two North Spain plantings were significantly better in height growth than the control (Table 10). With the exception of the other North Spain lot and Landes 1 (S2860), all other provenances were significantly poorer in height growth than the adjacent Portuguese control.

Trees of the Spanish source located on the higher site quality end of the trial were significantly smaller in diameter than the control, but the other Spanish samples and all Portuguese provenances equalled or exceeded the control. Three Tunisian groups, Landes 2 (S2865) and both Italian provenances were significantly inferior in diameter growth.

Form – The percentage of trees with above average bole straightness in Figure 4 varied from 8 to 63 for the control (Table 11) over the range of the trial. Similarly, the same Spanish provenance at each end of the trial varied from 14 to 56 per cent. There is no reason for such differences to be associated with site variation and the trend is not in accord with variations measured in site index. This wide variation, present in the assessment procedure for this attribute, makes the data most suspect and difficult to interpret.

Variation in results in the control provenance for other form characteristics restricts interpretation. It should be noted however, that for form characteristics, the adjacent full-sib groups S2 and the half-sib PDL have good agreement. Most differences in the trial can thus be associated with actual variation within the provenance groups and not necessarily with site or measurement effects.

The results clearly demonstrate the flatter branch angle in the Tunisian and Italian trees as distinct from the typical high angled branching pattern present in all Atlantic provenances.

Discussion

This field trial demonstrates the importance of replication in interpretation and validity of results. By itself it has little merit for provenance evaluation other than as a reconnaissance procedure. However, results for height and diameter growth are in accord with those of other trials and it has extended the findings on the grey sands at Gnangara to the drought-prone limestone sands at Yanchep (trial XS09).

The results show that the Atlantic group (Portuguese, Landes and north-coastal Spain) performed best in height and diameter growth and the Tunisian and Italian groups were inferior in these respects.

The Spanish and Portuguese groups did not differ in stem straightness (Table 11) from the control. This

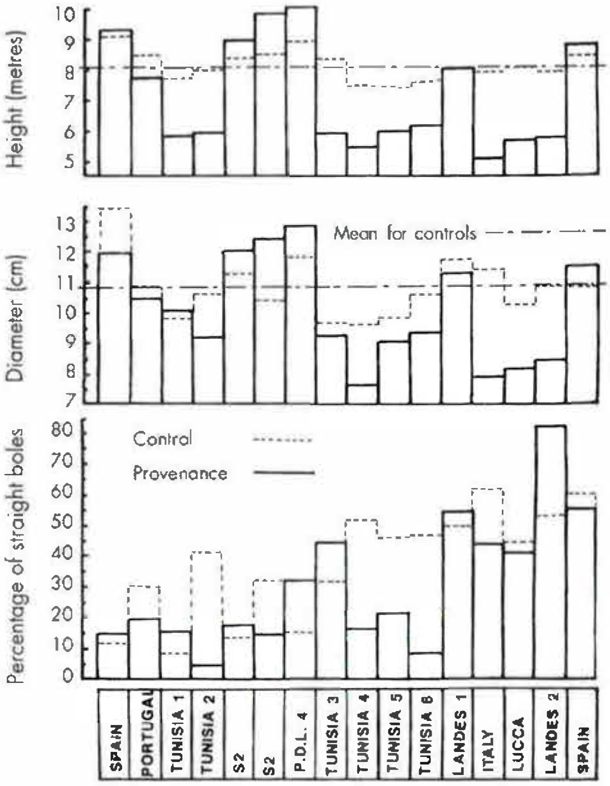


Figure 4. Variation in height, diameter and bole straightness for the provenances in trial XR1 at Yanchep. The general mean for all routine (Leiria) control plots and the actual control means for each comparison are superimposed as dashed lines. Plants were 13 years old at measurement.

performance is as expected from descriptions of the provenance in the field (Perry and Hopkins 1967). The Landes group was as good or better than the control in straightness and the Tunisian and Italian groups were generally inferior.

No useful comment can be made for results on the frequency of trees without forks, ramicorns or damaged leaders (Table 11). Most provenances are as good as, or better than, the imported Portuguese seed batch. Forking and ramicorns have long been recognized as major form defects in imported Portuguese stock.

Results for branch angle shown in Table 11 suggest that the Tunisian and Italian provenances have a higher proportion of flat (low angle) branching. This supports field observations in trials 3/65 and XS09 and the general expectation of Mediterranean races. Spanish and Landes groups have higher angled branching, similar to the Portuguese group and a characteristic of the Atlantic race.

Trial results for branch thickness cannot be interpreted to show any real advantage over the control (see also trials YS51, YS52, YS53).

This preliminary analysis of the trial suggests that excessive variation is associated with inconsistency of measurement and an inadequate sample size in each plant group. Data do not warrant covariant analysis

TABLE 10

Mean survival, height and diameter of unreplicated strip plantings of various provenances at age 13 years for trial XR1. Significance is at the 0.05 level and represents differences between the provenance and the adjacent control, evaluated by 't' tests. The Routine Leirian seed batch was used as the control.

PROVENANCE	SURVIVAL (%)		MEAN HEIGHT (m)			MEAN DIAMETER (cm)		
	PROV.	CONTROL	PROV.	CONTROL	SIGNIF.	PROV.	CONTROL	SIGNIF.
Spain (Barreiros)	90	100	9.2	9.0	NS	11.9	13.3	*
Spain (Barreiros)	83	97	8.8	8.3	*	11.5	10.8	NS
Tunisia 1	90	90	5.9	7.7	*	10.1	9.7	NS
Tunisia 2	90	90	5.9	7.9	*	9.1	10.5	*
Tunisia 3	87	93	5.8	8.3	*	9.1	9.6	NS
Tunisia 4	87	93	5.4	7.3	*	7.6	9.5	*
Tunisia 5	100	97	5.9	7.3	*	8.9	9.8	NS
Tunisia 6	80	100	6.0	7.5	*	9.2	10.5	*
Landes S2860	97	93	7.9	7.9	NS	11.2	11.7	NS
Landes S2865	80	87	5.7	7.8	*	8.4	10.8	*
Italian	53	90	5.0	7.8	*	7.8	11.4	*
Lucca	97	97	5.6	7.9	*	8.1	10.2	*
Portugal (Lamego)	90	93	7.7	8.4	*	10.3	10.8	NS
Leiria S2	97	80	9.0	8.3	*	12.0	11.2	NS
Leiria S2	97	97	9.8	8.4	*	12.3	10.3	*
Leiria PDL 4	93	83	9.9	8.8	*	12.8	11.7	NS

Tunisia 1	S3543	
Tunisia 2	S3524	
Tunisia 3	S3528,29,35,46	Mixtures of W.A. serial numbers
Tunisia 4	S3526,30,33,40	Mixtures of W.A. serial numbers
Tunisia 5	S3525,32,36,47	Mixtures of W.A. serial numbers
Tunisia 6	S3537,39,42,44	Mixtures of W.A. serial numbers

Prov. – Provenance mean
Control – Control mean

unless a more comprehensive measurement is carried out. This is not expected as indications of provenance performances in the trial are satisfactorily explained in conjunction with associated trials.

Form assessment is a subjective procedure and consistent results can only be obtained using experienced and reliable assessment crews and allowance must be made for inaccuracy owing to inexperience of the students measuring the trial. It is not practical, however, to fully test all provenances or progeny groups which may have merit to a local program and as a broad based screening medium the trial procedure may be useful. It is well backed by trial XS09, on the sands at Gnangara, to provide for a satisfactory evaluation of the Tunisian and Spanish groups.

If the design must be employed in future, several obvious improvements are worth considering:

1. A full-sib or half-sib family should be used as the control to reduce the excessive variation inherent in non-selected routine seed collections.
2. If it is not possible to use a full-sib family as a control measurement units of the order of 50 trees should be employed to improve the sample of each provenance.
3. Several provenances should be duplicated to gauge the extent of variation in comparisons.
4. Form assessment should be kept simple and restricted to experienced assessors.

Drought Deaths – During the 1976 drought, scattered deaths occurred within the trial. Assessment of survival numbers (Table 10) revealed that the Italian and one Tunisian batch fared worse than the routine control. In general, however, survival of all other provenance groups, in particular the full-sib and half-sib Leirian selections, is considered most satisfactory under the conditions.

TABLE 11

Comparisons of stem form in unreplicated plantings of various provenances in trial XR1 at age 13 years. The Routine Leirian seed batch was used as the control.

PROVENANCE	PERCENTAGE OF ABOVE-AVERAGE STEMS: STRAIGHTNESS		BRANCH THICKNESS		BRANCH ANGLE		NOT FORKED	
	PROV.	CONTROL	PROV.	CONTROL	PROV.	CONTROL	PROV.	CONTROL
Spain (Barreiros)	14	11	7	14	7	21	69	43
Spain (Barreiros)	56	61	4	4	0	7	100	75
Tunisia 1	15	8	7	4	26	33	78	71
Tunisia 2	4	41	11	15	41	30	52	78
Tunisia 3	44	32	24	14	28	7	92	61
Tunisia 4	16	52	24	22	20	4	96	93
Tunisia 5	21	46	28	14	62	0	97	100
Tunisia 6	8	47	0	17	50	3	100	100
Landes 1(S2860)	55	50	10	0	7	4	97	89
Landes 2(S2865)	83	54	4	4	0	15	96	81
Italian	44	63	0	7	31	7	100	85
Lucca	41	45	3	10	34	21	90	86
Portugal (Lamego)	19	30	5	11	5	15	86	59
Leiria S2	17	13	3	0	0	25	76	54
Leiria S2	14	32	0	7	0	0	72	86
Leiria PDL 4	32	14	11	0	0	0	68	68

Prov. – Provenance mean

Control – Control mean

Landes Half-sib Families

A further group of trials (XS11, YS08, YS09, YS10) within the early improvement program incorporated half-sib families of plus trees selected in forests of the French Landes region. These were compared with routine Leirian imported seed, full-sib Leirian crosses from local selections and half-sib Leirian families from plus trees in Portugal.

At the time, plus tree selection and evaluation accounted for a major part of the time spent on tree breeding. Interest in French half-sib material was high as some West Australian foresters still favoured the Landes seed and therefore it required thorough testing.

Trial XS11 was established at Gnangara in 1967 and included 14 Landes half-sib families. Trials YS08, YS09 and YS10 contained 4, 9 and 10 Landes families respectively, of which at least four are common to two sites. They have the routine, half-sib Portuguese and at least 9 full-sib Leirian crosses in common and represent a wide range of soils at Gnangara, Yanchep and Mundaring.

Trial XS11 – Comparisons of Leirian and Landes Families at Gnangara

Establishment

Provenances – Trial XS11 incorporates a routine imported Leirian seed batch (S3697), a mixture of half-sib seeds from plus phenotypes selected in Portugal (MPDL), 4 full-sib crosses from Portuguese plus trees selected in local plantations and 14 half-sib families from plus trees selected in French Landes forests.

Design – The families were planted out in 10-tree line plots with 10 replications in a randomized block design.

Procedure – The trial was established in June 1967, with tubed stock, in Clover Block, Gnangara plantation. Planting was at 3 m x 3 m spacing (1080 stems ha^{-1}). In August 1977, the trial was thinned to 540 stems ha^{-1} (10 trees to 5 per plot) and in September 1980 the stand was further reduced from 5 trees to 2 per plot.

Fertilizer was added as a spot application of 60 g of superphosphate per seedling at time of planting and 500 kg ha^{-1} of superphosphate was broadcast on the trial in September 1972. In 1976 a further 500 kg ha^{-1} of superphosphate plus 200 kg ha^{-1} of urea was broadcast.

The trial was pruned progressively to 7 m height.

Measurement – Heights were measured and survivors counted in January 1971. Height and diameters were measured in December 1976. In 1977 a drought damage assessment was made prior to thinning.

Results

Results for the measurements and analysis are set out in Table 12.

Height and Diameter – At 3.5 years of age superior height growth was evident in the Portuguese families. By age 9.5 years this superiority was significantly (.01 level) taller and of greater diameter than any of the Landes families. At this stage the MPDL was similar to the Portuguese routine batch in both height and diameter. All crosses from local selections were significantly better than the imported routine seed batch.

The Landes families varied significantly among themselves in both height and diameter.

Drought Damage – Drought damage was well distributed over the entire trial area. Damage was greatest in the Landes families (Table 12) and was reasonably high for the Portuguese routine. It was negligible for the full-sib crosses and the half-sib Portuguese selections.

Discussion

Results from this trial containing half-sib families of a number of the best plus trees selected in the French breeding program show that their growth was significantly inferior to the Portuguese control and improved Leirian families under Western Australian conditions. This is supported by other performances of Landes half-sib groups in trial XS12 (Table 7) on limestone soils, and trials YS08, YS09, YS10.

The clear and consistent results for resistance to drought damage in this and other trials (XS12, YS09) establishes the superiority of the Leirian provenance in drought resistance. The full-sib crosses resulting from selections among acclimatized plus trees in Western Australia have retained and improved on the drought resistance of the imported routine control.

The significance of the superior drought resistance of the Leirian race can be appreciated better when it is realized that at the onset of the drought in 1976-77, the Portuguese trees carried 150 per cent more stem volume and 28 per cent more basal area and hence had a far greater water requirement than trees of the Landes provenance. These results are confirmed by details of mortalities in trial YS09 (See Table 16) to be discussed later.

Variation within the Landes half-sib group and the highly significant differences obtained by acclimatization and selection in the Portuguese group (Table 12) reveal the scope for provenance improvement, to meet specific conditions. The data also indicate the degree of variation that may be experienced between different provenances within a major geographic group and with different standards or procedures for seed collection. Obviously there is need for replication in provenances and a defined basis for seed collection, if one is to be confident that trials clearly demonstrate the relative potentials of the different geographic groups.

Trial YS08 – Comparisons of Leiria and Landes Families at Gnangara

Establishment

Provenances – Trial YS08 compared 20 seed lots covering the following provenance groups:

1. Leiria full-sib – 14 full-sib families from controlled crosses of plus trees selected in Western Australia. One of these crosses was a selfing (E40xE40).
2. Routine – a commercial seed batch (S3697) imported from Portugal, reputedly from the forest of Leiria, used as the control.
3. Leirian half-sib – MPDL, a mixture of half-sib seed lots from plus trees selected in Portugal.
4. Landes cross – LSMA, a mixture of seed from crossings between Landes and Leiria plus trees.
5. Landes half-sib – three separate seed lots from plus trees selected in the Landes forests in France (L60252, L60253 and L1103).

Design – The families or provenances were planted out in 10-tree line plots with 10 replications in a randomized block design.

Procedure – The trial was established from tubed stock in June 1967 on grey sands in Clover Block, Gnangara Plantation. Planting was at 3 m x 3 m spacing. Thinning in August 1977 reduced the stocking from 1080 to 540 stems ha^{-1} (from 10 to 5 trees per plot). The stand was further reduced in October 1980 from 5 trees to 2 trees per plot.

Fertilizer was added as a spot application of 60 g of superphosphate per seedling at time of planting and 500 kg ha^{-1} of superphosphate was broadcast in September 1972. In August 1978, 500 kg ha^{-1} of Agras (NP) fertilizer was broadcast.

Lupins were sown on the trial area in 1981 with dressings of 200 to 300 kg ha^{-1} of superphosphate in 1981 and 1983.

The trial was pruned in stages to 7.5 m height.

Measurement – Heights were measured in January 1971, April 1975 and August 1977. Diameters were measured in April 1975, August 1977 and March 1980. A form assessment for stem straightness and branch thickness was carried out in October 1975.

Results

Height and Diameter – Results for height and diameter are listed in Table 13. Two of the three Landes families, the Portuguese mixed half-sib group (MPDL) and 4 full-sib families were significantly poorer in height growth than the routine control at age 3.5

TABLE 12

Results for growth and drought survival for full-sib Leirian families and half-sib Landes families in trial XS11 at Gnangara up to age 10 years.

FAMILY	AGE 3.5 YEARS HEIGHT		AGE 9.5 YEARS HEIGHT		AGE 9.5 YEARS DIAMETER		AGE 10 YEARS DROUGHT DEATHS
	MEAN (m)	RANK	MEAN (m)	RANK	MEAN (cm)	RANK	%
E5xE40	2.40	1	7.3	1	10.6	3	2
E45xE40	2.10	3	7.1	2	10.8	1	0
E40xE2	2.01	6	7.1	3	10.8	2	0
E19xE40	2.16	2	7.0	4	10.6	4	0
(E)MPDL	2.06	4	6.5*	5	9.7*	6	2
(E)Routine	2.05	5	6.4*	6	9.8*	5	5
L64391	1.92	9	5.9	7	9.1*	8	1
L64437	1.98	8	5.9	8	9.2*	7	3
L62354	1.87	12	5.9	9	8.5	13	4
L622368	1.99	7	5.8	10	8.7	10	20
L64417	1.87	11	5.7	11	8.6	12	14
L62366	1.82	14	5.7	12	8.5	14	5
L62365	1.74	19	5.7	13	8.7	11	1
L64432	1.8[illegible]	16	5.5	14	8.4	15	2
L64430	1.85	13	5.5	15	8.0	18	13
L62355	1.81	15	5.5	16	8.7	9	11
L62348	1.78	18	5.5	17	7.9	19	2
L64434	1.88	10	5.4	18	7.9	20	10
L64422	1.79	17	5.3	19	8.0	17	12
L62362	1.66	20	5.2	20	8.0	16	12
LSD .05	—		0.34		0.70		—
LSD .01	—		0.44		0.92		—

Family designation commencing E – Portuguese.
Family designation commencing L – Landes.

* Not significantly (.05 level) different to Routine.

years. By age 7.5 years all Landes half-sib groups and the Leiria selfing (E40xE40) were significantly inferior in height and diameter to all other Portuguese families and the Landes by Leiria cross (LSMA). This was also the position with respect to diameter at 13 years of age.

Tree Form – Means obtained for the form assessment at age 8.5 years are presented in Table 14. These refer to the percentage of trees scored in the two better classes (out of 3) for each trait (See Table 2). Percentages are left in the arcsin transformation to allow comparison of means by the least significant difference (LSD) values.

Branch thickness comparisons in Table 14 at age 8.5 years reveal that the Leirian routine, the Landes and two Leirian full-sib groups (E15xE2, E15xE40) contained most trees with heavy branching and were similar in this respect. The Portuguese half-sib (MPDL) and remaining Leirian full-sib crosses were significantly superior in fine branching.

Results for branch angle show little variation in the proportion of flatter branching between families from both Portugal and France. Two full-sib families (E5xE40, E33xE40) show improvement through selection while another family (E28xE2) was inferior to the routine source.

The provenances poorest for stem straightness were the Landes, the Portuguese routine and three full-sib Leiria crosses (E40xE2, E5xE40, E28xE2). Variation within the Leiria pedigree group ranged from 41 to 8 per cent trees with acceptable stem straightness. Plus tree selection in Portugal (MPDL) and local plantations provided superior stem straightness coupled with superior vigour. The good tree form of the selfed family (E40xE40), in Table 14, indicates that selfing may offer a useful pathway to form improvement in the Leirian population.

TABLE 13

Comparison of Portuguese and Landes families for height and diameter growth with age in trial YS08.

FAMILY	AGE 3.5 YEARS HEIGHT (m)		AGE 7.5 YEARS HEIGHT (m)		AGE 7.5 YEARS DIAMETER (cm)		AGE 13.0 YEARS DIAMETER (cm)	
	MEAN	RANK	MEAN	RANK	MEAN	RANK	MEAN	RANK
E5xE40	2.79	2	7.2	2	10.9*	6	17.3*	6
E14xE40	2.43	14	6.7*	12	10.6*	12	17.0*	7
E15xE50	2.79	1	7.0	6	11.7	1	18.7	2
E19xE40	2.54*	8	6.8*	10	10.7*	10	16.6*	14
E28xE40	2.57*	6	6.8*	11	10.5*	13	16.5*	15
E33xE40	2.46*	12	7.0	5	10.6*	11	16.7*	10
E40xE40	2.26	19	6.1	17	9.1	18	14.6	17
E41xE40	2.71*	3	7.0	4	10.9*	5	16.7*	12
E45xE40	2.67*	4	6.8*	9	10.7*	8	17.0*	8
E47xE40	2.35	17	6.7*	13	10.3*	16	16.8*	9
E15xE2	2.54*	7	6.9	7	11.5	2	19.0	1
E28xE2	2.45*	13	6.9	8	10.9*	7	17.7	5
E33xE2	2.40	16	7.2	1	11.2	4	18.1	4
E40xE2	2.49*	10	7.1	3	11.4	3	18.6	3
MPDL	2.42	15	6.6*	14	10.3*	15	16.7*	11
Routine	2.60*	5	6.5*	16	10.7*	9	16.3*	16
LSMA	2.53*	9	6.6*	15	10.5	14	16.6*	13
L60251	2.47*	11	6.1	18	9.5	17	14.0	18
L60253	2.30	19	5.6	20	8.6	20	12.7	20
L61103	2.20	20	5.7	19	8.9	19	13.4	19
LSD .05	0.16		0.30		0.76		1.10	

The Landes are designated by L.

* Not significantly different (.05 level) to the Routine control.

Discussion

The trial results support other local studies in demonstrating the superiority in height and diameter growth of stands from Leirian seed over those from the Landes region.

Within the Leirian group the only family significantly poorer for growth than the routine control was the selfing E40xE40 (Table 13). Generally the families resulting from crosses between plus trees were significantly better than the routine control.

The Landes by Leiria cross (LSMA) is interesting in that its growth was intermediate between that of Landes and Leirian families. This result was confirmed from other trials (YS51, YS52, YS53) and reports of early selection work in France by Alazard (1982).

The superiority of vigour of Leirian families has already been demonstrated in other trials. The major value of the current trial is in the further definition of characteristics of stem form and branching between the Leirian and Landes provenances. No differences could be detected for percentage of fine branches between the routine Portuguese, LSMA and two of the three Landes half-sib families. This is contrary to similarities between the provenances demonstrated in trial 3/65 (Table 6).

It was not possible to distinguish between the Landes and most of the Leirian families on the basis of branch angle. In trial 3/65 (Table 6) the Landes provenance contained a higher percentage of trees with favourable branch angle. There are reasons to suspect, however, that the seed lot used to represent the Landes area in that trial had greater affinity with the Corsican race than with the normal Landes population. Evidence for future improvement within the Portuguese group is shown in Table 14 where the proportion of trees with acceptable branching in E5xE40 and E33xE40 is significantly (.01 level) superior to the rest. Lack of attention to this factor in selection could worsen the situation as demonstrated by the cross E28xE2 which is significantly (.01 level) poorer in branching than all other families in the trial. Parent E28 was culled from seed orchards as a result of early test results.

Stem straightness was similar between the Landes families and the imported Portuguese control. This was

TABLE 14

Comparison of Portuguese and Landes provenances for branch size, branch angle and stem straightness in trial YS08 at 8.5 years of age. Means are for percentage of acceptable stems.

FAMILY	PERCENTAGE OF ACCEPTABLE TREES					
	BRANCH THICKNESS		BRANCH ANGLE		STEM STRAIGHTNESS	
	MEAN	RANK	MEAN	RANK	MEAN	RANK
E5xE40	76.5	1	88.2	1	20.7*	13
E14xE40	71.7	6	76.2*	5	31.2	4
E15xE50	48.0*	16	70.5*	13	8.1*	17
E19xE40	64.9	10	75.6*	6	22.8	10
E28xE40	72.6	5	61.5*	18	25.8	8
E33xE40	73.2	4	85.5	2	41.4	1
E40xE40	75.0	2	78.0*	4	34.5	2
E41xE40	66.3	8	72.9*	11	29.1	7
E45xE40	74.1	3	73.8*	9	30.6	6
E47xE40	64.2	11	66.0*	16	32.4	3
E15xE2	52.8*	14	67.8*	14	22.8	11
E28xE2	60.9	12	35.4	20	22.2 *	12
E33xE2	66.3	9	73.8*	8	30.6	5
E40xE2	71.4	7	78.6*	3	19.5*	14
MPDL	58.8	13	73.5*	10	24.3	9
Routine	43.2*	17	66.9*	15	10.5*	16
LSMA	52.5*	15	75.0*	7	19.5*	15
L60251	39.6*	19	63.6*	17	1.8*	20
L60253	30.9	20	55.7*	19	4.5*	19
L61103	43.2*	18	71.1*	12	8.1*	18
LSD .05	11.0		12.3		9.6	
LSD .01	14.0		16.0		12.7	

The Landes are designated by L.

* Not significantly different (.05 level) to the Routine control.

also the case in one of two Landes families in trial XS12 (Table 7) but the other family and the seed lot used in trial 3/65 (Table 6) had better straightness than the unimproved Leirian plants.

The improved straightness of the top 11 Leirian crosses in the current trial (Table 14) and the excellent performance of the selfing E40xE40 in this respect, indicates that selection within the provenance is effective in improving this characteristic. Selfing may be of future assistance in this area and an extensive selfing program was carried out for many of the initial local plus tree selections.

Two features of these results are the favourable branch size shown by the less vigorous selfing E40xE40 (Table 14) and the relatively poor form displayed by E15xE2 and E15xE40. The plus parent E15 was subsequently culled from the breeding program on the basis of consistent poor performance in branching and the use of E2 was restricted on the basis of poor form and early height growth.

Trials YS09 and YS10 – Comparisons of Leirian and Landes Families at Yanchep and Mundaring

Establishment

Trials YS09 and YS10 are similar to YS08 and were designed to evaluate a wider range of Landes half-sib families on two further, very different soil types. YS09 is located on the more fertile limestone soils at Yanchep where drought is more significant. YS10 is planted on good quality red loam soils at Mundaring some 60 km east of Perth in the Darling Range. Here, superior soil, temperature and rainfall conditions favour the growth of *Pinus radiata*, and *P. pinaster* cannot compete as a commercial alternative.

Provenances – Trial YS09 includes 11 Leirian (9 full-sib, 1 routine, 1 half-sib) groups and 9 Landes (half-sib) groups (Table 15). YS10 has 10 Leirian and 11 Landes groups (Table 16).

Design – Trial YS09 is a randomized block experiment with 10 replications of 10-tree line plots.

YS09 was fertilized with 500 kg ha^{-1} of super-copper-zinc fertilizer in October 1972 and 500 kg ha^{-1} Agras (NP) in September 1978. Thinning was to 5 trees per plot in August 1977 and to 2 trees per plot in October 1980.

Pruning was completed to height 7.5 m by March 1981.

YS10 is a randomized block experiment with 20 replications of 5-tree line plots. Smaller plots were used on account of the greater site variation present.

YS10 was fertilized with 500 kg ha^{-1} of super-copper-zinc fertilizer in September 1973 and 400 kg ha^{-1} of super-copper-molybdenum-zinc with 20 kg ha^{-1} of Seaton Park clover in May 1982. Thinning was from 5 to 2 trees per plot (430 stems ha^{-1}) in November 1977 and from 2 to 1 trees per plot (215 stems ha^{-1}) in March 1982.

Pruning was completed to 4.5 m in March 1978.

Measurement – Trial YS09 was measured in January 1971 for height, in April 1975 and August 1977 for height and diameter and in March 1980 for diameter only. In October 1975 a form assessment for stem straightness, branch angle and branch thickness was undertaken on all Portuguese families and one Landes family.

Trial YS10 was measured in 1971 for height and in February 1976, October 1977 and March 1981 for diameter.

Results

Height and Diameter – In both trials the growth of the Landes families (Tables 15 and 16) was inferior to that of the Portuguese groups. This confirmed other results for the complete separation of the two provenance (racial) groups for growth characteristics, over a wide range of soil conditions, in Western Australia.

TABLE 15

Results for growth and straightness comparing Leirian and Landes (L) provenances in trial YS09 planted in 1967 at Yanchep.

RANK	AGE 3.6 YEARS HEIGHT (m)		AGE 7.5 YEARS # STRAIGHTNESS (TRANSFORMED)		AGE 10 YEARS VOLUME (m³)		AGE 12.7 YEARS DIAMETER (cm)	
	FAMILY	MEAN	FAMILY	% 1,2	FAMILY	MEAN	FAMILY	MEAN
1	E5xE40	3.28	E47xE40	41.1	E15xE40	.020	E15xE40	19.0
2	E19xE40	3.26	E40xE2	37.5	E19xE40	.018	E40xE2	18.7
3	E15xE40	3.22	E41xE40	35.4	E45xE40	.018	E19xE40	18.2
4	E41xE40	3.17	E45xE40	34.5	E5xE40	.018	E41xE40	17.9
5	E45xE40	3.07*	E28xE40	31.2	E40xE2	.018	E45xE40	17.8
6	E28xE40	3.04*	E28xE2	28.8	E41xE40	.017	E47xE40	17.7
7	E40xE2	3.04*	E5xE40	28.2	E47xE40	.016*	E5xE40	17.7
8	Routine	2.99*	E19xE40	24.3	E28xE40	.015*	LSMA	17.6
9	MPDL	2.97*	E15xE40	19.2	E28xE2	.015*	E28xE2	17.3*
10	E47xE40	2.96*	L60252	7.2*	Routine	.015*	E28xE40	17.0*
11	E28xE2	2.93*	Routine	5.4*	LSMA	.014*	Routine	16.7*
12	LSMA	2.88*			MPDL	.014*	MPDL	16.5*
13	L61238	2.86*			L61104	.012	L61104	15.2
14	L61240	2.77			L61238	.011	L61103	15.0
15	L61104	2.74			L61240	.010	L61238	15.0
16	L60252	2.70			L60252	.010	L61105	14.7
17	L61105	2.59			L61105	.010	L61240	14.7
18	L60253	2.52			L61103	.009	L62065	14.3
19	L62065	2.44			L60253	.009	L60252	14.2
20	L61103	2.41			L62065	.009	L60253	14.0
LSD .05		0.13		9.6		.001		0.8
LSD .01		0.17		12.7		—		1.1

* Not significantly (.05 level) different to the Routine.

E – full-sib Portuguese plus families. L – Landes half-sib families

\# Percentage of trees in classes 1 and 2 on a ranking scale from 1 (excellent) to 5 (poorest).

The Landes by Leiria half-sib cross (LSMA) from parents selected within local plantations provided some improvement in growth through selection.

Form – The one Landes family assessed for form in trial YS09 (Table 15) did not differ significantly from the Portuguese routine in proportion of acceptable straight stems in the population. In both trials, all Leirian crosses were significantly (.01 level) better than the routine in this respect.

Drought Resistance – In trial YS09 the routine, full-sib and half-sib Portuguese groups were virtually unaffected by drought death while most of the Landes families had one or more deaths attributable to this cause (Table 17).

Discussion

These two trials conclusively support previous data concerning the differences between trees of French Landes and Portuguese provenances for a wide range of soils and climatic conditions in Western Australia. The superiority of the Portuguese provenance for growth rate, tree form and drought resistance has confirmed the practice of using it for commercial planting.

Trials YS51, YS52 and YS53 – Inter Provenance Crosses at Gnangara, Yanchep and Busselton

Within the breeding program in Western Australia a limited amount of intra- and inter-provenance crossing was carried out with trees of other than Portuguese origin. Analysis of results of this work is mainly of interest to studies of species improvement and inheritance. Certain aspects however, assist to clarify the performance of major provenance groups of *P. pinaster* in Western Australia and to identify the dominant genetic characteristics of each group.

TABLE 16

Comparisons of Leirian and Landes (L) provenances for height and diameter development to age 10 years in trial YS10. The trial was planted in 1967 on fertile soils at Mundaring and samples the best sites available for the species.

RANK	AGE 3.6 YEARS HEIGHT (m) FAMILY	MEAN	AGE 10 YEARS DIAMETER (cm) FAMILY	MEAN
1	E5xE40	3.70	E5xE40	18.5
2	E19xE40	3.58	E40xE2	18.4
3	E47xE40	3.51*	E19xE40	18.3
4	E41xE40	3.44*	E28xE40	18.0
5	E28xE2	3.42*	E41xE40	17.8
6	E45xE40	3.42*	E45xE40	17.6
7	Routine	3.38*	E47xE40	17.6
8	E28xE40	3.37*	E28xE2	16.8*
9	E40xE2	3.33*	Routine	16.6*
10	MPDL	3.21*	MPDL	16.2*
11	L61238	3.14	L61104	15.2
12	L61240	3.05	L61105	15.1
13	L61104	3.00	L62347	14.8
14	L61105	2.96	L61240	14.7
15	L62347	2.83	L61238	14.5
16	L62083	2.82	L62083	14.4
17	L62090	2.77	L62069	14.1
18	L62069	2.70	L62073	14.1
19	L62065	2.70	L62065	13.7
20	L62073	2.68	L62090	13.7
LSD .05		0.18		0.70

* Not significantly different (.05 level) to the Routine.

TABLE 17

Drought damage recorded in trial YS09 in summer 1977. Stand age was 10 years. Each family contained 100 trees and each block had a total of 200 trees.

FAMILY	NUMBER OF DEAD AND DYING TREES — TRIAL BLOCK NUMBER 1	2	3	4	5	6	7	8	9	10	TOTAL
E40xE2											0
E28xE2											0
E5xE40											0
E15xE40					1						1
E19xE40											0
E28xE40											0
E41xE40											0
E45xE40											0
E47xE40											0
LSMA											0
MPDL	1										1
L60252	2	1	1	1	2		1		1	1	10
L60253				1	1				1		3
L61103				1				1		2	4
L61104											0
L61105	2			1	1						4
L61238								1			1
L61240	1		1								2
L62065			1			1	2				4
Routine											0
TOTAL	6	1	3	4	5	1	3	2	2	3	30

Plus trees of Corsican and Landes origin selected from Western Australian plantations were crossed with plus parents of Leirian origin. The progeny were compared in three trials designed to observe the transmission of specific characters between these inter-provenance crossings.

A secondary objective was to evaluate site by provenance interaction by planting the trials at three separate geographic centres. These include yellow and grey sands of the Swan Coastal Plain north of and adjacent to Perth and poorly drained lateritic sands in the Donnybrook Sunklands, near Busselton, 250 km south of Perth. The locations tested represent the principal sites considered for *P. pinaster* afforestation within the State.

Provenances – The basic trial (Table 18) comprises 26 full-sib families, a routine bulk imported Portuguese seed batch (S5000) as a control and a seed batch from the local Joondalup seed orchard (SN5047). The 26 families comprise three groups, including 9 crosses (ExE) among superior trees from local stands of Leirian (E) origin, 9 inter-provenance crosses (ExL) between locally selected superior trees of Leirian (E) and Landes (L) origin and 8 crosses (ExC) between locally selected Leirian (E) and Corsican (C) plus trees. At one centre, Gnangara, 30 families were compared and a replacement was necessary for the family E53xL20 which was common to the other two sites.

Design – A complete randomized block design was used to replicate 5-tree line-plots for each of the 28 groups in 10 blocks at each of 3 sites.

Procedure – All stock was raised in tubes at the Wanneroo nursery and planted in June 1974 at 3 m x 3 m spacing. Superphosphate was added at the rate of 60 g per seedling at time of planting and 500 kg ha^{-1} of Agras (NP) fertilizer was broadcast in 1979. The initial low pruning was carried out to 2 m height in 1978.

Measurement – Tree heights were measured in January 1979 at age 4.5 years. Diameter at breast height, and form were measured in March 1983 at Gnangara (YS51) and Yanchep (YS52) and in April 1984 at Busselton. Form was assessed to provide values for stem straightness, forking, butt sweep, branch size and branch angle.

Results

Height and Diameter – Mean heights and diameter for each family and its ranking (R) within the trial are shown in Table 18. The data are presented in provenance groups for convenience.

The majority of the controlled crosses of acclimatized, dominant, well formed trees in local plantations have superior height and diameter growth to that of the routine batch of non-selected, non-acclimatized seed imported from Portugal. Several of the Leirian by Landes crosses (E19xL21, L13xE29) are amongst the fastest growing families in the series.

The relative growth performance of the three groups was summarized by considering the percentage of families in each provenance group which were ranked within the best one-third performers of all families (i.e. ranked 1-9).

For early height growth, the ExE crosses and ExL crosses had equal representation in the best third of families at Gnangara (44 per cent) and Busselton (33 per cent) whereas at Yanchep the proportion was 56 per cent and 33 per cent respectively. No ExC families were in the top one-third at Gnangara and Yanchep but 25 per cent were there at Busselton.

For diameter at 9 years, the ExE crosses were superior at all sites with 74 per cent of families in the best one-third. ExL had 11 per cent in the top third and ExC had 8 per cent. For both height and diameter the ExC crosses were represented in the top third only at Busselton.

The extent of these differences in growth from the routine, non-selected, Portuguese control is detailed in Table 19. Clear superiority of the Leirian provenance is emphasized by the performance of seed from the Leirian seed orchard, the mean of which did not differ significantly (.05 level) from that of the top ranked families at all three locations (Table 18).

Interaction with Site – Data for diameter at age 8 years at all three sites were subject to an analysis of variance (ANOVA). Family, block and site differences were highly significant (.001 level) but associated with a significant (.030 level) site by family interaction.

Examination of the means at each site revealed that some families had altered in relative ranking from one trial to the other suggesting favourableness for either the hotter, drier northern sites or the cooler, wetter southern site (Fig. 5). These obvious fluctuations in mean rankings were few and appeared to be mainly associated with the ExE and ExC crosses. There was a trend however, for the ExL and ExC crosses to improve relative to the dominant ExE values, with progression of trials from Yanchep to Gnangara to Busselton. All provenance crosses performed best at Busselton.

To test this possibility, for each trial the mean diameter (mean of 10 blocks) for each full-sib family, common to the three sites, was regressed against the general (environmental) mean for those families on all sites. Results in Table 20 show that up to 92 per cent of the variation in the interaction is associated with a linear relationship between family diameter at each site, and the general mean. The association is poorest at Busselton with $R^2 = 48.2$ but still highly significant. The individual regressions are significantly different and show the tendency for all families to become more comparable at Busselton ($b = 0.53$) than at Yanchep ($b = 1.40$).

To assess the extent that this trend was valid for the provenance crosses, results for the routine and orchard families were excluded from the data set. An ANOVA was carried out for 24 provenance crosses, common to the three sites, as three provenance groups each containing 8 crosses (Table 21). The site by provenance interaction was highly significant and can be largely attributable to the improvement in growth of the Corsican and Landes crosses with progressive testing south to cooler, wetter sites (Table 22).

Form – Results for the form assessment are set out in Tables 23, 24, 25 and 26. Again the families are grouped by provenance and ranked by means to aid comparisons at each of three trial locations.

The tables include separate assessments of stem straightness based initially on the percentage of stems with scores of average or better straightness (acceptable stems) and secondly on the comparison of arithmetic mean score (all points 1 to 5 are added). Similarly, mean scores for branch thickness and branch angle assessments accompany results for the percentage of better stems assessed. This latter is the system most often used in Western Australia (See Tables 6, 7, 12) as it can be directly associated with commercial acceptance of the population. For the mean score results a least significant difference (LSD) value is calculated and included in the tables.

From the rankings in Tables 23 and 24 it can be seen that for straight stems, butt sweep and normal stems (not forked and without ramicorns) the ExE crosses performed very poorly within the range of variation sampled. For straightness at Gnangara, Yanchep and Busselton, only 1, 0 and 5 of the ExE crosses respectively, were not significantly inferior to the best family. For butt sweep (Table 24) all but one of these crosses, located at Busselton, were inferior to the best family. The Corsican crosses were definitely superior in these respects with the Landes crosses intermediate in performance.

These comparisons are clarified in Table 27 in which families are grouped to show representation within the best third (1-9) of the ranking range. The high incidence of stem forks and/or ramicorns previously noted in the Portuguese populations is still clearly depicted in these results for crossings of selected plus phenotypes. In Table 27, for the combined trial results, only 4 per cent of the ExE crosses occurred in the best third of the results while 79 per cent of the Corsican were in this class.

Results for branch thickness vary with site for both the Leirian and the Corsican crosses (Tables 25, 27). At Gnangara the Leirian crosses had the smallest branches whereas the Corsican crosses were clearly superior at the

TABLE 18

Height and diameter results for provenance crosses in trials YS51, YS52 and YS53. Leirian parents are designated by E, Landes by L and Corsican by C. The routine is a commercial seed batch from the forest of Leiria.

FAMILY	HEIGHT (m) AT 4.5 YEARS						DIAMETER (cm) AT 9 YEARS					
	GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53		GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53	
	MEAN	RANK	MEAN	RANK	MEAN	RANK	MEAN	RANK	MEAN	RANK	MEAN	RANK
E19xE2	3.66	14	3.56	10	2.75	16	16.1	1	14.4	5	16.8	2
E19xE15	3.81	7	3.52	11	2.61	21	15.8	2	14.4	7	16.1	7
E19xE40	3.68	11	3.58	7	3.29	1	14.8	13	14.3	8	17.2	1
E53xE15	3.66	15	3.32	14	2.85	11	15.7	3	14.1	10	16.2	6
E53xE29	3.76	10	3.57	9	2.90	8	15.5	7	14.4	4	15.8	14
E53xE40	3.68	13	3.46	12	3.10	3	14.8	14	13.9	14	16.6	3
E40xE15	3.86	4	3.57	8	2.55	24	15.6	4	14.5	3	16.0	9
E41xE40	3.93	2	3.80	2	2.81	13	15.3	9	14.8	1	15.9	12
E5xE41	4.01	1	3.80	1	2.69	19	15.6	5	14.4	6	15.7	18
L13xE29	3.93	3	3.60	5	3.05	4	15.4	8	14.2	9	15.9	11
L17xEM	3.56	16	3.26	16	2.78	14	14.2	21	12.6	19	15.8	15
L20xEM	3.39	21	3.00	26	2.70	18	13.9	25	12.2	24	15.5	20
E5xL3	3.86	5	3.59	6	3.10	2	15.1	11	14.0	12	15.9	10
E19xL3	3.76	9	3.45	13	2.85	10	15.5	6	14.0	13	15.7	16
E5xL20	3.53	18	3.19	21	2.77	15	13.8	26	12.5	22	15.3	24
E19xL20	3.46	21	3.18	22	2.64	20	14.1	24	12.6	20	15.0	26
E53xL20	—	—	2.92	27	2.70	17	—	—	11.8	28	14.9	27
E19xL21	3.80	8	3.61	3	3.[illegible]3	5	14.9	12	14.1	11	15.5	19
E5xC3	3.51	18	3.23	17	2.91	7	14.4	16	12.4	23	15.4	21
E19xC3	3.48	20	3.27	15	2.83	12	14.4	15	12.9	17	15.7	17
E41xC3	3.27	27	3.21	18	2.87	9	13.5	27	12.5	21	15.9	13
E53xC3	3.27	26	3.07	24	2.50	26	14.2	22	12.1	25	15.2	25
E5xC4	3.28	25	3.01	25	2.48	27	14.3	17	12.0	27	16.0	8
E19xC4	3.33	23	3.21	19	2.56	23	14.3	18	13.1	15	15.3	22
E41xC4	3.31	24	3.13	23	2.58	22	14.2	20	12.9	16	16.2	5
E53xC4	3.17	28	2.87	28	2.47	28	14.2	23	12.1	26	15.3	23
Orchard	3.84	6	3.61	4	2.93	6	15.2	10	14.7	2	16.3	4
Routine	3.55	17	3.21	20	2.55	25	14.3	19	12.7	18	14.7	28
L21xE33	3.73	12	—	—	—	—	14.9	14	—	—	—	—
LSD .05	0.28		0.20		0.42		1.00		0.71		1.02	

other two sites. Results for the Landes crosses were uniform with site. The overall result indicates that the Corsican crosses have the best branching with the Leirian and Landes crosses following in that order.

Results reveal little difference in propensity for flat angle (wide angle) branching between provenance groups (Tables 26, 27). As a group, the Corsican crosses are better with the Portuguese and Landes following in that order. The differences are of a minor nature, vary with site and are not considered to have any significance in these trials.

Differences in the number of trees with acceptable branch thickness between orchard and routine seed lots (Table 25) were not significant. Branch angles were similar for both the orchard and routine sources at each location (Table 26). Improvements of orchard stock over the routine source for stem straightness and butt sweep are, however, significant at the.05 level (Tables 23 and 24).

Discussion

Replication of the trial at the three centres gives consistent results for the major attributes of provenances measured in previous trials. Characteristics for vigour in height and diameter growth are dominant in the Portuguese (ExE) crosses while the major defects noted in the form of the species are still present in them. The favourable aspects of these latter attributes are dominant in the Corsican crosses as they were in

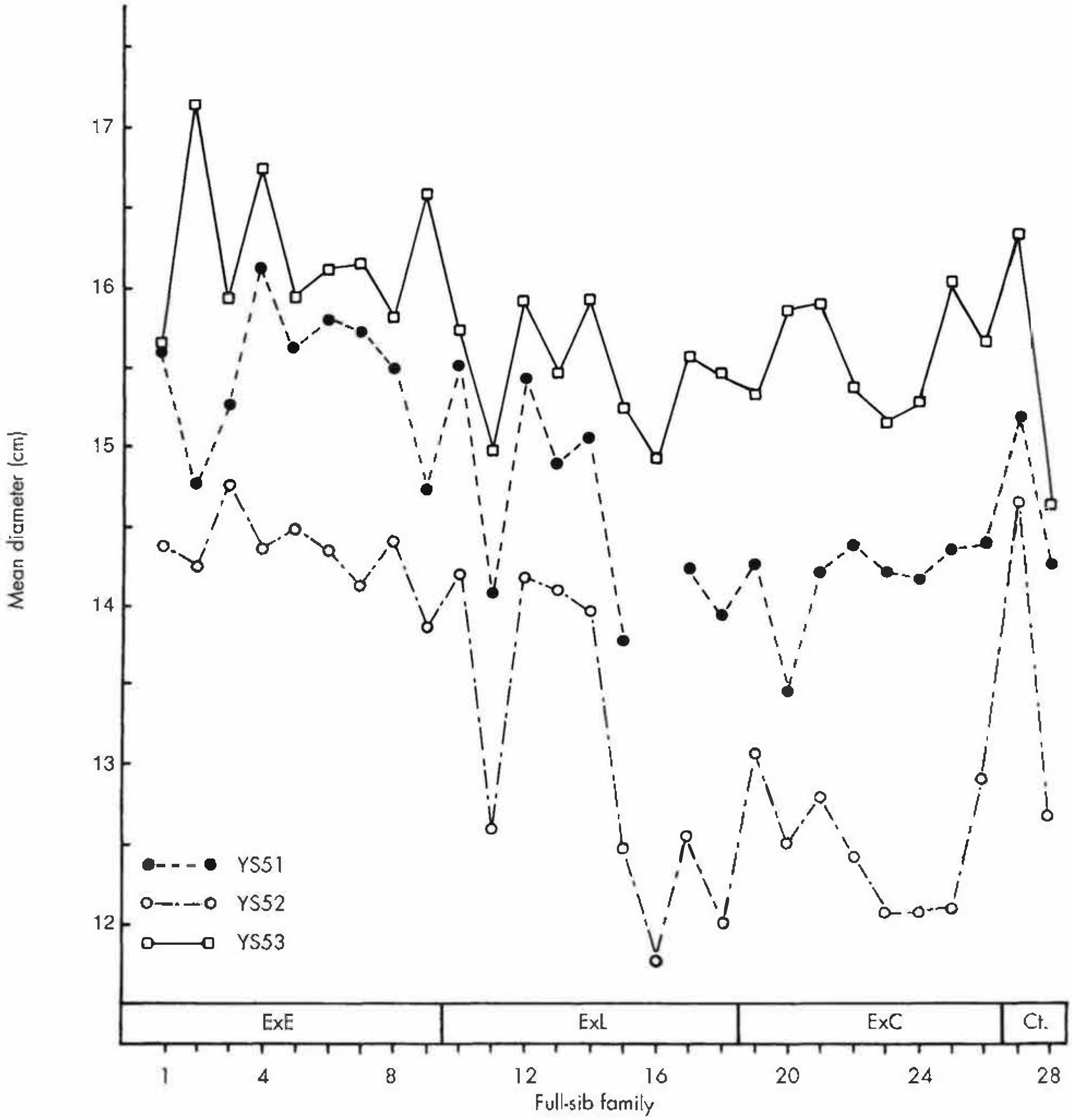


Figure 5. Diameter development of 28 common families in trials YS51 (Yanchep), YS52 (Gnangara) and YS53 (Busselton) comparing performance of Leirian crosses (ExE), Leirian and Landes crosses (ExL) and Leirian and Corsican crosses (ExC). Families 27 and 28 (Ct.) are the seed orchard and routine controls.

this provenance in previous tests (See Tables 6, 7). Consistency of the results over the range of sites and the dominance of these specific attributes following inter-provenance crossing confirms that these are features of geographic races and strongly inherited.

Corsican crosses displayed desirable branch angle and branch size but these were not very different from the Leirian crosses. The negligible improvement in these attributes in the seed orchard stock indicates lower heritabilities and limited scope for selection within the provenance range. The family E5xE41, the highest ranked family for branch thickness (Table 25), and family E41xE40 are ranked high for branch angle. These two attributes can obviously be improved to the maximum for the species from within variation in the Portuguese population.

The establishment of the trials over the range of sites shows the tendency for the genotypes of the Corsican and, to a lesser extent, the Landes provenance to favour diameter development under more southern, cooler, wetter conditions.

The trials extend comparisons of provenances to the cooler, southern sites near Busselton. The performance of the seed orchard stock shows that considerable

TABLE 19

Variation in height and diameter from values for Routine imported Portugese seed for inter- and intra-provenance crosses in trials YS51, YS52 and YS53.

PROVENANCE	HEIGHT AT 4.5 YEARS		DIAMETER AT 9 YEARS	
	MEAN (m)	% DIFFERENCE FROM ROUTINE	MEAN (cm)	% DIFFERENCE FROM ROUTINE
GNANGARA (YS51)				
Leiria x Leiria	3.80	7	15.5	9
Leiria x Landes	3.70	4	14.7	4
Leiria x Corsican	3.30	–7	14.2	0
Seed Orchard Leiria	3.85	8	15.2	7
Routine Leiria	3.55	0	14.2	0
YANCHEP (YS52)				
Leiria x Leiria	3.58	12	14.4	13
Leiria x Landes	3.33	4	13.1	3
Leiria x Corsican	3.13	2	12.5	–2
Seed Orchard Leiria	3.61	12	14.7	16
Routine Leiria	3.21	0	12.7	0
BUSSELTON (YS53)				
Leiria x Leiria	2.84	11	16.2	10
Leiria x Landes	2.85	12	15.4	5
Leiria x Corsican	2.65	4	15.6	6
Seed Orchard Leiria	2.94	15	16.4	12
Routine Leiria	2.55	0	14.7	0
COMBINED				
Leiria x Leiria	3.41	10	15.4	11
Leiria x Landes	3.29	6	14.4	4
Leiria x Corsican	3.03	–2	14.1	1
Seed Orchard Leiria	3.47	12	15.4	11
Routine Leiria	3.10	0	13.9	0

TABLE 20

Values for regression (y = a + bx) of the mean diameter for families, at each site, in trials YS51, YS52 and YS53 against the general (environmental) mean obtained for the families over the three sites. The Routine, orchard and non common crosses have been omitted.

TRIAL	COEFFICIENT B	S.D. OF B	CONSTANT A	S.D. ABOUT REGRESSION	R^2	N
YS51 Gnangara	1.07	1.28	–0.96	0.28	86.7	23
YS52 Yanchep	1.40	0.09	–7.13	0.27	92.0	23
YS53 Busselton	0.53	0.11	8.09	0.35	48.2	23

TABLE 21

ANOVA for diameter at age 9 years for provenance crosses in trials YS51, YS52 and YS53. The analysis is for full-sib families common to the three trials and for three provenance groups Leiria x Leiria, Leiria x Landes and Leiria x Corsican.

SOURCE OF VARIATION	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFICANCE
FULL-SIB FAMILIES				
Site	2	350.00	30.39	0.000
Block (Site)	27	11.52	10.57	0.000
Families	23	12.99	11.93	0.000
Site x Families	46	2.15	1.94	0.000
Error	621	1.09		
Total	719			
PROVENANCE GROUPS				
Site	2	350.00	30.39	0.000
Block (Site)	27	11.52	9.50	0.000
Provenance	2	104.59	86.26	0.000
Site x Provenance	4	8.84	7.29	0.000
Error	684	1.21		
Total	719			

improvement in height and diameter and stem straightness and absence of forking has been obtained in the early selection program for Portuguese material. The relatively high standards achieved by the Corsican crosses for stem straightness, absence of butt sweep and absence of forks show there is considerable scope for improvement to meet the population limits for the species under Western Australian conditions.

The dominance and inheritance of provenance characteristics on crossing with Leirian stock are summarized in Table 27. This analysis assists to quantify the consistency and strength of expression of attributes for plant vigour and form of the three provenance groups Leirian, Landes and Corsican. The Landes group is intermediate between the outstanding vigour of the Leirian provenance and the excellent form of the Corsican provenance. Although inferior in vigour to the Leirian population it is slightly superior to that population in the absence of forks and butt sweep.

Inter-provenance crossing supports other provenance tests carried out in Western Australia. It verifies that the height, diameter and volume advantage of the Portuguese provenance is consistent over the range of climate and soils which could be available for afforestation in Western Australia. Controlled crosses of Leirian parents with selected Landes and Corsican material (which has been acclimatized) provide vigour at least equal to that of the unselected Portuguese imports. Selected crosses with Landes parents may produce hybrid families with vigour akin to that of Leirian crosses (i.e. L13xE29). However, apart from perhaps improving frost resistance, reasons for such a

TABLE 22

Mean diameters for provenance crosses of Leiria x Leiria (ExE), Leiria x Landes (ExL) and Leiria x Corsican (ExC) in trials YS51, YS52 and YS53 at Gnangara, Yanchep and Busselton. Values in brackets denote the mean of the cross as a percentage of the dominant Leirian x Leirian group at the same site.

PROVENANCE GROUP	MEAN DIAMETER AT EACH SITE (cm)			GROUP MEAN
	YANCHEP	GNANGARA	BUSSELTON	
Leiria x Leiria	14.40 (100)	15.56 (100)	16.20 (100)	15.39
Leiria x Landes	13.27 (92)	14.61 (94)	15.58 (96)	14.49
Leiria x Corsican	12.50 (87)	14.81 (91)	15.61 (96)	14.10
LSD 0.01		0.04		
Latitude	31°25'	31°43'	33°46'	
Longitude	115°42'	115°54'	115°37'	

cross for Western Australian conditions are not apparent.

Results for the ranking of form characteristics from the inter-provenance crosses indicate strong inheritance of aspects of form ascribed to different provenances in previous studies. There are very marked differences between the populations.

The Corsican race carried many aspects of its superior form into the inter-racial crosses. It is significant that the high propensity for forking and ramicorns observed for the Portuguese source is still evident after the first generation of selection and crossing. However, the plus trees used in this trial are not elite and of a quality suitable for orchard production. Parents E2, E15, and E52 used in the early crossing trials have subsequently been excluded from the orchard program owing to their proven transmission of poor form characteristics.

In conclusion, the comparisons of the inter-provenance crosses show a tendency for the Corsican and, to a lesser extent, the Landes genotype to adaptation favourable in diameter growth to cooler, moister conditions.

FLOWERING CHARACTERISTICS

Introduction

Perry (1940, 1949) compared the timing of pollen development of imported seed lots of *Pinus pinaster* grown in plantation stands on the Swan Coastal Plain near Perth. Under conditions of similar climate, soils and culture the flowering behaviour of major geographic provenance groups was distinctive as follows:

1. Portugal – Staminate inflorescences began to appear in mid-August and pollen shed commenced in early September. All pollen was shed by the end of September.
2. French Landes – Staminate flowers began to appear by early September and were fully mature by early October. Pollen was dispersed by the end of October.
3. French Esterel – Staminate flowers were produced in profusion by mid-September and were fully mature by mid-October.
4. Corsican – Staminate flowers were few, appeared about the middle of October and were shedding pollen by the end of the month.

Following a visit to Portugal and France, Perry noted the impact of latitude and altitude on time of flowering (Perry and Hopkins 1967).

Detailed observation of flowering bud receptivity was part of the breeding crossing program for *Pinus pinaster* in Western Australia. Pollination was carried out in a scion arboretum where clonal variation in flower inception and receptivity to pollen is recorded over a period of years. Quantitative data on the propensity for flowering and cone production at a young age was also available from established provenance trials.

Procedure

Flowering Receptivity

Times for the receptivity of female flowers to pollen were recorded during the controlled crossing program at the Neaves Road Scion Arboretum near Perth. The arboretum, maintained for grafts of plus phenotypes of Portuguese stock, contained some clones of Landes and Corsican parents selected from local stands. All grafts were made with scions of mature trees grafted on to stocks of Portuguese origin.

TABLE 23

Assessment results for stem straightness for trials YS51, YS52, YS53. Trees were ranked on a scale of 1 (excellent) to 5 (poorest). The Routine is a commercial seed lot from Leiria.

	STRAIGHTNESS (% CLASS 1,2,3)						STRAIGHTNESS (MEAN OF SCORES)					
FAMILY	GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53#		GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53	
	%	RANK	%	RANK	%	RANK	MEAN	RANK	MEAN	RANK	MEAN	RANK
E19xE2	42	24	64	16	40	25	3.56	24	3.32	17	2.66	25
E19xE15	31	28	46	26	35	26	3.70	28	3.54	25	2.70	27
E19xE40	51	11	40	28	61	12	3.42	10	3.60	28	2.35	11
E53xE15	51	11	66	15	57	17	3.50	15	3.26	14	2.39	13
E53xE29	46	16	61	18	64	9	3.50	15	3.34	18	2.28	9
E53xE40	44	20	60	19	59	15	3.48	13	3.38	20	2.43	17
E41xE15	40	26	44	27	61	12	3.60	26	3.54	25	2.33	10
E41xE40	41	25	54	22	64	9	3.56	24	3.44	22	2.36	12
E5xE41	58	6	58	21	46	21	3.34	8	3.38	20	2.54	21
L13xE29	55	9	68	13	74	5	3.42	10	3.20	10	2.20	5
L17xEM	38	27	49	24	35	26	3.62	27	3.46	23	2.67	26
L20xEM	51	11	70	11	52	19	3.45	12	3.22	11	2.52	20
E5xL3	46	16	60	19	57	17	3.48	13	3.34	18	2.43	17
E19xL3	47	15	52	23	44	23	3.54	20	3.48	24	2.60	23
E5xL20	58	6	82	5	45	22	3.32	6	3.04	6	2.55	22
E19xL20	44	20	72	10	43	24	3.54	20	3.24	12	2.61	24
E53xL20	—	—	86	2	52	19	—	—	3.02	4	2.50	19
E19xL21	21	30	70	11	60	14	3.78	29	3.28	16	2.40	14
E5xC3	58	6	64	16	71	7	3.24	2	3.24	12	2.27	8
E19xC3	59	5	84	3	73	6	3.32	6	2.96	2	2.21	6
E41xC3	61	4	84	4	79	2	3.34	8	2.86	1	2.17	2
E53xC3	65	2	88	1	78	4	3.24	2	2.96	2	2.14	1
E5xC4	55	9	74	9	59	15	3.30	4	3.14	8	2.41	16
E19xC4	44	20	78	6	79	2	3.54	20	3.14	8	2.19	4
E41xC4	45	18	78	7	71	7	3.50	15	3.08	7	2.25	7
E53xC4	76	1	76	8	80	1	3.12	1	3.02	4	2.18	3
Orchard	64	3	68	13	62	11	3.30	4	3.26	14	2.40	15
Routine	22	29	48	25	28	28	3.80	30	3.54	25	2.77	28
L21xE33	45	18	—	—	—	—	3.54	20	—	—	—	—
LSD .05							0.22		0.23		0.22	
.01							0.29		0.30		0.30	

% Class 1,2 trees only.

TABLE 24

Assessment results for butt sweep and percentages of single (normal) stems in trials YS51, YS52, YS53. Families are ranked within trials. The Routine is a commercial seed lot from Leiria.

FAMILY	BUTT SWEEP						PERCENTAGE OF SINGLE STEMS					
	GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53		GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53	
	MEAN	RANK	MEAN	RANK	MEAN	RANK	%	RANK	%	RANK	%	RANK
E19xE2	2.66	27	2.66	19	3.21	28	26	27	62	16	26	28
E19xE15	2.40	22	2.96	27	3.07	27	31	22	52	25	54	19
E19xE40	2.32	13	2.70	22	2.85	23	37	15	40	28	35	27
E53xE15	2.54	26	2.60	17	2.61	16	57	2	72	11	53	20
E53xE29	2.36	16	2.62	18	2.62	17	34	17	55	23	55	18
E53xE40	2.24	11	2.56	16	2.65	18	33	19	56	22	65	12
E41xE15	2.34	14	2.78	24	2.57	14	26	27	50	26	53	20
E41xE40	2.36	16	2.68	20	2.40	4	27	26	62	16	52	22
E5xE41	2.35	16	2.50	15	2.56	12	31	22	54	24	46	25
L13xE29	1.95	1	2.08	2	2.26	1	25	24	62	16	63	13
L17xEM	2.34	14	2.68	20	2.85	23	23	29	57	21	61	15
L20xEM	2.36	16	2.44	13	2.80	20	43	11	74	10	72	6
E5xL3	2.22	9	2.30	9	2.53	9	34	17	58	20	51	23
E19xL3	2.68	28	2.92	26	3.00	25	29	24	64	14	69	10
E5xL20	2.22	9	2.38	12	2.45	5	44	9	82	2	57	17
E19xL20	2.70	29	2.86	25	3.04	26	36	16	86	1	71	7
E53xL20	—	—	2.36	10	2.87	19	—	—	80	6	73	5
E19xL21	2.48	25	2.76	23	2.83	21	33	19	64	14	63	13
E5xC3	2.04	2	2.10	3	2.33	3	38	14	60	19	71	7
E19xC3	2.05	4	2.12	5	2.56	12	47	5	82	2	75	3
E41xC3	2.04	2	1.83	1	2.49	6	47	5	69	12	60	16
E53xC3	2.09	5	2.26	8	2.49	7	55	3	82	2	78	2
E5xC4	2.14	6	2.14	6	2.59	15	45	8	80	6	80	1
E19xC4	2.28	12	2.10	3	2.55	10	44	9	78	8	68	11
E41xC4	2.38	20	2.36	10	2.50	8	51	4	82	2	71	7
E53xC4	2.18	7	2.22	7	2.30	2	73	1	76	9	74	4
Orchard	2.18	7	2.48	14	2.55	10	46	7	66	13	51	23
Routine	2.82	30	3.00	28	2.84	22	22	30	48	27	44	26
L21xE33	2.42	24	—	—	—	—	33	19	—	—	—	—
LSD .05	0.25	0.31	0.29									
.01	0.33	0.41	0.39									

TABLE 25

Comparisons of branch thickness for families in trials YS51, YS52, YS53. Trees were scored on a scale of 1 (finest branching) to 5 (coarsest branching). The Routine is a commercial seed lot from Leiria. Families are ranked within trials.

FAMILY	BRANCH THICKNESS (% CLASS 1,2,3)						BRANCH THICKNESS (MEAN OF SCORES)					
	GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53*		GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53	
	%	RANK	%	RANK	%	RANK	MEAN	RANK	MEAN	RANK	MEAN	RANK
E19xE2	70	14	76	19	32	23	3.28	14	3.30	19	2.70	15
E19xE15	53	19	64	24	33	22	3.44	18	3.34	24	2.80	22
E19xE40	84	4	76	15	50	5	3.12	5	3.22	12	2.59	5
E53xE15	43	26	72	18	35	20	3.56	25	3.28	18	2.76	20
E53xE29	34	30	73	17	40	12	3.66	28	3.27	17	2.74	18
E53xE40	76	9	80	10	35	20	3.22	8	3.20	11	2.71	17
E41xE15	82	5	70	19	47	6	3.14	6	3.30	19	2.59	6
E41xE40	82	5	80	10	40	12	3.04	3	3.16	7	2.62	9
E5xE41	98	1	82	8	67	1	2.76	1	3.16	7	2.35	1
L13xE29	45	24	44	27	37	16	3.54	22	3.56	27	2.83	23
L17xEM	73	11	90	3	30	24	3.26	13	3.11	4	2.85	24
L20xEM	51	20	66	23	28	27	3.48	20	3.32	22	2.86	25
E5xL3	92	2	74	16	63	2	3.02	2	3.26	16	2.39	2
E19xL3	35	28	50	26	25	28	3.68	30	3.50	26	2.98	28
E5xL20	76	9	88	5	36	19	3.22	8	3.12	5	2.74	18
E19xL20	51	20	60	25	29	25	3.54	22	3.40	25	2.96	27
E53xL20	—	—	70	19	29	25	—	—	3.30	19	2.94	26
E19xL21	56	18	44	27	42	9	3.44	18	3.56	27	2.69	13
E5xC3	88	3	96	1	56	3	3.08	4	3.04	1	2.46	3
E19xC3	57	17	86	6	42	9	3.40	17	3.14	6	2.60	7
E41xC3	78	7	94	2	43	7	3.24	11	3.06	2	2.68	12
E53xC3	49	22	78	12	37	16	3.52	21	3.22	12	2.69	14
E5xC4	78	7	90	3	51	4	3.22	8	3.10	3	2.55	4
E19xC4	44	25	82	8	43	7	3.56	25	3.18	10	2.62	8
E41xC4	65	15	78	12	38	15	3.36	15	3.22	12	2.71	16
E53xC4	35	28	78	12	42	9	3.66	28	3.22	12	2.66	11
Orchard	72	12	84	7	40	12	3.24	11	3.16	7	2.66	10
Routine	63	16	68	22	37	16	3.32	15	3.32	22	2.77	21
L21xE33	41	27	—	—	—	—	3.60	27	—	—	—	—
LSD .05							0.18		0.18		0.25	
.01							0.24		0.24		0.33	

* % Class 1,2 trees only.

TABLE 26

Assessment of branch angle for trials YS51, YS52, YS53. Trees were scored on a scale of 1 (widest angle) to 3 (steepest angle). The Routine is a commercial seed lot from Leiria. Families are ranked in each trial.

FAMILY	BRANCH ANGLE (% CLASS 1,2) GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53		BRANCH ANGLE (MEAN OF SCORES) GNANGARA YS51		YANCHEP YS52		BUSSELTON YS53	
	%	RANK	%	RANK	%	RANK	MEAN	RANK	MEAN	RANK	MEAN	RANK
E19xE2	22	8	10	26	38	22	2.82	8	2.94	25	2.68	22
E19xE15	29	7	24	13	43	17	2.74	7	2.80	14	2.57	16
E19xE40	39	3	28	8	65	3	2.66	3	2.72	6	2.37	3
E53xE15	6	24	16	24	43	14	3.16	28	2.84	19	2.55	13
E53xE29	6	24	22	16	40	20	3.10	25	2.82	17	2.60	20
E53xE40	20	13	26	9	55	7	2.94	14	2.80	14	2.45	7
E41xE15	20	13	24	13	41	18	2.88	10	2.78	12	2.59	18
E41xE40	41	2	34	4	48	11	2.64	2	2.66	2	2.54	11
E5xE41	67	1	34	4	40	20	2.36	1	2.72	6	2.60	21
L13xE29	10	22	26	9	59	4	3.00	21	2.76	8	2.46	8
L17xEM	21	12	29	7		17	2.94	14	2.76	8	2.59	17
L20xEM	16	16	18	22	44	15	3.02	22	2.90	23	2.56	14
E5xL3	10	22	20	19	53	9	3.06	24	2.92	24	2.47	10
E19xL3	6	24	14	25	19	28	3.04	23	2.94	25	2.88	28
E5xL20	22	8	38	2	53	9	2.84	9	2.66	2	2.45	5
E19xL20	16	16	22	16	41	18	2.96	17	2.78	12	2.59	18
E53xL20	—	—	38	2	27	27	—	—	2.66	2	2.77	27
E19xL21	35	4	18	22	14	15	2.70	5	2.88	22	2.56	15
E5xC3	34	5	32	6	79	1	2.68	4	2.68	5	2.17	1
E19xC3	33	6	26	9	58	5	2.72	6	2.76	8	2.46	9
E41xC3	16	16	20	19	66	2	2.96	17	2.86	21	2.34	2
E53xC3	22	8	40	1	29	25	2.90	11	2.60	1	2.71	24
E5xC4	22	8	22	16	57	6	2.94	14	2.80	14	2.43	4
E19xC4	15	21	8	27	55	7	2.90	11	2.96	27	2.45	5
E41xC4	4	28	8	27	50	10	3.18	29	3.00	28	2.54	12
E53xC4	6	24	20	19	28	26	3.12	26	2.82	17	2.74	25
Orchard	18	15	26	9	34	24	2.96	17	2.76	8	2.77	26
Routine	16	16	24	13	37	23	2.90	11	2.84	19	2.70	23
L21xE33	4	28	—	—	—	—	3.12	26	—	—	—	—
LSD .05							0.20		0.20		0.22	
.01							0.27		0.26		0.29	

TABLE 27

Proportion of families from provenance crosses with superior growth and form characteristics assessed in trials YS51, YS52, YS53. The Leiria and Landes means are from 9 families, the Corsican is from 8 families and show the percentage representation of each provenance group in the best one-third of families i.e. within ranking 1 to 9.

TREE CHARACTERISTIC ASSESSED	FAMILY CROSSED WITH LEIRIA	PERCENTAGE OF FAMILIES RANKED IN THE TOP ONE-THIRD OF THE TRIAL			
		TRIAL REPLICATION			
		GNANGARA	YANCHEP	BUSSELTON	COMBINED
Stem Height (3.5 years)	Leiria	44	56	67	56
	Landes	44	33	0	26
	Corsica	0	0	25	8
Stem Diameter (9.5 years)	Leiria	78	78	67	74
	Landes	22	11	0	11
	Corsica	0	0	25	8
Stem Straightness (Means of Point Scores)	Leiria	11	0	11	7
	Landes	11	22	11	15
	Corsica	75	87	87	83
Stem Straightness (Percentage of Class 1,2,3 Trees)	Leiria	11	0	22	11
	Landes	22	22	11	19
	Corsica	75	87	87	83
Butt Sweep (Means of Point Scores)	Leiria	0	0	11	4
	Landes	33	22	33	30
	Corsica	75	77	63	75
Single Stems (Percentage without Forks or Ramicorns)	Leiria	11	0	0	4
	Landes	11	33	33	26
	Corsica	77	75	75	79
Small Branch Thickness (Percentage of Class 1,2,3 Trees)	Leiria	56	11	33	33
	Landes	22	22	22	22
	Corsica	38	63	75	58
Flat Branch Angle (Percentage of Class 1,2 Trees)	Leiria	56	44	22	41
	Landes	22	44	33	33
	Corsica	50	37	62	50

Fruitfulness

The percentages of trees carrying male and female strobili at age 5.5 years, and bearing cones at 10.5 years of age were recorded in trial 3/65 (Table 1) at Gnangara plantation.

Results

Flower Receptivity

Pollination records for a range of clones and five seasons, from 1965 to 1970, are contained in Table 28. The clonal record in any one year includes several ramets and observations on up to 26 female flowers.

In Figure 6 a line is drawn from the data for individual clones to represent the period from when the first female flower was receptive until the last flower isolated had closed its scales.

From Figure 6 it is obvious that the Portuguese provenance is the first to become receptive to pollen in spring and the Corsican is the last. The Landes trees occupy a position in between these two extremes. There is considerable clonal variation within provenance groups and some variation between seasons (i.e. much earlier flowering in 1968 and 1970).

Fruitfulness

Results from trial 3/65 at age 5.5 years (See Table 5) showed the highest percentage of flowering trees to be in the Leirian provenances. The Italian seed lot had the next greatest number of young trees with cones and was significantly greater than the Corsican and Landes seed lots. For pollen development at this age the Landes, Corsican and Italian provenances were significantly poorer than the Leirian trees.

At age 10.5 years (Table 6) the Leirian routine and Italian seed lots again had the most cone producing trees and were significantly greater than the Leirian 2 seed lot. The Landes and Corsican trees continued to have the least cone bearing trees at this age.

Discussion

Flowering Times

The clonal ranges shown in Figure 6 represent the period from the first record of receptivity of the first flower produced by the clone until the last flower isolated had closed its scales. Each flower is usually receptive for a period of approximately 10 days. Release of pollen was not recorded but it is of the order of 10 days after the first female flower on the ramet becomes receptive. Pollen flies for 5 to 10 days from a single tree, depending on weather conditions.

The crossing program, which aimed to obtain a quota of successful pollinations for each clone provides details for the inception of flower receptivity for all clones. Records do not, however, cover all conelets produced and it is possible that the length of the receptive period in any one clone in any one season could be longer than that recorded. This possibility is partly accounted for by presenting the pattern within different seasons and including the same clone in different seasons, wherever possible.

The strip comparison trial XR1 (Table 1) also proved ideal for comparing the flowering times of various provenances. The several Portuguese and two Spanish provenances from the northern coastal plain, included in the trial, flowered at the same time producing heavy crops of pollen in early September 1988 (age 22 years). Some Landes groups ripened next, flowering heavily and shedding at peak just as the process for the Portuguese was terminating. Tunisian trees followed, just after the peak for the Landes trees, in late September. The Italian trees flowered sparsely and pollen shed did not begin until mid-October. The Corsican provenance also shed lightly at about the same time.

The Landes provenance S2865, used in trial 3/65 and incorporated in the strip comparison, did not begin to shed pollen until most other Landes seed lots had terminated. It was obvious from tree appearance and time of pollen shed that this group is more akin to the Corsican race than to the usual Landes groups.

These recent studies confirm the general trends reported by Perry. They reveal, however, great variation between genotypes within a population and overlapping flowering times between some provenance groups. Results suggest that provided the population sample is representative and environmental conditions are similar, the three provenance groups will show distinctive flowering patterns.

The relatively early flowering of the Corsican clones in the 1970 results (Fig. 6) were rather unexpected and associated with an early spring.

In practice it is unlikely that Portuguese material could naturally cross with Corsican stock but crossing with Landes and Landes with Corsican is quite possible (where geographic separation of populations does not exist). Little success was obtained in initial attempts to cross Portuguese with Corsican trees by applying Portuguese pollen to Corsican female conelets. Crossing between the provenances was only readily obtained by applying stored Corsican pollen to receptive Portuguese flowers. It is possible that there could be natural incompatibility between Portuguese pollen and Corsican conelets.

Precocious Cone Development (Fruitfulness)

Results shown in Table 5 separated the Leiria provenances from the slower growing Italian provenance on percentage of trees bearing cones at age 5.5 years. Differences are significant at the .05 level. The Landes and Corsican groups are similar and significantly less in this respect than the other provenances in the trial.

TABLE 28

Pollination record for clones of Leirian (E), Landes (L) and Corsican (C) provenances within the Neaves Road Scion Arboretum.

YEAR	CLONE	NUMBER OF RAMETS USED	NUMBER OF POLLEN EXCLOSURES	DATE POLLINATION COMMENCED	DATE POLLINATION TERMINATED	NUMBER OF CONES PRODUCED
1965	E14	7	23	8/9	16/9	20
	E16	5	20	8/9	15/9	29
	E34	14	23	2/9	20/9	38
	E40	13	29	8/9	16/9	60
	L70	9	9	24/9	1/10	19
	L26	8	8	24/9	29/9	27
	C2	1	1	15/10	19/10	0
	C3	3	4	29/9	22/10	3
1966	E14	4	13	5/9	20/9	10
	E28	9	14	8/9	22/9	22
	E40	3	13	5/9	15/9	22
	E47	4	18	5/9	22/9	30
	L26	1	8	30/9	5/10	16
	C2	1	1	17/10	21/10	1
	C3	4	7	14/10	21/10	0
1967	E8	5	6	4/9	26/10	8
	E16	5	8	11/9	2/10	10
	E19	6	16	11/9	26/9	30
	E37	2	15	11/9	26/9	34
	L3	4	6	2/10	23/10	11
	L13	6	14	4/9	13/10	14
	L17	5	13	26/9	22/10	11
	L20	4	13	11/9	27/10	5
	L21	4	5	11/9	14/9	2
	C2	1	1	19/9	26/9	0
	C3	3	7	19/9	13/10	0
	C6	1	1	18/10	27/10	1
1968	E19	6	12	28/8	16/9	23
	E47	4	8	28/8	16/9	10
	E58	3	5	3/9	26/9	17
	E118	4	4	28/8	12/9	3
	L3	2	5	12/9	26/9	11
	L17	4	4	3/9	23/9	9
1970	107	3	9	28/8	1/10	11
	E108	2	9	28/8	18/9	14
	E118	2	4	28/8	18/9	4
	E128	2	8	28/8	9/9	9
	E135	2	5	31/8	15/9	13
	L17	1	6	18/9	1/10	9
	L20	4	7	9/9	28/9	9
	L21	1	1	14/9	28/9	0
	C2	1	1	14/9	21/9	0
	C3	4	19	9/9	28/9	0

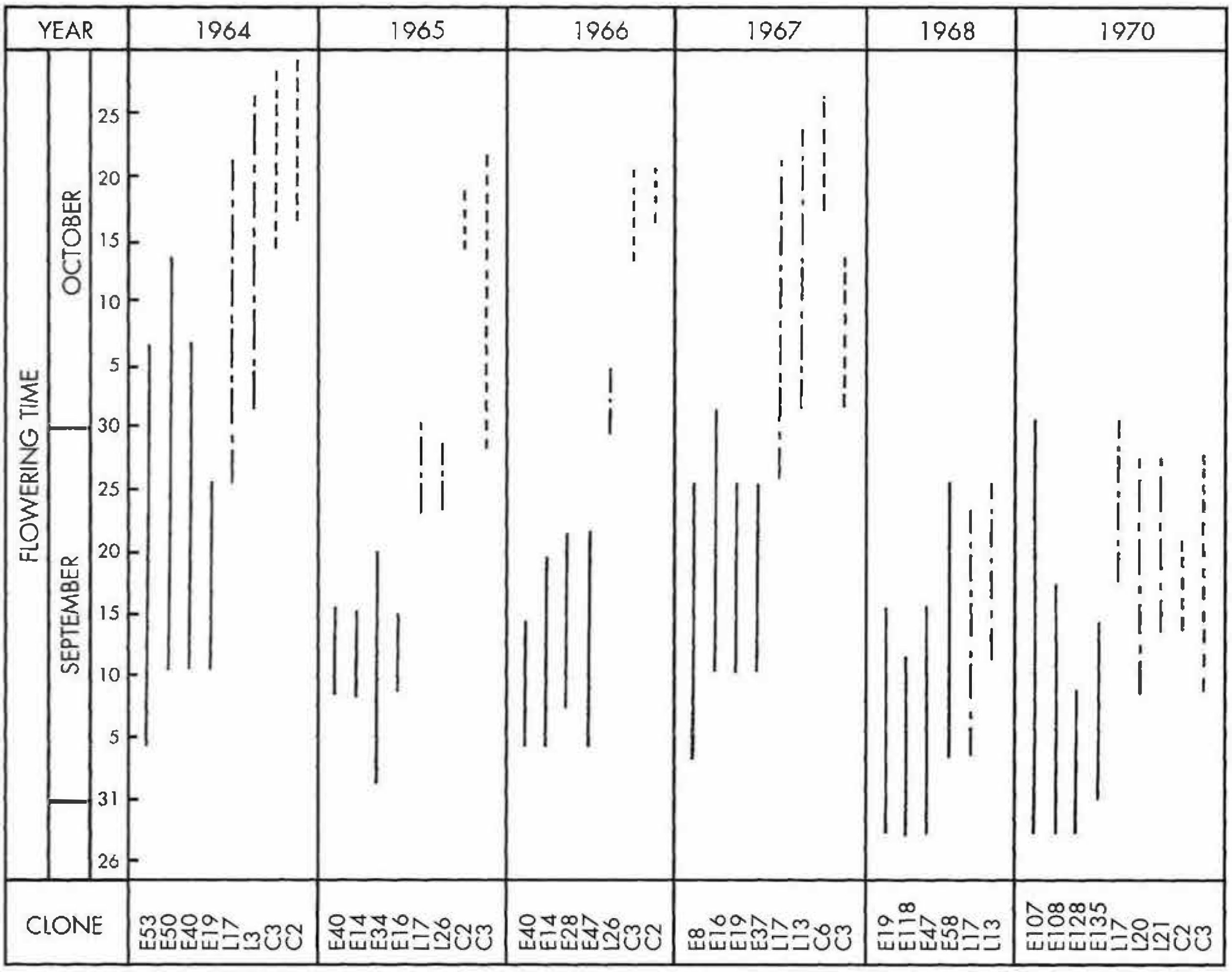


Figure 6. Variation in flower receptivity of clones of three provenances in the Neaves Road Scion Arboretum. The period of receptivity for each clone is designated by the lines in the graph. Clone identification beginning with E refers to Leirian origin, L refers to Landes origin and C refers to Corsican origin.

Sampling age is shown to be important within the Portuguese seed lots in data presented in Tables 5 and 6. At age 10.5 years the Leiria R exceeded the Leiria 2 source in the proportion of trees with cones. Both lots were equivalent at age 5.5 years while Leiria 2 had the most cone bearing trees at age 4.5 years. These differences are minor in nature.

The representativeness of the seed lot must be considered. The Landes provenance in trial 3/65 was similar in height growth, form and flowering characteristics to the Corsican (Tables 5 and 6). However, the wide range of comparisons of these two provenances in Western Australia (Hopkins 1960) usually showed the Landes provenance to have a height advantage over the Corsican and the form characteristics of Landes sources to be more like the Portuguese than the Corsican. Examination of the flowering time for the Landes population concerned in trial 3/65, left little doubt that it is more like the Corsican group than the general Landes groups. This could account for the unexpectedly low fecundity recorded for the Landes provenance in this trial and the rather high order of stem straightness also recorded for the group.

Conclusion

Results obtained within the improvement program quantify variation associated with flowering time and precocity in some provenances of *Pinus pinaster*. Differences are obviously due to genetic control within populations. The Portuguese stock is the first to flower in spring, under Western Australian conditions, and the Corsican is the last to flower. The differences between the two are distinct in the cases measured. The Landes provenance flowers in between these two extremes, is followed by the Tunisian, then the Italian and Corsican.

The Landes and Corsican provenances studied showed less precocity at age 5.5 years than Portuguese and Italian seed lots and had significantly less trees with cones at age 10.5 years.

SIGNIFICANCE OF PROVENANCE VARIATION TO TREE IMPROVEMENT

Introduction

The improvement program for *P. pinaster* in Western Australia began in 1957 (Hopkins and Butcher 1992) and work was centred on the Portuguese provenance for improvement of stem straightness, branching characteristics and uniformity of the commercial tree. The possible contribution of other provenances to improvement in stem straightness, hybrid vigour, branch size, spiral grain, wood density and drought resistance required consideration. In this section results of local evaluations are summarized and reviewed with respect to improvement possibilities for the species.

Tree Vigour

Leirian, Landes, Corsican, Italian Provenances

Three field trials, 3/65, XS12 and XS09 (Table 1), compare major provenance groups from Portugal, Landes, Italy and Corsica.

Trial 3/65 compared the performance of Leiria, Landes, Corsican and Italian provenances and was established at Gnangara plantation in 1964. Growth in the Leirian provenance was significantly greater in height, diameter and volume than in the other provenances, which were similar to each other (Table 4). At age 21 years Landes, Corsican and Italian provenances were 26, 29 and 37 per cent poorer in height growth and had less than half the stem volume of the Portuguese trees.

Growth of the Leiria, Landes and Corsican provenances is also compared in trial XS12 at Yanchep. The trial has 10 families (Table 29) and is well replicated to provide comparisons of both inter- and intra-provenance variation for the major groups. The site has a limestone influence and is more drought-prone than that tested in trial 3/65.

At age 19.5 years (Fig. 7, Table 29) the Landes and Corsican representatives were 19 and 31 per cent respectively poorer in height growth than the Portuguese routine and 51 and 57 per cent less in volume growth. The Landes families are from French collections of half-sib seed from plus trees. Corsican seed came from good stands in the vicinity of Vivario, Porto-Vecchio, Zonza and Ghisoni and represents an altitudinal range from 700 to 900 m.

The MPDL family in trial XS12 (Table 29) is a mixture of half-sib seed from plus trees selected in Portugal (Perry and Hopkins 1967). Average performance was not significantly different from that of the routine source which was bulk collected in the forest of Leiria. The plus trees, selected as dominants or codominants but mainly to favour stem straightness and improved branching, retained their natural vigour in the environmental change. Controlled crosses from plus stems selected in local stands of Portuguese origin (E5xE40, E19xE40) have a 20 per cent increase in tree volume over the non-selected routine (Table 7), at age 20 years (Table 29).

These differences in growth performance between geographic groups occurred from seedling to semi-mature stand (Fig. 7).

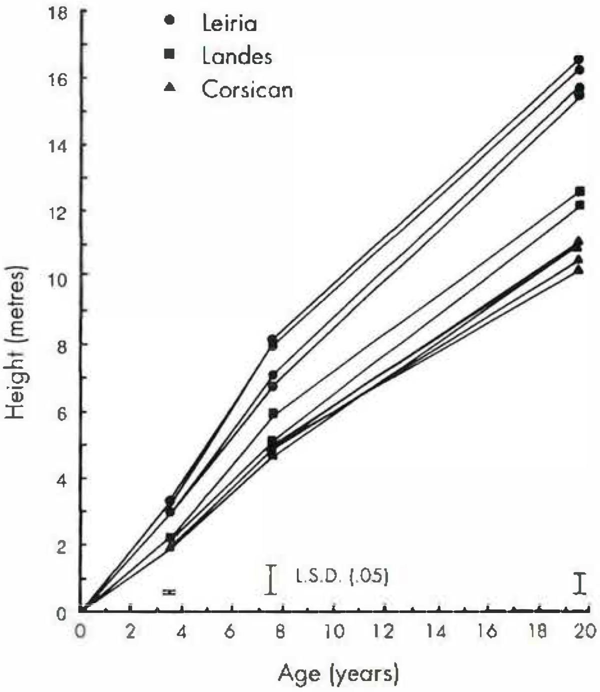


Figure 7. Height growth of provenances in trial XS12. The levels of difference between means, significant at the .05 level of probability, are included for each measurement.

Portuguese, Tunisian, Spanish Provenances

The superiority in vigour of the Portuguese provenances was also found to exist over 24 half-sib Tunisian families from Ain Baccouch in trial XS09 at Gnangara (Table 9). In this trial no significant differences between the routine seed lot from Leiria and two Spanish provenances, collected on the north-west coast near Barreiros (north) and La Toja (west), could be found. At the time of collection the latter were considered to be similar in appearance to stands at Leiria (Perry and Hopkins 1967).

The Barreiros provenance was also tested on limestone soils in the partly controlled trial (XR1) at Yanchep and found to have similar height and diameter growth to the Leirian routine (Table 10). In this comparison of adjacent strips on drought-prone soils the Tunisian half-sib lots were again significantly inferior in height and diameter growth to the Leiria routine (See Table 10, Fig.4).

TABLE 29

Performance of provenance groups in trial XS12 on limestone sands at Yanchep. The mean result for each provenance has been expressed as a percentage deviation from the Leirian Routine control.

PROVENANCE GROUP	STEM STRAIGHTNESS	AGE 19.5 YEARS			DROUGHT LOSSES
	ACCEPTABLE %	MEAN HEIGHT (m) (m² ha⁻¹)	MEAN BAOB (m³ ha⁻¹)	MEAN VOLUME %	
Leiria Improved					
E5xE40	79	16.5	25.21	149	0.0
E19xE40	81	16.3	25.92	147	0.6
MPDL	75	15.8	24.92	139	1.1
Mean	78	16.2	25.35	145	0.6
Deviation	(+29)*	(+5)	(+14)	(+21)	(–65)
Leiria Routine	61	15.4	22.12	120	1.7
Deviation	(0)	(0)	(0)	(0)	(0)
Landes					
L64445	85	12.6	14.29	62	12.8
L64435	76	12.2	12.96	56	6.7
Mean	81	12.4	13.36	59	9.7
Deviation	(+33)	(–19)	(–38)	(–51)	(+471)
Corsican					
C3749	90	10.6	13.73	50	12.8
C3750	87	11.1	13.84	54	8.9
C3751	89	11.0	13.73	53	5.6
C3752	86	10.3	12.96	50	13.3
Mean	88	10.7	8.56	52	10.1
Deviation	(+44)	(-31)	(–39)	(–57)	(+494)

( )* Percentage deviation from the Leiria Routine control.

Half-sib Leiria and Landes

Thirty half-sib seed lots from plus trees collected in the Landes region as part of the French improvement program were supplied for testing in Western Australia. Two lots were included in trial XS12 (Fig. 7) and results of the remaining comparisons are expressed in Tables 13 to 17. The four trials concerned (XS11, YS08, YS09, YS10) sampled soil types and climatic variation at Gnangara, Yanchep and Mundaring plantations.

In trial XS11 (Table 12) all 14 Landes families tested were less than the Portuguese routine in height growth and only 2 families were equivalent in diameter growth at age 10 years. None of the other 13 Landes families tested in other trials (Tables 13, 14, 15, 17) achieved height and diameter growth equivalent to the Portuguese routine.

Three of eleven half-sib families collected from plus trees in Portugal, included in trial XS09, were superior to the routine control in height growth (Table 9). The remainder were comparable to the routine.

Inter-provenance Crosses

The family LSMA in Tables 13 to 16 was an open pollinated cross between ramets of locally selected Landes plus trees and a pollen mix from Leirian plus trees. This family is one of the rare cases in which a seed source associated with the Landaise origin matches, under local conditions, the vigour of the Portuguese routine. Parent selection and/or crossing may have improved the family vigour over that expected in imported Landes groups.

The significance of the dominance in vigour of the Leirian stock in inter-provenance crossing was tested in trials YS51, YS52, and YS53 in which 9 Leirian by

Leirian crosses (ExE) were compared with 9 Leirian by Landes crosses (ExL) and 8 Leirian by Corsican crosses (ExC). All parents were plus trees selected in local stands and the trial was repeated at Gnangara, Yanchep and Busselton. The first two sites are on the coastal plain adjacent to and north of Perth and are respectively, acid grey sands and limestone sands. Busselton, in the southern limit of sites available for *Pinus pinaster* afforestation in the State, is considerably cooler and less drought-prone.

The means in Table 30 for all families of similar crossing show the Leiria by Leiria cross is superior for height and diameter growth at each of the three sites. This growth advantage averages about 10 per cent better than the routine source but is slightly less than the result for the orchard seed which has exclusively superior plus trees as parents (Table 31).

The Portuguese dominance carried into the Leiria by Landes group is 4 to 6 per cent more than the routine for height and diameter growth. Several of the nine families within the Leiria by Landes group did not differ significantly from the best Leiria by Leiria family at each site.

The mean for the Leiria by Corsican group is equivalent to or slightly less than the routine.

The differences in vigour between the crossing groups is further defined in Figure 8. In this Figure the percentage of the families in each crossing group which are ranked within the top one third of the 28 families (i.e. ranked 1–9) for each trial are listed. For height and diameter measurements the Leiria by Leiria crosses dominate at all sites, except for early height growth at Gnangara.

Parents used in these crossings were among the best phenotypes selected from plantations in Western Australia. They are not, however, proven elite trees and several of the Leiria parents used have been culled from the seed orchard as a result of testing.

Relative improvements in the vigour of Landes and Corsican material through crossing with the Portuguese clearly depicts the genetic nature of attributes for vigour within the provenances.

Provenance Stability

The inter-provenance crossing trials YS51, YS52 and YS53 provide the opportunity to examine adaptability and stability of provenance groups over the range of local site conditions (Finlay and Wilkinson 1963; Bilbro and Ray 1976).

The diameter means for the 28 families, at age 9 years, plotted for each site (Fig. 5) show general superiority of the Portuguese influence (ExE) over that of the Landes (ExL) and Corsican (ExC), respectively.

Analysis of variance of the combined results found the site by family interaction to be significant and associated with some changes in the relative ranking of individual families with site (Fig. 5).

To further examine the contribution of provenance to the interaction the routine and orchard families were removed from the data which were re-analysed in a balanced design of 8 common crosses for each provenance group. The site by provenance interaction was highly significant (Tables 21 and 22). This was largely due to the Corsican provenance increasing diameter growth relative to that of the Portuguese provenance as site conditions altered.

Regressions for the mean of each provenance group (8 families) for each block (30 blocks), against the mean for all families in that block provided significantly different lines for the range of sites (Fig. 9). The Leiria by Leiria crosses ($b = 0.83$, $R^2 = 0.88$) tend to below average adaptability (Finlay and Wilkinson 1963) and the Leiria by Corsican crosses ($b = 1.20$, $R^2 = 0.94$) tend to above average adaptability over the range of sites. The Landes crosses ($b = 0.97$, $R^2 = 0.94$) have average adaptability. Very high correlation coefficients for the Landes by Leiria and the Corsican by Leiria data sets are indicative of high stability under the site conditions (Bilbro and Ray 1976). The stability of the Portuguese crosses, although still high, is lower than the others over the site range.

Discussion

The consistent and strong superiority of seed from the forest of Leiria over Landes, Corsican and Italian seed in respect to height, diameter and volume growth, demonstrated in these trials, supports preliminary conclusions (Hopkins 1960). The current series of trials is statistically controlled, cover the full range of sites available for afforestation and embrace a number of different seed collections. These requirements were not satisfied in earlier tests. The Tunisian provenance had not previously been tested locally.

No difference in vigour could be distinguished between the Portuguese routine and two provenances from the Spanish north-west Atlantic coast. Sweet and Thulin (1962) were also unable to separate Spanish Atlantic coastal provenances from those of the Portuguese and French Atlantic coast in trials in New Zealand. In trials on the Spanish north-west coast with 23 provenances from Spain, Portugal, France and Corsica, Rodriguez (1966) reported that the local provenances were superior to all in slenderness and favourable branching. They were also the best in height growth along with provenances from the French Landes region and the Portuguese Leirian forest. From a comparison of 22 provenances at age 7 years at Servanches in the Landes region, Alazard (1982) found that a Spanish seed lot, from Pontevedro, was slightly inferior in height growth to local provenances and Leirian provenances. The form of the Spanish, Landes and Leirian trees was similar.

The dominance of the Leirian in vigour over that of all other provenances of the species has been shown for Western Australia (Hopkins 1960), South Africa (Rycroft and Wicht 1947) and Greece (Matzyris 1982). Rodriguez (1966), in comparing 24 provenances on the north-west coast of Spain, did not separate the local

TABLE 30

Mean values for provenance crosses, the Leirian Routine and seed orchard seed at Gnangara (1), Yanchep (2) and Busselton (3). Heights are for 4.5 years of age, all other measurements at 9.5 years of age.

PROVENANCE GROUP	TRIAL LOCATION	MEAN HEIGHT (m)	MEAN DIAMETER (cm)	PERCENTAGE OF TREES WITH			
				STRAIGHT STEMS	NORMAL STEMS	FINE BRANCHES	FLAT BRANCHES
Leiria	1	3.8	15.5	45	33	69	28
x	2	3.6	14.4	55	45	75	24
Leiria	3	2.8	16.2	54	48	42	46
	Mean	(3.4)	(15.4)	(51)	(42)	(62)	(33)
Leiria	1	3.7	14.6	45	33	58	15
x	2	3.3	13.1	67	69	64	25
Landes	3	2.8	15.5	51	64	35	34
	Mean	(3.3)	(14.4)	(55)	(56)	(52)	(25)
Leiria	1	3.3	14.2	51	50	55	17
x	2	3.1	12.5	68	76	76	19
Corsican	3	2.7	15.6	73	72	39	47
	Mean	(3.0)	(14.1)	(70)	(66)	(64)	(31)
	1	3.6	14.3	22	22	63	16
Routine	2	3.2	12.7	48	48	68	24
	3	2.6	14.7	28	44	37	37
	Mean	(3.1)	(13.9)	(33)	(38)	(56)	(26)
Seed	1	3.8	15.2	64	46	72	18
Orchard	2	3.6	14.7	68	66	84	26
	3	2.9	16.3	62	51	40	34
	Mean	(3.5)	(15.4)	(65)	(54)	(65)	(26)

( ) Group Mean for the three locations.

TABLE 31

Variation from Routine seed lot values of composite means (3 locations) for provenance groups in trials YS51, YS52, YS53. Plus trees of Leiria, Landes and Corsican origin are coded E, L and C, respectively.

PROVENANCE GROUP	NO. FAMILIES	PERCENTAGE DEVIATION FROM ROUTINE SEED					
		HEIGHT (4.5YR)	DIAMETER (9.5YR)	STRAIGHT STEMS	NORMAL STEMS	FINE BRANCH	FLAT BRANCH
ExE	9	10	11	55	10	11	27
ExL	9	6	4	67	47	−7	−4
ExC	8	−3	1	112	74	14	19
Routine	Mix	0	0	0	0	0	0
Orchard	Mix	13	12	97	42	16	0

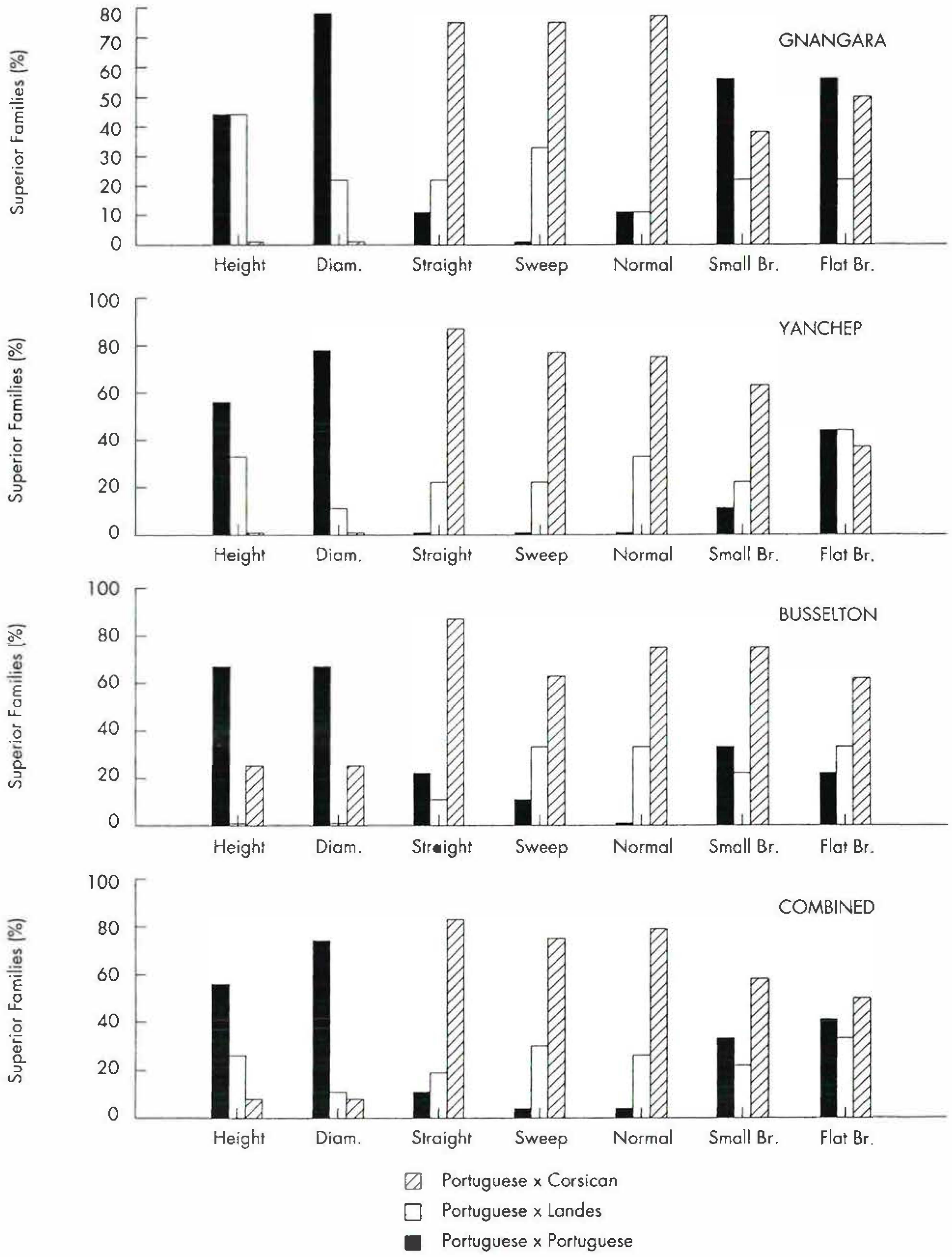


Figure 8. Proportion of inter-provenance crosses in trials YS51, YS52 and YS53 with superior growth and form and ranked within the best one third of all families.

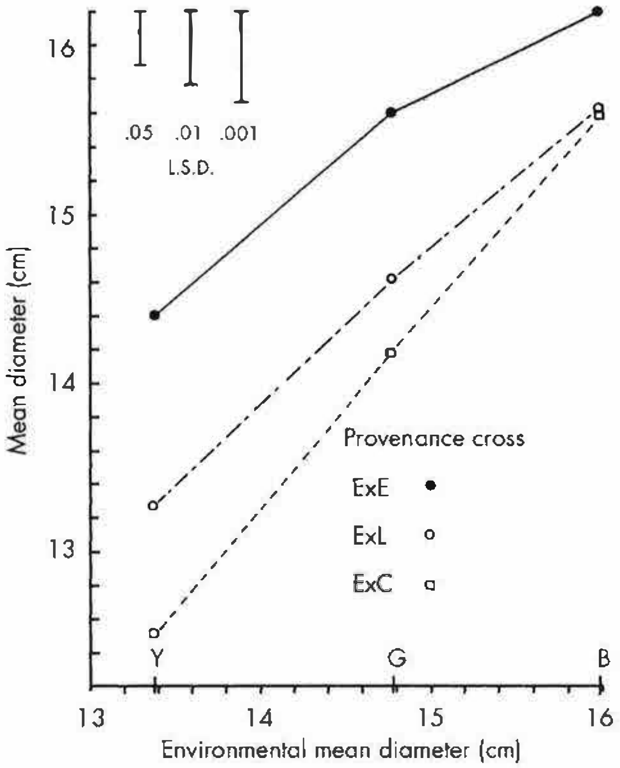


Figure 9. Interaction in diameter growth between provenance groups (8 families each) planted at Yanchep (Y), Gnangara (G) and Busselton (B). The Corsican influence (ExC) and to a lesser extent the Landes influence (ExL) is associated with better growth with the cooler, moister conditions progressing from Yanchep in the north to Busselton in the south.

source, the Landes, Leirian and an Esterel seed batch for top height and volume growth. Similarly, in New Zealand, Sweet and Thulin (1962) found that Landes and Leirian lots performed best of a wide range of provenances tested for height growth at age 5 years but were not significantly different from each other. They suggested there were no grounds to separate the Landes and Leirian groups on the basis of their results.

Illy (1966) and more recently Alazard (1982) have conclusively established the dominance in vigour of the native provenance over all others tested under Landes conditions. They attribute this largely to the relatively cooler nature of the sites and the inherent frost resistance of the local source. Reports on the performance of the species under recent severe winters in France (Alazard 1986; Chaperon 1986) identify the Landes as the most resistant and the Leirian provenance as the least resistant to frost damage. The Corsican is second in resistance with the Moroccan and the north coast Spanish following.

The inter-provenance crossings in the current trials clearly show an overall dominance in vigour for the Portuguese provenance (See Figs 5 and 9) while demonstrating some decline in adaptability and stability of diameter growth along a north-south gradient of increasingly cooler and wetter conditions (See Fig. 9, Table 22). Although the Portuguese provenance has superiority in vigour at this southern site, the data suggest that the Corsican and possibly the Landes genotypes are becoming more competitive under the cooler conditions.

Different performance of provenances in France (Alazard 1982) and New Zealand (Sweet and Thulin 1962) compared with that in Western Australia (Hopkins 1960), South Africa (Rycroft and Wicht 1947) and Greece (Matzyris 1982) may be attributed largely to adaptation of the Portuguese provenance to the warm, frost free conditions of these three regions.

DROUGHT RESISTANCE

During the development period of the current local provenance trials, the worst drought recorded for the area (1976–77) was common to the planting sites. The trial provenances were then aged approximately 10 years, embraced both favourable and drought-prone sites and provided ideal conditions to compare the drought resistance of provenances of the species.

Drought damage was assessable in trial XS12 (Table 8) and trial YS09 (Table 16) at Yanchep and trial XS11 (Table 12) at Gnangara. Results show superior drought resistance in the Leirian provenance to that in Landes and Corsican seed batches.

At the onset of the drought the Leiria routine in trial XS12 carried 80 per cent more stem volume and 20 per cent greater basal area than the Landes and Corsican stands and thus was more prone to drought. Yet it had only 2 per cent drought mortality compared with 10 per cent in the stands of smaller biomass and different origin (Table 8).

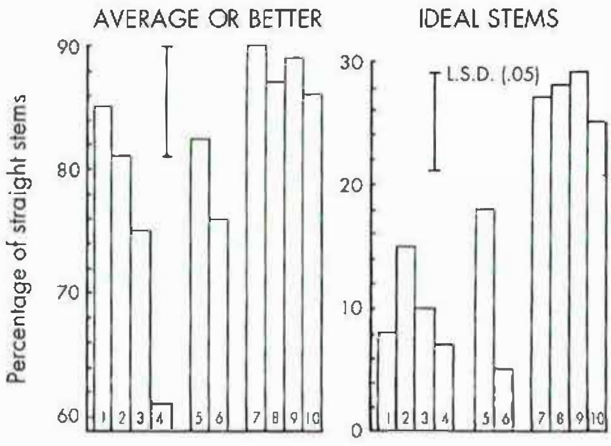
Results also show that selection and controlled crossing have favoured drought resistance over that in the non-selected, routine seed batches. This desirable trait, resulting from selecting dominant stems in local stands of Leirian origin, is accompanied by significant increases in vigour (Table 29). Also, in trial YS09 (Table 17) drought deaths in the half-sib Landes families varied from 0 to 10 per cent with the more vigorous locally selected Leiria by Landes cross (LSMA) suffering negligible drought damage. The results suggest there is scope for improvement in drought resistance within the Landes provenance.

Trial XS09 at Gnangara incorporated Spanish and Tunisian provenances. No mortality owing to the drought occurred in either of these provenances although surrounding trials were affected. The high survival rate could have been due to a favourable site but it is believed to be associated with a resistance like that of the Portuguese. This was partly confirmed by the non-replicated trial XR1 at Yanchep where performance between these three groups was similar, despite considerable mortality in the trial. The Italian provenance was almost destroyed in this trial (Table 10) and appears as the least resistant of all provenances tested.

No other quantitative comparisons of field drought resistance of provenances of *Pinus pinaster* exist but Destremau *et al.* (1982) note that the north African groups have high drought resistance. Hopkins (1971b) assessed the relative drought resistance of Portuguese, Landes, Tunisian and Corsican provenances from controlled studies of seedlings. The results, particularly from the viewpoint of improved resistance of selected material, are verified by the current field results.

Nguyen and Lamant (1989) report that Guyon (1980, 1982) and Sarrauste (1982) characterized different populations of *P. pinaster* according to shoot growth, needle water potential and biomass responses to drought. They found two provenances that differed greatly in drought sensitivity. Compared with the Tamjoute provenance from Morocco, the Landes provenance grew vigorously in well watered conditions, but relatively poorly when subjected to drought. Nguyen and Lamant (1989) found the Moroccan seedlings had a higher root elongation rate than the French seedlings. They also had a greater capacity for osmotic regulation, enabling them to maintain a greater water potential difference between root and soil, favouring water extraction under drying conditions.

The high drought resistance recorded in Western Australian trials supports a hypothesis of natural selection to favour the Leirian race on frost free, warm sites and the Landes race on frost prone, cooler sites.



LEIRIA	LANDES	CORSICAN
1 – E5 x E40	5 – L64445	7 – C3750
2 – E19 x E40	6 – L64435	8 – C3753
3 – MPDL		9 – C3749
4 – Routine		10 – C3752

Figure 10. Frequencies of straight stems in provenances tested in trial XS12. Average or better refers to stems scored 1 to 3 on a 1 (best) to 5 (poorest) scale. Ideal stems were scored 1 and 2.

Stem Form

Straightness

Results for assessment of stem straightness in trial 3/65 (Tables 5 and 6) do not separate the two Portuguese provenances on the basis of proportion of leaning trees, straight stems, ramicorns and steepness of branching. Both were significantly inferior to the Corsican seed lot in all of these respects and to the Landes in all attributes except the proportion of trees with ramicorns. The Italian provenance had the least straight stems.

Stem straightness was also compared at stand age 7.5 years in trial XS12 (Fig. 10). The routine, MPDL half-sib and one Landes group were low in percentage of average and above average straight stems. One Landes group and all the Corsican groups were significantly superior to the routine. Within the Portuguese group the two improved full-sib families were also significantly straighter than the routine group (Fig. 10). This showed success in the plus tree selection process which aimed to favour stem straightness. In trial YS08 (Table 14) no difference in straightness could be found between the Landes half-sib families and the Portuguese routine. Again, in this trial, highly significant improvement (.01 level) in stem straightness over the routine batch resulted from selection and controlled crossing within the Portuguese provenance.

The heritable nature of stem straightness within provenances of the species is measured by crosses between Leiria, Landes and Corsican trees selected for straightness, with Leiria plus trees, in trials YS51, YS52, YS53. The Corsican crosses (ExC) were consistently superior in percentage of straight stems and non-forked normal stems at the three sites tested (Fig. 8, Table 30). The Landes crosses (ExL) were next in order of importance with the Leiria crosses (ExE) similar to the Landes in straightness but definitely inferior on the basis of apical dominance. Stem forking is a major defect in the provenance and this is borne out by the low percentage of non-forked stems obtained for both the routine Portuguese batch and the Leiria by Leiria cross in Tables 30 and 31. Results from the progeny of the Leirian seed orchard show a definite early improvement in the proportion of straight stems and apical dominance, through selection.

Differences in the inheritance of attributes for stem straightness are perhaps more clearly expressed in Figure 8. This Figure shows the percentage of families in each group of controlled crosses (ExE, ExL, ExC) occurring in the best families ranked for stem straightness and non-forked stems. For straightness the Corsican crosses have absolute superiority (83 per cent). There is little difference between the Leirian and Landes crosses (7 and 15 per cent) for straightness.

Seventy-nine per cent of the Corsican cross trees had a single leader compared with only 4 per cent for the Leirian crosses, again emphasizing the deficiency of the Leirian race in this respect.

These results show a remarkable improvement in the Leirian provenance through selection and controlled crossing. It may also be desirable to improve to the full potential for the species by hybridizing with Corsican select stems, a strategy recommended for improvement of the Landes group by Alazard (1982).

Branching

Steep, high angle branching is usually associated with the Atlantic race. Compared with the Corsican race, branching of the Landes and Leiria provenances is also considered to be relatively heavy and irregular.

In trial 3/65 (Table 6) the Portuguese provenances had significantly steeper branching than the Landes, Corsican and Italian provenances, which were inseparable in this respect. Results from trial YS08 (Table 14), however, showed no significant differences in branch angle between Landes, routine and selected families.

It can be seen from Table 14 that selection may alter the proportion of trees with low (flat) angled branching in the Portuguese population. Superior branch angle characteristics were recorded in only 2 of 14 full-sib families, and in 1 of the 14 branching was significantly steeper than in all other families in the trial.

Differences in branch thickness between the two Atlantic provenances are not so distinctive. In trial YS08 (Table 14) three of the four Landes families were not significantly different from the routine Portuguese in percentage of favourable small branched trees while the remaining family was poorer in this respect. Most full-sib families in the trial had better branch size characteristics than the routine seed source.

Inter-provenance crossing of Leiria by Leirian, Landes and Corsican groups in trials YS51, YS52, YS53 revealed considerable variation in the branch angle and branch thickness, with site (Table 30, Fig. 8). On the basis of average values for each provenance group shown in Table 31, the Leiria and Corsican have similar proportions of trees with acceptable flat branching with the Landes less acceptable. Comparison of the percentages of the families in each provenance group which occur in the top third of rankings for branch angle (Fig. 8) does not alter the situation. Similarly, the percentage of trees with fine branching alters somewhat with site. Results suggest that the Corsican crosses have a small advantage in the number of favourable stems.

Results for branch angle (Table 31) showed no improvement in the proportion of favourably branched stems in the orchard progeny over the unimproved routine. Improvement in branch thickness due to selection in the seed orchard population is considerable and the quality obtained approaches that of the Corsican crosses. Of the individual families which are the best or not significantly different to the best in branching, in the three trials, several are from crosses between Leirian plus trees (Tables 26 and 27). Improvement in branching could thus be obtained through tree selection within the provenance and there appears to be little merit in inter-provenance crossing to achieve this objective.

Discussion

Early studies in South Africa and Western Australia revealed the superiority of provenances from Corsica in stem straightness, absence of forks, regular, flat and fine branching and symmetrical crowns (Rycroft and Wicht 1947; Hopkins 1960). The outstanding form of this provenance has since been acknowledged from tests in France (Alazard 1982), Greece (Matzyris 1982), New Zealand (Sweet and Thulin 1962) and north Spain (Rodriguez 1966). It would appear that for decreasing ranking of stem straightness the Corsican provenance is followed first by provenances from Morocco and the Mediterranean coast of France and these are followed by the Atlantic coast and Genova-La Spezia provenances. The Luccan and some of the inland Spanish seed lots were inferior in stem straightness in New Zealand (Sweet and Thulin 1962). For percentage of trees judged acceptable for leader dominance in New Zealand, the Corsican, Italian and Moroccan seed lots had high values while the Atlantic coast provenances were less acceptable.

Experience in Western Australia and South Africa would generally place the Portuguese race slightly superior to the Landes in straightness. Sweet and Thulin (1962) were not able to separate these two geographic provenances on the basis of percentage of acceptable trees in trials in New Zealand. However, the high level of stem forking and ramicorn development is a major commercial defect in plantations of Portuguese origin (Rycroft and Wicht 1947; Hopkins 1960).

The Atlantic races have usually been attributed with long clean internodes and relatively high angle branches, with the Portuguese origin the most pronounced in these respects (Perry 1949; Hopkins 1960). Destremau *et al.* (1982) suggested that the Corsican race is usually uninodal, the Leirian race is occasionally multinodal and the Landes and Tunisian races are nearly always systematically multinodal. The present studies support these observations.

Flowering

Perry (1940, 1949) noted that the onset of flowering in provenances compared in the same plantation, under identical cultural conditions in Western Australia, was genetically controlled. The Portuguese race was the first to flower in early spring, followed by the French Landes and French Esterel and last of all the Corsican. This separation of approximately three weeks in onset of flowering between the Portuguese and Landes and Landes and Corsican races is also recorded for French provenance comparisons by Destremau *et al.* (1982).

Propensity for cone production has also been noted to vary with provenance. Prolific flowering of the Esterel and sparse flowering and cone production of Corsican seed lots noted by Perry is recorded for young plantation trials in New Zealand by Sweet and Thulin (1962). They also commented on the sparse flowering of trees of Moroccan origin. Rycroft and Wicht (1947) recorded sparse cone production of Corsican seed lots under South African conditions. Matzyris (1982) measured significant differences in the proportion of provenances bearing cones at the age of 9 years in trials in Greece. The most prolific provenances were Landes and Cevennes from France while the Corsican provenance produced the least cones at this age. Matzyris reported that the Portuguese provenance was also a low cone producer. Destremau *et al.* (1982) noted that the Tunisian race was a very precocious flower producer and flowered abundantly in the second year in the plantation. This fact was verified in trials of Tunisian plus trees in Western Australia.

Flowering Times

Results obtained within the improvement program quantify variation associated with flowering time and precocity in some provenances of *Pinus pinaster*. Differences are obviously due to genetic control within populations. The Portuguese and north-west Spanish provenances were the first to flower in spring, under Western Australian conditions, and the Corsican was the last to flower. The differences between these two extremes are distinct in the cases measured. The Landes provenance flowers in between these two extremes, is followed by the Tunisian, then the Italian and Corsican.

Fruitfulness

The Landes and Corsican provenances studied showed less precocity at age 5.5 years than Portuguese and Italian seed lots and had significantly less trees with cones at age 10.5 years.

Discussion

Results obtained are in accord with the general trends reported. They reveal, however, the great variation between genotypes within a population. Population means for a large sample should demonstrate that the Portuguese flowering is distinct from that of Landes with Corsican latest of the three. Variation within the species is in fact continuous and small or non representative samples could confuse the results.

The requirement for comprehensive sampling to overcome natural variability was also noted as essential for differentiation of terpene contents of provenances by Bernard-Dagan *et al.* (1971). They found that intra-specific variability of monoterpene contents of trees in the Landes district was not strong enough to be clearly shown with less than ten trees in a sample.

The importance of the representative nature of the seed lot in provenance comparisons was demonstrated in the field trials. The Landes provenance in trial 3/65 was similar in height growth and flowering characteristics to the Corsican (Tables 5 and 6). This is contrary to previous comparisons of these two provenances in Western Australia (Hopkins 1960). Examination of the flowering time for the Landes population used in trial 3/65 left little doubt that it has more akin to the Corsican group than to the general Landes group. Hence, although significant differences in precocity and stem straightness were associated with genetic origin in the trial, the provenance groups were not truly representative. Sampling to define the variation both within and between provenance areas is essential for realistic generalizations of differences between geographic groups of a species.

Results support reports of genetic control of precocity in provenances of *Pinus pinaster* (Sweet and Thulin 1962; Destremau *et al* 1982; Matziris 1982). The Landes and Corsican provenances studied showed less precocity at age 5.5 years than Portuguese and Italian seed lots and had significantly less trees with cones at age 10.5 years.

Knowledge of the variability in the time of flowering and fecundity between clones was important in designing the complement of grafts in seed orchards. Some clones within the populations under selection had a limited probability of crossing during the different optimum periods of receptivity. Other clones were prodigious cone producers and required less representation in stems in the orchard. Variation in the period of flowering and propensity for seed production are important to orchard balance. Fruitfulness also has a direct bearing on the unit cost of seed produced in an orchard.

Wood Properties

There is little information on the physical wood properties of the various provenances although considerable research has been carried out in Europe on resin properties and wood chemistry of trees and provenances (Bernard-Dagan *et al.* 1971).

Rycroft and Wicht (1947) measured wood density of sample discs from comparative trials in South Africa and found the Portuguese trees to have the highest density. Landes was next in order with Esterel, Corsican and Moroccan of lowest density. Generally the fastest growing trees yielded wood of highest density but the overall density range was small.

Nicholls *et al.* (1963) assessed wood properties of trees from early Western Australian provenance trials at Gnangara comparing provenances of Corsican, Landes, Esterel and Leirian origin. Basic density of Corsican wood was found to be markedly lower than the others. Differences in tracheid length were small. This study was followed (Nicholls 1967) with another using material from the Somerville provenance trial in Western Australia (Hopkins 1960). The Leirian provenance had the most favourable (least) grain deviation characteristics and again the Corsican was the poorest of the four provenances in this characteristic. Average tracheid length was similar in all provenances except in mature wood where the Esterel was significantly (.01 level) higher. Basic density of the Leiria was significantly higher than all other provenances.

Nicholls (1967) concluded that the trees of the Corsican provenance were inferior in wood quality and that the Leiria provenance offered the best potential for the improvement of wood characters in *Pinus pinaster*.

Perry measured spiral grain in 85 plus trees selected in Portugal and also took cores for analysis by the Commonwealth Scientific and Industrial Research Organisation (Perry and Hopkins 1967). Spiral grain varied from 0 to 6 degrees and density of mature wood ranged from 0.42 to 0.58 g/cc, within this selection (Nicholls 1968). The range of variation in basic density in both juvenile and mature wood is quite adequate to allow for improvement through breeding.

Racial Groupings

Provenance field trials in Western Australia (see Table 1) are of conventional field plot designs which effectively determine the significance of similarities or differences between individual attributes measured. For such designs normal analysis of variance (ANOVA) procedures assess the significance of the variation between treatments or families. Where significance is established for treatment variation, differences between the means of treatment attributes are assessed by least significant difference procedures.

The practice assesses accurately the superiority of families for height growth, stem straightness, time of flowering and one could ensure that parents employed in the breeding program were superior to a standard or control at a specified level of significance. This provides a reproducible selection differential. Selection becomes more complicated when breeding a number of traits concurrently and procedures such as combined index selection (Cotterill 1986), which integrate the family means and individual tree values for multiple traits into a single number or index, have been developed.

Similarly, from the point of defining provenance groups, it is desirable to be able to consider the commonality of grouping of the typical attributes, rather than the difference in one particular attribute. For this requirement the ANOVA is not necessarily satisfactory (Freeman 1973).

For trials 3/65 and XS12 which include a useful geographic range in families, discriminant analysis was used to confirm the importance of the differences of attributes measured in standard ANOVA procedures and to test the strength of expression of attributes that were assumed from results to be representative of major provenance groups.

Trial 3/65

Data obtained for each of the five provenances for pollen, cones, height, bends, multinodes, butt sweep, high angle branching, ramicorns and straightness in trial 3/65 (Tables 4, 5 and 6) were analysed by discriminant methods. All data except those for height were transformed to angle arcsin for the analysis.

The first analysis, termed Run 1, considered the five provenances Leiria R, Leiria 2, Landes, Italian and Corsican and all of the attributes mentioned above. Two of the four functions separated (Table 32) were highly significant and a territorial map was plotted for the centroids of each group, assuming all functions but the first two were zero (Fig. 11). The analysis correctly classified 92 per cent of the 25 actual groups. One Leiria R case was incorrectly classified as Leiria 2 and one Leiria 2 case was incorrectly classified as Leiria R; all other groups were correct.

Run 2 was similar to Run 1 but omitted height data, the most obvious difference measured between the groups and one in which the phenotypic expression is known to vary with climate of the test site (Alazard 1982). From Table 32 it can be seen that height was the major factor determining Function 2 in the scatterplot.

Run 2 correctly classified 84 per cent of the cases (Table 32) confusing one Leiria R for one Leiria 2, one Leiria 2 for one Leiria R, one Landes for Corsican and one Corsican for Landes. Again, three main groupings Leiria, Corsican and Landes and Italian were distinguished in which Leiria R and Leiria 2 and Landes and Corsica were not completely separated from each other (Fig. 11). The major contributors to Function 1 were the percentage of trees bearing cones in 1978 and percentage of trees with favourable branch angle. Percentage of straight stems was the major contributor to Function 2.

For Runs 3 and 4 the provenances were coded into three groups 1 – (Leiria R and Leiria 2), 2 (Landes and Corsican) and 3 (Italian). The analysis was highly significant and correctly grouped 100 per cent of the actual members. In Run 3 data for height, high angle branching and cones counted in 1968 were analysed. Again for Run 4 height data were omitted and groups were tested against cones in 1968, high angle branching, straightness, bends and ramicorns.

Trial XS12

Trial XS12 is a randomized block experiment with five replications. In ANOVA there were no significant block effects in measurements for height, diameter, average stem straightness (percentage 1, 2, 3 classes) and ideal stem straightness (percentage 1, 2).

In Run 1 the ten provenance families were analysed for the above mentioned attributes and two of the four canonical functions were highly significant (Table 33). Thirty-five of the 50 groups were placed correctly. Of those misplaced, five were Leirian placed in different Leirian groups, one Landes group was placed in the other Landes group and the other nine were Corsican placed in other Corsican groups. The scatter diagram in Figure 12 shows that although 70 per cent success was achieved in placing data groups into their correct family, there was virtually 100 per cent success in separating three distinct geographic races.

Run 2 used only five provenance groups – 1 (Portuguese Full-sib 1 + Full-sib 2) + 2 (Portuguese MPDL) + 3 (Portuguese Routine) + 4 (Landes 1 +

TABLE 32

Results from canonical discriminant analyses of measured attributes in trial 3/65.

CANONICAL DISCRIMINANT FUNCTIONS

	RUN 1				RUN 2		RUN 3	
Function	1	2	3	4	1	2	1	2
Eigenvalue	135	20.5	2.46	0.31	76.4	3.25	49.5	1.01
Percent of Variance	85.4	12.9	1.6	0.2	95.4	4.1	98.0	2.0
Cumulative Percent	85.4	98.3	99.8	100	95.4	99.5	98.0	100
Canonical Correlation	1.00	0.98	0.84	0.48	0.99	0.88	0.99	0.71
Wilks' Lambda	0.00	0.01	0.22	0.77	0.00	0.16	0.01	0.50
Degrees of Freedom	36	24	14	6	20	12	6	2
Significance	0.00	0.00	0.03	0.60	0.00	0.00	0.00	0.00
Provenance Groups		5			5		3	

STANDARDIZED CANONICAL DISCRIMINANT FUNCTION COEFFICIENTS

FUNCTION	1	2	3	4	1	2	1	2
Pollen 69	0.94	-1.18						
Cones 68	1.63	-0.02			1.28	0.18	1.11	-0.43
Height 75	-1.89	2.83					0.58	0.88
Bends 75	-0.27	0.59	Not		0.18	-0.30		
Multinode 75	0.14	0.21						
High Angle 75	1.10	0.21			0.79	0.18	0.89	0.18
Ramicorns 75	0.94	-0.64	Relevant		0.61	0.23		
Straightness 75	-0.73	0.21			-0.51	0.94		
Cones 75	1.59	-1.53						
Percentage of Groups Correctly Classified		92%			84%		100%	

Landes 2) + 5 (Corsican 1 + Corsican 2 + Corsican 3 + Corsican 4).

The analysis for the first two canonical functions was again highly significant, differentiating mainly in coefficients for height in Function 1 and for d.b.h.o.b. and straightness in Function 2. All but six of fifty cases were correctly classified. Of these six, all were Leirian misplaced into alternative Leirian cases, generally from full-sib and routine into the half-sib (MPDL). The scatter diagram in Figure 12 depicts three distinct racial groups.

Run 3 grouped the provenance family data into three groups, Leiria, Landes and Corsican. The analysis was highly significant and correct grouping was achieved for 98 per cent of cases, the exception being the one Corsican case that is actually closer to the centroid for the Landes data (Fig. 12).

Discussion

Discriminant analysis assists in the interpretation of provenance variation in four aspects:

1. It provides an alternative method to evaluate the utility of the classification procedures used for assessment of attributes of form and flowering.
2. A further appreciation is obtained of the factors or attributes which are strongest in separating the provenances.
3. Further to 2, it shows that the geographic groupings are valid (in trial 3/65) independent of height data which may vary in expression in different countries (Sweet and Thulin 1962; Alazard 1982).
4. It substantiates the extent to which measured attributes relate to the original families, i.e. inheritance.

Results, which employ different provenance groups in each trial, substantiate the basis for identified geographic races (Destremau *et al.* 1982). The Portuguese, Italian, Corsican and Landes appear as distinct groups. Even in the analysis for trial 3/65 where the Landes and Corsican and Leiria were grouped to show close relationships, in the initial Run 1 the Landes and Corsican groups were correctly separated and only one in five of the cases in each of the

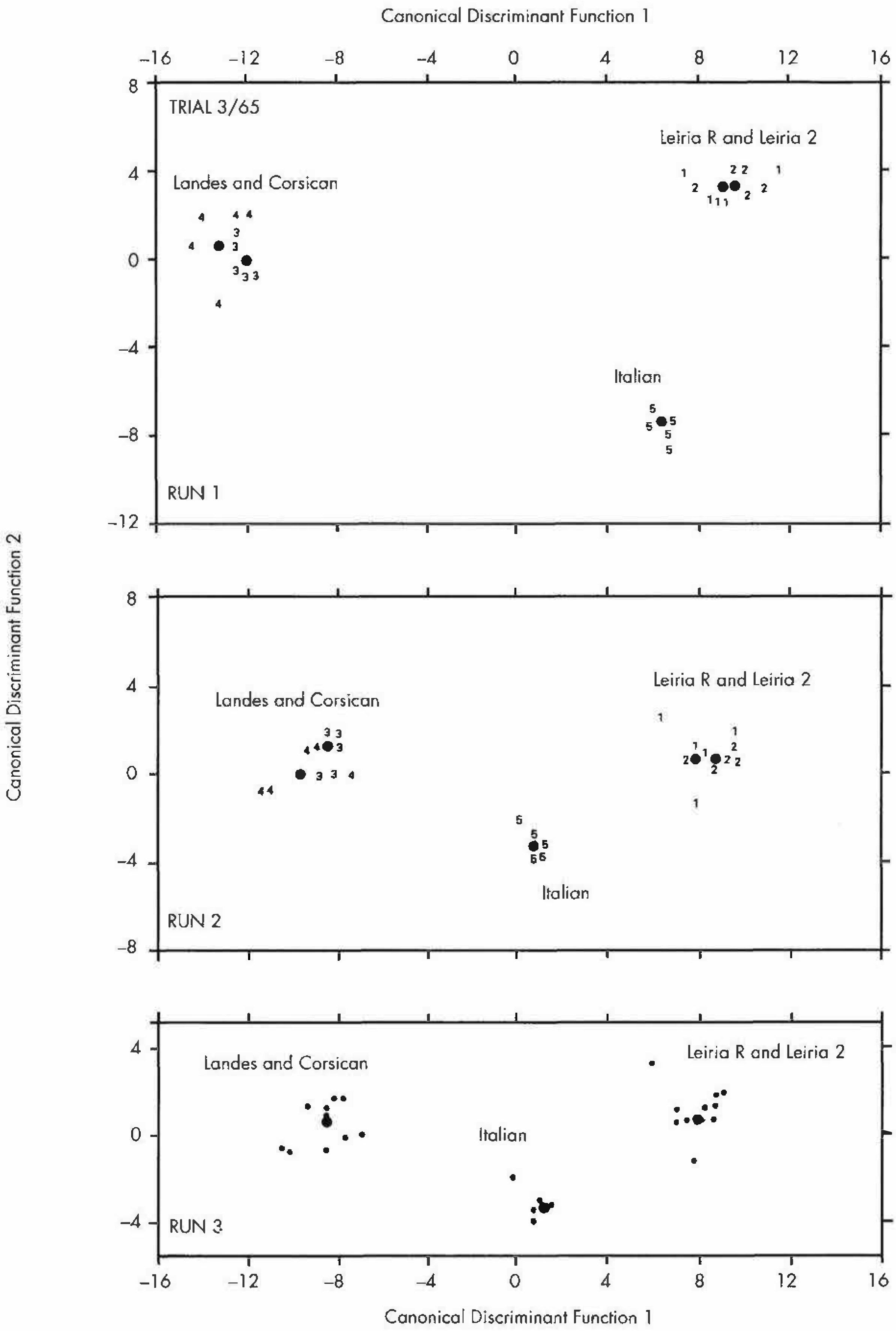


Figure 11. Discriminant analysis of field data measured in trial 3/65 showing clear separation of provenance groups.

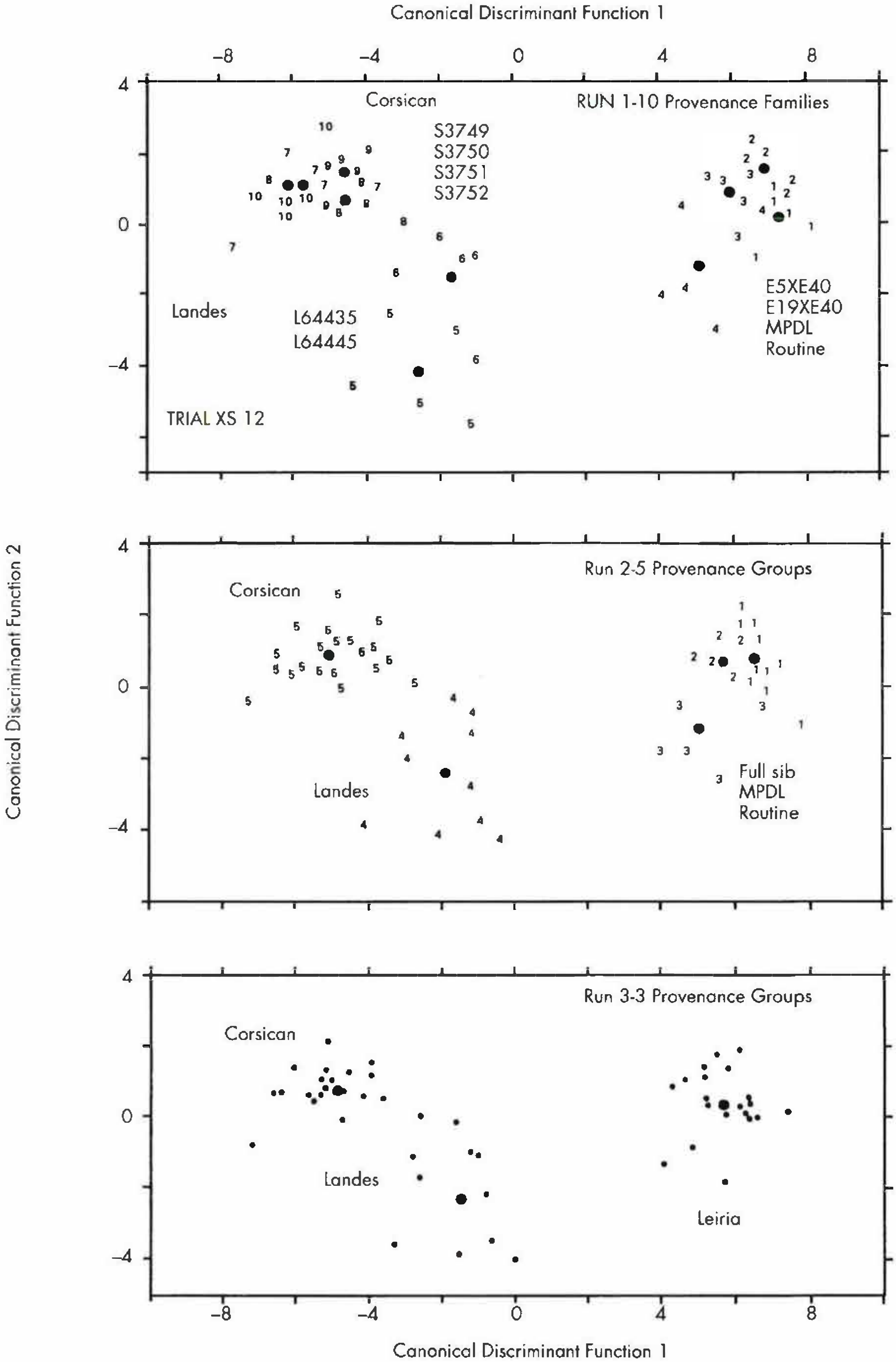


Figure 12. Discriminant analysis of field data measured in trial XS12 showing separation of provenance groups.

TABLE 33

Results from discriminant analyses of measured attributes in trial XS12.

CANONICAL DISCRIMINANT FUNCTIONS

	RUN 1				RUN 2		RUN 3	
Function	1	2	3	4	1	2	1	2
Eigenvalue	35.6	3.71	0.36	0.18	28.5	2.01	24.7	1.41
Percent of Variance	89.4	9.3	0.9	0.5	92.6	6.5	94.6	5.4
Cumulative Percent	89.4	98.7	99.6	100	92.6	99.1	94.6	100
Canonical Correlation	0.99	0.89	0.51	0.39	0.98	0.82	0.98	0.77
Wilks Lambda	0.00	0.13	0.63	0.85	0.01	0.26	0.02	0.42
Degrees of Freedom	36	24	14	6	16	9	8	3
Significance Level	0.00	0.00	0.14	0.33	0.00	0.00	0.00	0.00
Provenance Groups		10			5		3	

STANDARDIZED CANONICAL DISCRIMINANT FUNCTION COEFFICIENT

FUNCTION	1	2	3	4	1	2	1	2
Height	0.89	–0.46	Not		0.88	–0.51	0.99	–0.54
Dbhob	0.27	1.05			0.26	0.99	0.15	1.02
Straightness 1,2,3	–0.17	0.27	Relevant		–0.19	0.36	–0.43	–0.00
Straightness 1,2	0.00	0.86			–0.12	0.58	–0.15	0.67
Percentage of Groups Correctly classified		70%			88%		98%	

Leiria R and Leiria 2 data were confused with the adjacent provenance. This common grouping supports the similarities found for individual traits by the ANOVA procedures and provides a desirable integration of the ANOVA results.

It has previously been noted that the Landes family (S2865) used in trial 3/65 was more akin to the Corsican norm for time of flowering, low vigour and high percentage of straight stems (Tables 4, 5 and 6). This observation is supported by the present analysis in the close affinity of the Landes bulk provenance with the Corsican, demonstrated in Figure 11.

The tight grouping of the Leirian routine, half-sib and full-sib families represents a tree type typical of seed from Leiria and the refinement of major variabilities within the population.

Within the present study, discriminant analysis provides a clear illustration of the unique and heritable characteristics of geographic races within the species.

Adequacy of Studies

Bernard-Dagan *et al.* (1971) and Sweet and Thulin (1962) stress the need for provenance sampling to be fully representative and statistically identifiable with the population it is required to depict. Current studies support this and suggest that trials which do not permit intra-provenance as well as inter-racial comparisons are of limited value in commenting on geographic genotypes.

Trial XS12 in the local studies, although relatively small, was ideal in allowing inter-and intra-provenance comparisons. Most other trials had satisfactory representation within a geographic group and reliability in sampling for seed collection. Trial 3/65, on the other hand, was not replicated within provenance groups except for the Portuguese and provided uncharacteristic results for vigour, branching, straightness and fecundity for the Landes provenance. The deficiency demonstrates clearly the wide variation present within any geographic grouping.

Many trials designed for forestry purposes are also biased in that they sample specific phenotypic characters of commercial importance i.e. dominant height growth, diameter growth, stem straightness (Rycroft and Wicht 1947). Both the sampling procedure and the assessment procedure of the trials carried out may fall short of the requirements of a geneticist or physiologist. Despite these possible shortcomings, consistent and distinctive attributes are associated with provenances from different geographic areas. Association of the phenotypic variation of characters of commercial interest to forestry with a genetic imprint with geographic identity is proven.

Current studies reveal the continuous nature of variation within a species and the actual geographic ranges which could be associated with the dominant transmission of an attribute is still to be defined. To a degree, the extent of grouping or classification is a matter of convenience depending on the attributes measured, accuracy of measurement, range of variation studied and grouping or analysis procedure employed.

Knowledge obtained from a wide range of field trials and literature reports satisfactorily delineate populations for practical breeding programs. Characters of importance within each provenance can be separated and developed within breeding programs.

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