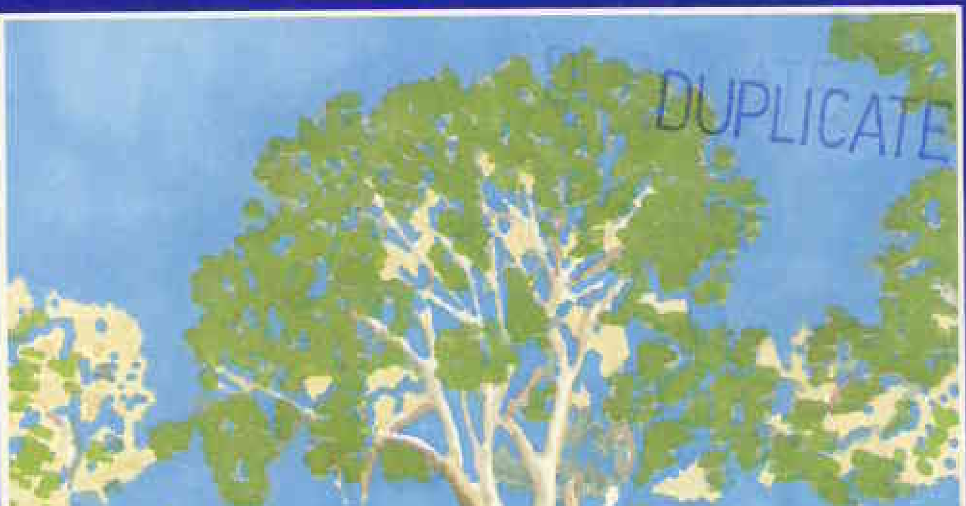
ECOLOGY OF JARRAH (*Eucalyptus marginata*) IN THE NORTHERN JARRAH FOREST OF WESTERN AUSTRALIA

by Ian Abbott and Owen Loneragan



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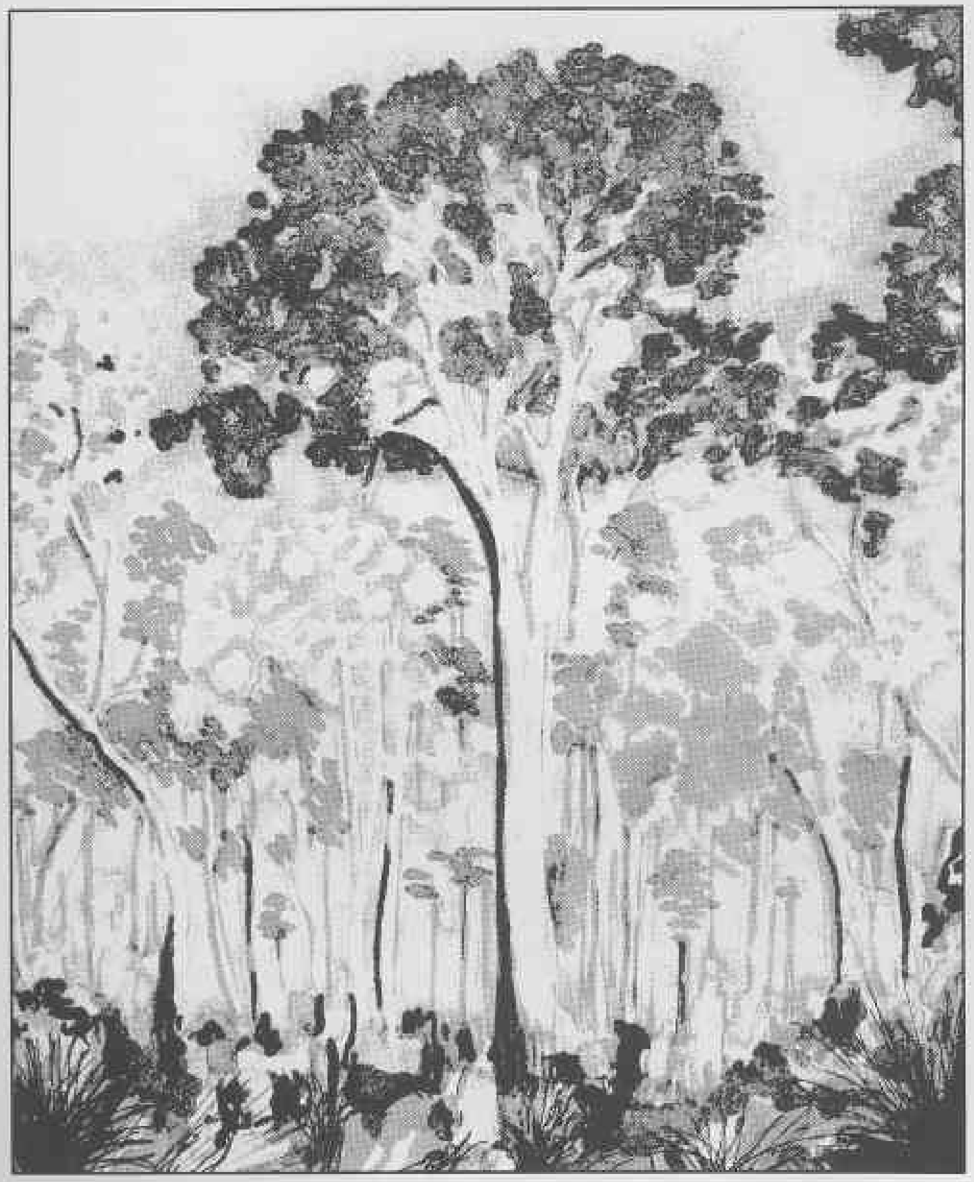

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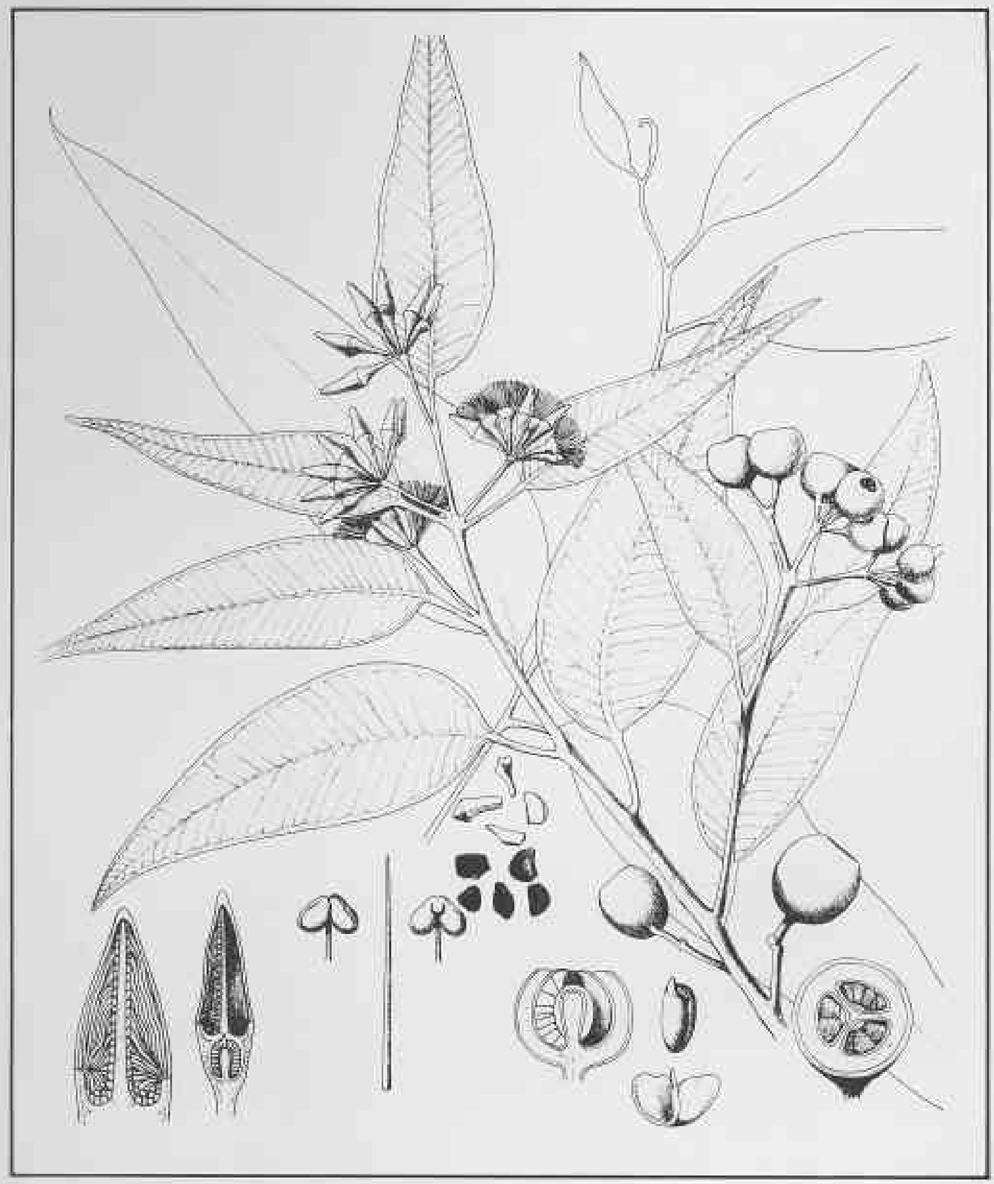

Frontispiece
The leaves, flower buds, flowers, fruit and seeds of jarrah (from von Mueller 1879)

CONTENTS

FIGURES

TABLES

ABBREVIATIONS

The following are used throughout:

A.P.I.	Aerial Photographic Interpretation.
b.a.	Basal area.
b.a.i.	Basal area increment.
b.a.o.b.	Basal area over bark, always based on diameters measured 1.3 m above ground level.
b.a.u.b.	Basal area under bark, ditto.
c.a.i.	Current annual increment.
CALM or Department of CALM	Department of Conservation and Land Management. (an amalgamation in 1985 of the Forests Department of W.A. with other Government agencies)
d.o.b.	Diameter over bark, always measured 1.3 m above ground level unless stated otherwise.
d.u.b.	Diameter under bark, ditto.
I.M.U.	Intensive Management Unit(s).
m.a.i.	Mean annual increment.
s.p.h.	Stems per hectare.
v.o.b.	Volume over bark, always based on diameters measured 1.3 m above ground level.
v.u.b.	Volume under bark, ditto.

CONVERSIONS USED

Values in Imperial or local units in original documents have been metricated as follows:

1 ha	=	2.47 ac
Diameter in cm	=	Girth in feet x 9.70 = Girth in inches x 0.809
$1\ m^2\ ha^{-1}$	=	$1\ ft^2\ ac^{-1}$ x 0.230
$1\ m^3\ ha^{-1}$	=	$1\ ft^3\ ac^{-1}$ x 0.070
1 load ($1.4\ m^3$)	=	$50\ ft^3$
$4.05\ m^2$	=	1 milacre

SUMMARY

We present a synthesis of current knowledge, from both published and unpublished sources, about the ecology of jarrah in the northern jarrah forest of Western Australia. Although the literature on jarrah is surprisingly sparse given the species' economic and ecological importance, we have had access to much information previously unpublished.

Growth, reproduction, and the description, establishment and development of stands are emphasized. Although jarrah is reputedly a very slow growing species, it has the potential for diameter growth of 1-2 cm yr^{-1} given appropriate silvicultural treatment (thinning and fertilizing).

Provided that forest is not cleared and is given hygiene protection and genetic selection for resistance to root-rot fungus, jarrah is virtually indestructible. Jarrah's lignotuber, very deep root system, thick fibrous bark protecting the dormant leaf buds, and its response to fire, fungi and insects allows an optimistic view for future forest management.

RESUMO

Ni prezentas sintezon de ĝis nuna scio, el publikigitaj kaj ne-eldonitaj fontoj, pri la ekologio de la ĵero en la norda ĵero arbaro de Okcidenta Aŭstralio. Kvankam troviĝas neabunda literaturo pri la ĵero (tre mirege, malgraŭ ĝia ekonomia kaj ekologia graveco) tamen estas havebla al ni multe da informo ĝis nuna nepublikigita.

Substrekendaj estas la stadioj pri la reproduktado, la kreskado kaj la specio kaj la disvolvado de la arbaretoj. Malgraŭ ĝia reputacio kiel specio, kiu tre malrapida kreskas, la ĵero entenas la potencialon ankaŭ de pliiĝo ĉe diametro po 1-2 cm je, per helpo de la taŭga silvikultura prizorgo (malamasigo kaj sterkigo).

Kondiĉe ke oni ne forigas la arbaron, sed faras higienan prizorgon kaj genetikan selekton pri rezisto kontraŭ radikputra fungo, la ĵero estas efektive nedetruebla. La lignotubero de la ĵero, ĝiaj profundaj radikoj kaj densa fibra ŝelo, ŝirmanta la latentajn foliburĝonojn, kaj la respondo de la ĵero al fajro, fungo kaj insektoj, permesas optimisman opinion al la futura administrado de la arbaro.

RESUME

Nous présentons une synthèse du savoir actuel des sources publiées et non publiées, de l'écologie du jarrah dans la forêt d' Australie Occidentale. Bien que la litterature du jarrah est étonnantement insuffisante en attention de l'importance économique et écologique de l'espèce, nous avons en accès à beaucoup des information ne préablement publiées.

Nous avons souligné la croissance, la reproduction, et la description, l'établissement et le developpement des peuplements. Malgré avoir la réputation d'être de croissance lente, le jarrah a aussi le potentiel, en reçu des traitments corrects (des éclaircies et d'engrais), pour une croissance d'un ou de deux centimètre par an.

Bien que la forêt n'a pas été coupé à blanc, et protégé hygiéniquement, et qu'une sélection génétique pour une résistance aux champignons attaquent les racines est conduite, le jarrah est pratiquement indestructible. Le lignotuber, le système très profond des racines, l'écorce grosse et fibreuse protégeant les bourgeons dormants, et la réponse du jarrah au feu, aux champignons, et aux insectes, permèttent au perspective optimistique pour l'administration de la forêt dans l'avenir.

ZUSSAMMENFASSUNG

Wir forstellen die Synthesis von heutigen kentniss, sowohl von herausgegebenen Quellen und auch die jenigen die bisher noch nicht herausgegeben sind, über die Oekologie von Jarrah (*Eucalyptus marginata*) in dem Norden Jarrah Waldes in Westaustralien. Obgleich die Literatur über Jarrah ist überraschend dünn wenn man die economische und oekologische Wichtiekeit von diesen Baumart betrachtet, wir könnten viele Erkundigugen benützen, die bisher nicht herausgegeben sind.

Wir betonen nachdrüklich das Wachstum und die Wiedererzeugung der Baumart, und die Beschreibung, die Einrichtung and die Entwicklung der Waldbestande. Obgleich Jarrah ist am meisten wie eine besonders langsam wüchsende Baumart angeseht, sie hat die Möglichket für 1-2 cm jahrlichen Durchmesserzuwachs solange sie die richtige Wirtschaft (Durchforstung und Düngung) erhaltet.

Solange der Wald nicht abgeholzt ist, und vor der *Phytophthora* Würzfaule beschutzt ist, Jarrah ist fast unwüstlich. Diese Baumart hat speciale Eigenschaften, so wie Lignotuber, dichte Borke welche die schlafende Auge Beschützt und besonders tiefe Bewurzelung. Diese Eigenschaften, und seine Kapazität für Beschutz wegen Feuer, Pilzen und Insekten, gibt uns eine optimistische Assicht für die Zukunft der Waldwirtschaft.

RIASSUNTO

Viene presentata una sintesi delle attuali conoscenze, provenienti da fonti sia pubblicate sia inedite, riguardanti l'ecologia dell' *Eucalyptus marginata* (jarrah) nella foresta ad eucalipto della Western Australia. Considerano l'importanza economica ed ecologica della specie, la letteratura è sorprendenteme scarsa, ma noi abbiamo avuto l'accesso a molte informazioni precedentementi inedite.

Particolare enfasi viene data sia alla crescita e alla riproduzione della pianta, sia alla descrizione, all' impianto e allo sviluppo delle parcelle. L'*Eucalyptus marginata*, sebbene venga considerata una specie a crescita lenta, ha un potenziale di crescita diametrale di 1-2 cm all'anno, una volta che siano eseguiti gli appropriati trattamenti silvicolturali (diradamento e fertilizzazione).

Se la foresta non viene troppo rarefatta, se si provvede ad una adeguata difesa fitosanitaria e si attua una selezione genetica per la resistenza ai marciumi radicali, l'eucalipto risulta praticamente indistruttibile. Grazie alle sue caratteristiche (presenza di lignotuberi, sistema radicale molto profondo, spessa corteccia fibrosa che protegge le gemme fogliari, resistenza al fuoco, ai funghi e agli insetti), l'*Eucalyptus marginata* permette ottimistiche previsioni di un suo utilizzo nella programmazione forestale.

RESUMO

Apresentamos uma síntese do conhecimento actual, tanto de fontes publicadas como nãs publicadas, da ecologia de jarrah (*Eucalyptus marginata*) na floresta do Norte na Austrália Ocidental. Embora a literatura em jarrah seja surpreendentemente escassa dada a importância económica e ecológica da espécie, tivémos acesso a uma tanta informação não publicada prèviamente.

Enfase é dada ao crescimento, reprodução, e descrição, estabelecimento e desenvolvimento de povoamentos. Embora se atribua à jarrah a reputacão de ser de crescimento muito lento, esta tem também o potencial para crescimento em diâmetro de 1-2 cm ano^{-1} dados os tratamentos silvícolas adequados (desbastes e fertilizações).

Desde que a floresta não seja cortada e protecção higiéenica e selecção genética para resistência ao fungo da podridão de raiz sejam conduzidas, jarrah torna-se pràcticamente indestrutível. O lignotuber de jarrah, o profundo sistema radicular e a casca grossa e fibrosa protegendo os gomos foliares dormentes e a sua resposta ao fogo, fungos e insectos, permitem uma perspectiva optimistíca para a futura getão da floresta.

RESUMEN

Presentamos una síntesis del conocimiento actual, tanto de fuentes publicadas como no publicadas, de la ecologia de jarrah del bosque del norte en Australia Occidental. Si bien que la literatura en jarrah sea sorprendentemente escasa dada la importancia economica y ecologica de la especie, tuvimos acceso a mucha información no publicada previamente.

Se acentua el crecimiento, reprodución, y descripción, establecimiento y desarollo de rodales. Si bien que jarrah haya una reputación de ser de crecimiento muy lento, esta tiene también el potencial para crecimiento en diámetro de 1-2 cm año dados los tratamientos silvicolas apropriados (raleos y fertilización).

Con tal que el bosque no sea cortado y que protección higiénica y selección genetica para la resistencia contra el hongo de pudrición de raiz sean dados, jarrah es praticamente indestructivel. El lignotuber de jarrah, el profundo sistema radicular, y la casca gruesa y fibrosa protegiendo los botónes foliosos durmientes y su respuesta à el fuego, hongos y insectos permiten una perspectiva optimista para la futura dirección del bosque.

CHAPTER 1

Introduction

The purpose of this Bulletin is to collate and summarize what is known about the life history, ecology and silviculture of jarrah (*Eucalyptus marginata*) in the northern jarrah forest of W.A. Given its commercial importance, the published literature on the ecology of jarrah is disappointingly thin. There exists, however, a wealth of experimental studies and observations varying in detail in the files of the Department of Conservation and Land Managment. We address two questions: What do all these published and unpublished details add up to? What generalizations can we draw from the past efforts of many foresters and research scientists?

Most of this information about jarrah derives from members of the Forests Department, in particular A.D. Helms (1934-38), O.W. Loneragan (1951-56), A.C. van Noort (1957-60), G.B. Peet (1961-65), P.C. Kimber (1963-70), F.D. Podger (1956-66, also of CSIRO), J.J. Havel (1967-72) and S.R. Shea (1973-83). These dates represent approximately the period when most of the data about jarrah ecology were collected and analysed. Many other members of the Forests Department have contributed important observations that in retrospect serve to fill out the framework established by those named above. These include J. Ednie-Brown, C.E. Lane-Poole, S.L. Kessell, T.N. Stoate, A.C. Harris, B.H. Bednall, W.R. Wallace, W.G. Chandler, J. O'Donnell, N. Tamblyn, N.T. Burbidge, C.D. Hamilton, P.H. Barrett, A.B. Hatch, F.J. Campbell, J.B. Campbell, S.J. Quain, and G.L. Airey.

Most of this information is contained in Departmental files, field books, or reports held in the Departmental library; little of this is available to the public in an accessible form. In the preparation of this Bulletin we had access to all such sources of information still in existence.

The fragmented nature of the effort put into this type of research was explained in detail by Stoate (1953):

> 'The broad study of the ecology and silviculture of Jarrah ..., from its range and distribution, as governed by ecological (climatic, edaphic, genetic and biotic) factors, to its silvicultural characteristics and regrowth treatment, has not been possible as a whole owing to staff limitations. Numerous facets of the whole have, however, received attention, partly as *ad hoc* investigations of specific problems. Other information, though perhaps meagre, accumulated by officers over the years is largely scattered throughout files and reports and is not easily available for reference. For this reason it has been the aim in the more strictly research work of the Department to summarise existing knowledge from time and record it in reports bound and placed in the Library, or publish it when possible.'

The scope of this Bulletin is encyclopaedic, being a survey of knowledge about the ecology and silviculture of jarrah in the northern jarrah forest, and hence by implication of what is unknown or poorly understood about the species' ecology. In spite of this, we have not attempted to repeat everything that has been written. Instead we shall be content to make critical evaluation, and state principles or conclusions established in the literature. We thus hope that this Bulletin will be useful as a bibliography of publications dealing with the ecology and silviculture of jarrah. This complements similar accounts about karri (*Eucalyptus diversicolor*) (White n.d.; Breidahl 1983).

The ecology of the jarrah forest ecosystem falls outside the scope of this Bulletin. We do not deal with animals, other plants or ecological processes in the jarrah forest unless these impinge directly upon the ecology of jarrah.

In addition, non-ecological information about jarrah, for example of a physiological or pathological nature, is given only where it advances our understanding of the ecology of jarrah. Our object has not been to provide a treatise on the biology of jarrah.

Because most information comes from the northern jarrah forest (Mundaring, Jarrahdale, Dwellingup, Harvey and Collie Forest Districts), we do not consider in any detail jarrah in the so-called southern jarrah forest or in the *Banksia* woodland of the coastal plain. Generalizations made in this Bulletin should not be extrapolated beyond the northern jarrah forest.

Extraction of information from archival and current files and published literature ceased in December 1983.

CHAPTER 2

Nomenclature and Taxonomy

The Aboriginals of south-western Australia used the name Djara, subsequently anglicized and mispronounced as jarrah. Abbott (1983) quotes fifteen variants in their original spelling: Cherring, Chiaragl, Djarrail, Djarryl, Djerral, Dyerral, Jarrah, Jarral, Jarril, Jarraly, Jeril, Jerral, Jerrail, Jerril and Jerryl. To these may be added Jerrile (von Mueller 1879-84, quoting A.C. Gregory) and tjirrala and tjiarral, used on the western and southern coasts respectively (von Brandenstein 1977).

The first European settlers of Western Australia in 1829 likened the timber to that of *Swietenia* sp., the Mahogany of Honduras, and called the tree Swan River Mahogany. Bentham (1866) quotes A. Oldfield for the names 'Mahogany' and 'Bastard Mahogany'. These names were superseded in the 1860s by the Aboriginal name to avoid confusion (Lane-Poole 1921). In that decade saw-milling machinery was adopted (W. Dunn, quoted in Maiden 1911) and jarrah was first exported in large quantities (Battye 1924).

The species was first collected in 1791 at King George Sound by Archibald Menzies, botanist to George Vancouver's naval expedition of discovery (Maiden 1909). The epithet *marginata* was first used in 1800 by James Donn, who is thought to have grown seed collected by Menzies.

However, it is possible that another eucalypt species was involved. In any case James Smith in 1802 definitely applied Donn's name *marginata* to the species. Thus until recently the Authority was cited as Sm. but this was replaced by Donn ex Sm. It appears that the latter Authority is correct (G.M. Chippendale personal communication*).

The epithet *marginata* alludes to the incrassate margins of the leaves. Subsequent knowledge, however, indicates that the leaf margin is not more specially thickened than many other *Eucalyptus* species (von Mueller 1879-84).

Blakely (1965, 1st ed. 1934) placed jarrah in Section Renantherae, subsection Cordatae, Series Occidentales. Recently, *Eucalyptus marginata* has been formally classified as follows (Pryor and Johnson 1971): MADCA, Subgenus *Monocalyptus*, Section Renantheria, Series Marginatae, Subseries Marginatae, Superspecies Marginata made up of two species, *E. marginata* and *E. staeri*. For the keying out of *E. marginata*, see Blackall and Grieve (1980). If the genus *Eucalyptus* as presently circumscribed is ever split into its component subgenera, the correct Latin binomial for jarrah would be *Eucalyptus marginata* and not *Monocalyptus marginata* (I. Brooker personal communication**). There is little doubt that such stability in nomenclature would be welcomed by foresters.

Surprisingly, only three synonyms have been published (Maiden 1909). These are *E. floribunda* Schauer (collected near the Swan River), *E. hypoleuca* Schauer (collected near Wuljenup) and *E. mahogani* F. Muell. How the first two names came to be given is discussed by von Mueller (1879-84). None of these names has ever gained recognition.

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*. G.M. Chippendale, retired, formerly Division of Forest Research, CSIRO, Canberra.

**. M.I.H. Brooker, Division of Forest Research, CSIRO, Floreat, W.A.

Only one variety of *E. marginata* has been formally described: var. *staerii*, found near Albany (Maiden 1914). This variety was later given full specific status (Maiden and Blakely 1926).

Bentham (1866) discussed variation based on specimens available to him, and Stoate (1953) informally recognized four 'botanical forms' of jarrah: *glauca*, a blue-leaf form in the northern and central jarrah forest; *viridis*, the typical form of the south-west; *pachyphylla*, a thick-leafed and big-fruited form south of Busselton; and *ramosa*, a more spreading and branched type of the coastal plain region. Stoate conceded that these forms 'may not achieve varietal status'. A weeping form having long pendulous branchlets called the Yalanbee provenance is another variant from which the seedlings are glaucous. A study of geographic and genetic variation in jarrah, using modern statistical and electrophoretic techniques, is required urgently to clarify the clinal variation of the characters used by Stoate and others. Some data from two provenance trials assessing performance in height and diameter are presented later.

The Section Renantherae as described by Pryor and Johnson (1971) has nearly 75 species, of which eleven occur in (and are restricted to) Western Australia. Natural hybrids would be expected between *E. marginata* and the other species overlapping in range with jarrah: *E. megacarpa*, *E. preissiana*, *E. patens*, *E. pachyloma*, *E. todtiana*, *E. buprestium*, and *E. staeri*. However, natural hybridization with *E. pachyloma*, *E. todtiana* and *E. buprestium* seems most unlikely because their flowering times do not overlap with that of jarrah.

Only two hybrids involving *E. marginata* have been formally recorded: *E. marginata* x *E. megacarpa*, and *E. marginata* x *E. preissiana* (Pryor and Johnson 1962). Nevertheless, several hybrids between *E. marginata* and *E. patens* have been noted by Forests Department personnel near Mundaring Reservoir (A. Selkirk), near Mounts Randall and Cooke (R. Edmiston), in Kennedy block in Dwellingup Division (P. Kimber), and near Lake Muir and west of Manjimup (O. Loneragan). These trees generally have *marginata*-like fruits and foliage and *patens*-like wood. In Kennedy block the tree had the bark, leaves, fruit and seeds of *E. patens* but the timber was red like *E. marginata*. Seed was germinated resulting in a hybrid swarm in seedling characteristics (P. Kimber personal communication*). Suspected hybrids between *E. marginata* and *E. haematoxylon* have been noted by R. Edmiston and O. Loneragan at Keysbrook, Kingsbury lookout and North Dandalup on the basis of *haematoxylon*-like fruit and *marginata*-like leaves. Such hybridization is most unlikely because *E. haematoxylon* belongs to a different subgenus from *E. marginata*. These populations may instead represent variations of *E. haematoxylon* (L.D. Pryor 1979 personal communication**). The 'species' *E. kalganensis* is now recognized (Pryor and Johnson 1971) as a hybrid between *E. marginata* and *E. preissiana*.

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CHAPTER 3

Distribution

The present geographical distribution of jarrah, determined from road traverses, is shown in Map 7 of Figure 1. It is restricted to the south-western corner of Western Australia from about Bindoon south-east to the Stirling Ranges and Beaufort Inlet. It occurs more or less continuously west of a line from near New Norcia, Northam, York, Dryandra, Williams and Cranbrook (Beard 1976, 1979 a,b,c; 1980 a,b; Smith 1974). The area occupied is about 64 000 km^2, calculated from Map 7, Figure 1. However, the eastern boundary of its distribution is quite fragmented. Several well-isolated populations occur to the east and north of this boundary (Lange 1960; Churchill 1968). Those at Mt Lesueur and Jilakin Rock are some 100 km from this boundary, and another (now destroyed) was nearly 400 km east of this boundary.

This last population was first recorded by P.H. Barrett[+] 13 km west of the Dalyup River (45 km west of the main Norseman-Esperance Road). W. Brennan (personal communication* 1983) sighted the stand in about 1952. It consisted of 'about a dozen' mallee jarrah, of height 3-4 m and d.o.b. 8-15 cm, occurring on a ridge west of Coolinbidgup Swamp. The stand disappeared when the land was cleared for agriculture in the late 1950s or early 1960s.

The extent of the range of jarrah is not particularly notable, as other Western Australian eucalypt species such as *E. wandoo, E. rudis, E. calophylla* and *E. salmonophloia* range more widely (Lange 1960; Churchill 1961). The past distribution (i.e. before 1829) was somewhat greater than its range in 1829.

Churchill (1968) argued that the occurrences of jarrah at Mt Lesueur and Jilakin Rock (he did not know of the Dalyup outlier) indicated a wider distribution in the past. Climatic change was postulated to have caused the northern and eastern boundaries of its range to contract further south and west respectively.

In contrast to the single map of the range of jarrah as a species (Map 7 of Fig. 1), there have been seven attempts, beginning in 1880, to record the extent of jarrah forest. (The version of Jutson 1934, is not shown because it is the same as that of Kessell 1928). The original maps, redrawn at a scale of 1:4 000 000, are gathered together in Figure 1. Comparison of the various interpretations of the occurrence of jarrah forest is hampered because in most cases the criterion used to delineate forest was not explicitly stated. In all cases the maps show where jarrah forest is predominant.

The first map, produced under the name of the Surveyor-General, shows jarrah forest absent from or not predominant on the coastal plain and south of Manjimup. However, it was correctly recognized that 'in no part of the Colony does any one class of trees prevail to the exclusion of all other varieties.' The area where jarrah forest is predominant was stated by Fraser (1882) to be 36 000 km^2, little different from Ednie-Brown's (1896) estimate of 32 000 km^2. In contrast, Lane-Poole (1921) reported the area of jarrah forest to be about 53 000 km^2. The area calculated from the latest map (Beard 1981, published by Forests Department of Western Australia) including jarrah forest now cleared for agriculture is 39 000 km^2. At present some 15 000 km^2 is reserved

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+. Forests Department file H.O. 675/49.

*. W. Brennan (retired), formerly Forests Department of W.A.

as State Forest and Timber Reserves (*Annual Report* 1983).

These maps differ most strikingly in the recognition of the eastern boundary of jarrah forest. Both Lane-Poole (1921) and Gardner (1952, map published by Forests Department of Western Australia) show jarrah forest extending to Narrogin. This difference is a matter that can never be resolved satisfactorily because the jarrah forest naturally fragments into pockets restricted to ridges amongst wandoo forest lower in the landscape. Jarrah then ceases to be a predominant element of the forest.

The extent of prime jarrah forest was first mapped by Lane-Poole (1921). This was bounded in the west by the Darling Scarp, in the north by Kalamunda, Sawyers Valley and The Lakes, and in the east by a north-south line passing near Beraking, Mt Wells, Marradong, Muja, Boyup Brook and Perup. The total area of prime jarrah forest was thus reckoned to be about 10 000 km^2. The next attempt to map the area of prime jarrah (Kessell 1928) differed most in recognition of a serpentine rather than linear eastern boundary: from near Beechina, Mt Dale, Mt Randall, Mt Cooke, Mt Wells, west of Mt Saddleback, Bowelling, Noggerup, Wilga, Hester, Bridgetown, Yornup, Willgarup, Balbanup, Mordalup and Mt Roe with isolated patches within the karri zone. Both maps, however, suffer to the extent that the criterion used to map prime merchantable forest was not stated.

Such a criterion was spelled out by Abbott and Loneragan (1983a) for the northern jarrah forest. We suggested that high quality jarrah forest could

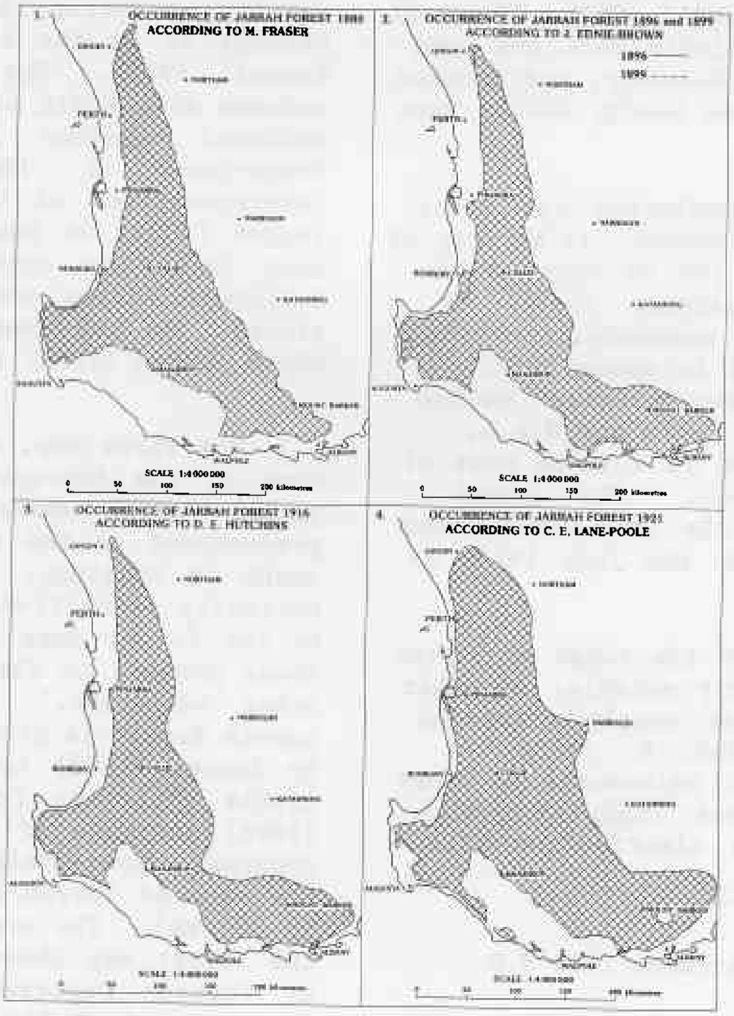
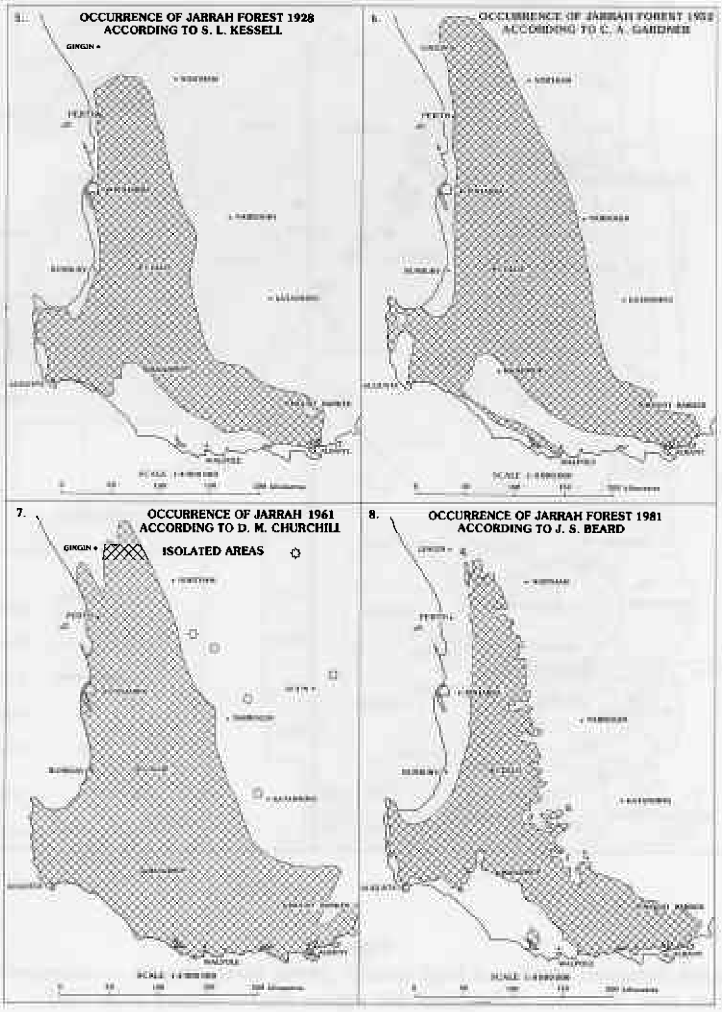


Figure 1
Occurrence of jarrah forest (Maps 1-6 and 8) and of jarrah (Map 7), according to various authorities. Note that the isolated population near Mt Lesueur is omitted from Map 7.

be distinguished from low quality jarrah on two criteria: (1) on site-vegetation types (Havel 1975 a,b; Heddle *et al.* 1980) T, S, O or P vs H or Z, or (2) on whether mature codominant height was greater or less than 25 m*.

Figure 1 of Abbott and Loneragan (1983a) was based on a combination of both criteria. We now think that the northern boundary is too far north and that we were misled by the presence of the understorey species *Adenanthos barbigerus* and *Grevillea wilsonii* north of Mundaring Weir (Fig. 2). Elsewhere in Mundaring and in Jarrahdale Divisions *Grevillea wilsonii* and *Adenanthos barbigerus* (see Havel 1975a; Nelson 1978) are good indicators of the eastern boundary of high quality jarrah forest. The delimitation of high quality stands of jarrah based on whether mean mature codominant height exceeds 27 m is shown in Figure 3. This information has been taken from Forests Department Aerial Photographic Interpretation (A.P.I.) type maps, scale 1:50 000. Comparison of Figures 2 and 3 yields a similar boundary between high and low quality stands. Roughly speaking this boundary follows the power line between Brookton Highway and Muja Power Station. Harris (1956) stated that 'optimum development' of the jarrah forest was attained over an area of about 16 000 km^2. This estimate agrees closely with the area of high quality jarrah forest calculated from Figure 3.

*. Rounded to nearest 5 m. The true value is 27 m.



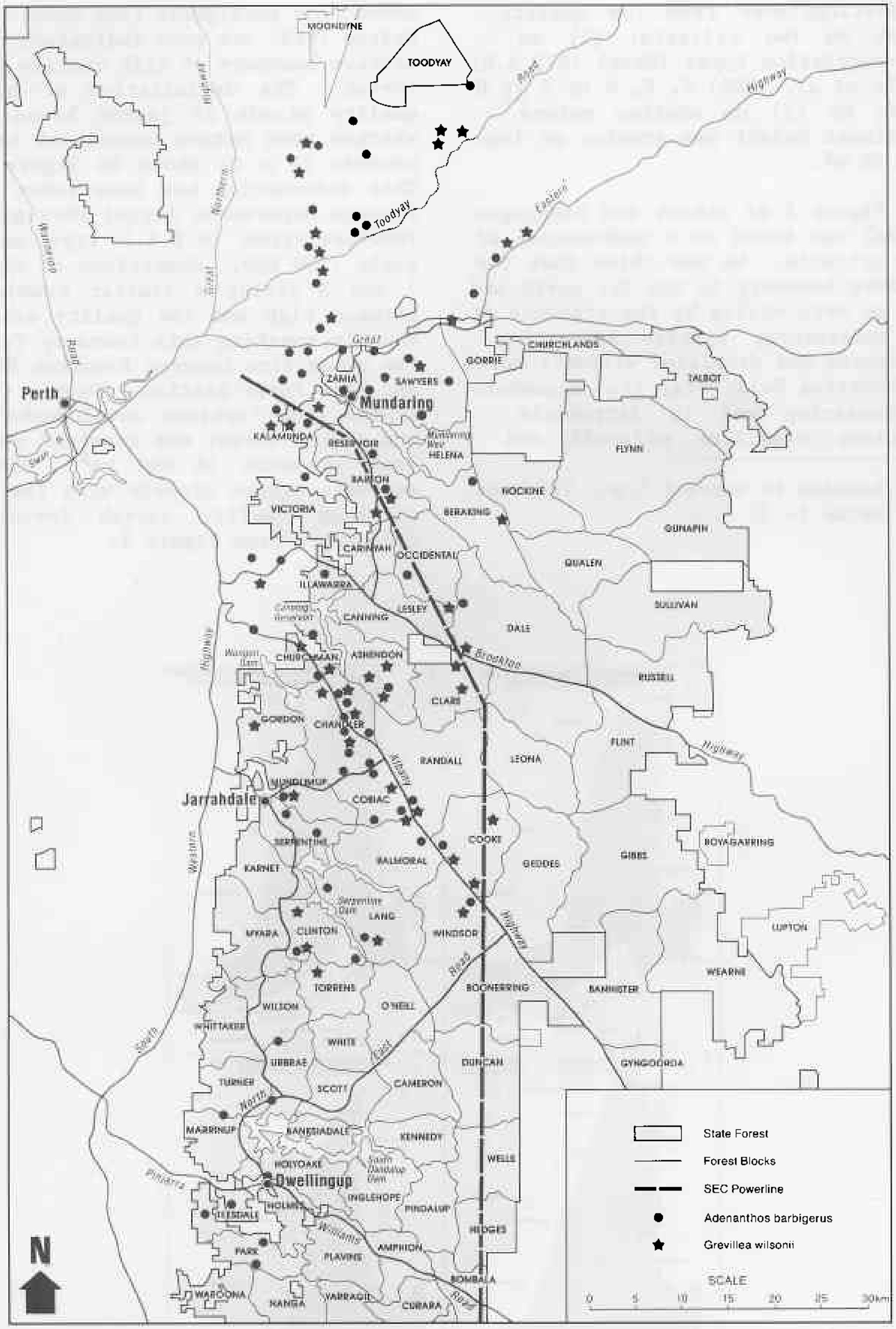


Figure 2
Occurrence of two important indicator species of high quality jarrah forest stands — *Adenanthos barbigerus* and *Grevillea wilsonii* — determined from road traverses throughout the region shown during 1979-1981.

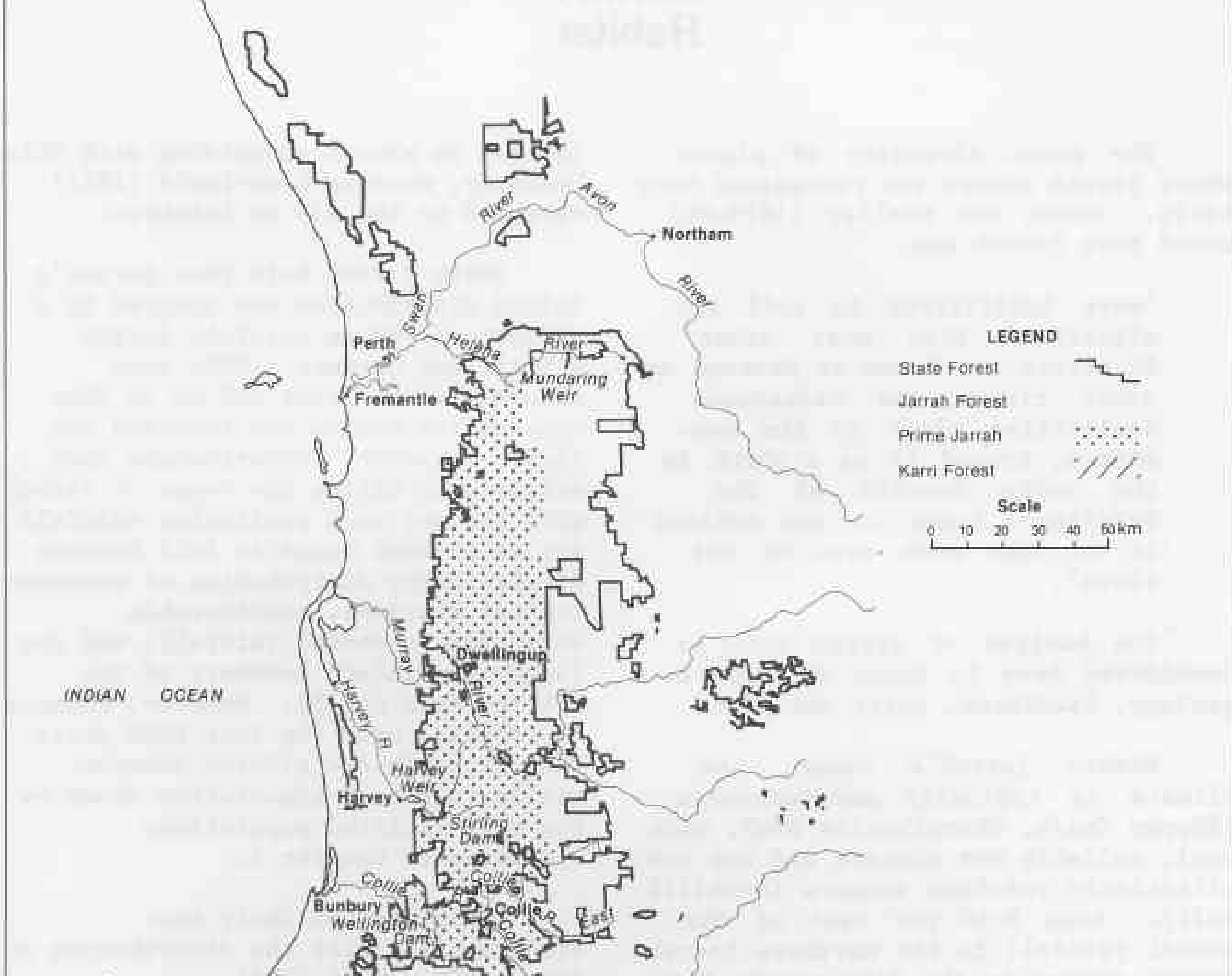


Figure 3
Occurrence of high quality jarrah forest, defined as forest with original mean mature height $\geq$ 27 m. A dot indicates the presence of high quality forest on each 1:50 000 Aerial Photographic Interpretation type sheet.

CHAPTER 4
Habitat

The great diversity of places where jarrah occurs was recognized very early. Baron von Mueller (1879-84) noted that jarrah was

> 'more indifferent to soil and situations than most other Eucalypts ... I saw it descend on sandy ridges and calcareous declivities close to the sea-shores, traced it as a shrub to the rocky summits of the Stirling's Range ... and noticed it to come down even to wet flats'.

The habitat of jarrah will be considered here in terms of climate, geology, landforms, soils and fire.

Within jarrah's range, the climate is typically mediterranean (Köppen Csa/b, Thornthwaite BBs), with cool, reliably wet winters and hot and effectively rainless summers (Gentilli 1971). Some 8-10 per cent of the annual rainfall in the northern jarrah forest occurs in the five months from November to March (Bartle and Shea 1979). This is illustrated for Jarrahdale, using the rainfall data from 1882 to 1980. For three months to the end of March, the total rainfall averages 50 mm (range 0-350). Corresponding figures to the end of May, July, September and November are 275 (30-950), 750 (150-1950), 1060 (190-2750) and 1100 mm (200-3125) respectively. The average date of the coming of the winter rains ('break of season') for the northern jarrah forest is 1-15 April (Anon. 1970). This would happen earlier towards the south. Maximum evaporation occurs when rainfall is lowest (Doley 1967). Frosts average about 11 per year (Hall *et al*. 1963).

Most authors emphasize the importance of rainfall in limiting the distribution of jarrah to the east and north. Diels (1906) quoted the 750 mm isohyet as almost coinciding with this boundary, whereas Lane-Poole (1921) referred to the 635 mm ishohyet.

Smith (1969) held that jarrah's inland distribution was limited by a minimum of 760 mm rainfall during winter, and Gardner (1942) that rainfall of at least 400 mm in four consecutive months was required for jarrah to occur. Nevertheless such attempts to define the range of jarrah with respect to a particular rainfall are at present bound to fail because of the patchy distribution of meteorological stations, considerable variation in annual rainfall, and the fragmented inland boundary of the species (see ch. 3). However, changes in rainfall over the last 6000 years have probably contributed substantially to this fragmentation shown by the well-isolated populations discussed in Chapter 3.

It is most unlikely that temperature limits the distribution of jarrah (Churchill 1968).

Geology and soils were considered by Stoate and Helms (1938) to be more important than climate in influencing the distribution of jarrah. The bulk of the northern jarrah forest occurs over a granitic basement mantled by lateritic soil (Stephens 1946). According to Dimmock *et al*. (1974) the depth to bedrock in the northern jarrah forest averages about 20 m (Range 5-42 m). These residual soils formed under peneplain conditions during the Oligocene and Miocene periods (Johnstone *et al*. 1973). The profile has been described many times in various degrees of detail (e.g. O'Donnell n.d.; Stoate and Helms 1938; Wallace and Hatch 1952; Mulcahy 1960; Turton *et al*. 1962; Gilkes *et al*. 1973; Bettenay *et al*. 1980; Carbon *et al*. 1980). As well as A, B, and C horizons of eluviation, illuviation and weathering, respectively dominated by ferruginous gravel and lateritic boulders with sheet laterite, mottled kaolinitic clay, and pure white kaolin, lateral flow of water has produced complex soils which contain the deepest bauxite under the best jarrah (Havel, personal communication*).

The textures of each horizon are sandy gravels (A), over clay (B and C). The ferruginous gravel content of the surface soil was noted by Turton *et al.* (1962) to be 'surprisingly constant in value (67-78 per cent)'.

Values of bulk density, pH and salts quoted by Bartle and Shea (1979) for the subsoil are high enough to limit root growth; yet as noted as early as 1917 by Lane-Poole (unpublished lecture notes) the subsoil has greater importance than the topsoil. If the roots of jarrah were confined to the topsoil they would never be able to survive the summer. This inhospitable soil environment is ameliorated by the occurrence of conductive channels in the subsoil (Kimber 1974). The relatively flat landscape, the receptiveness of the clay subsoils to infiltration, and the lack of leakage of water into basement rocks is responsible for storage of water at depth.

Added to these adverse physical properties of the soil is a highly weathered profile deficient in most nutrients (Turton *et al.* 1962; Hatch 1964). In particular N and P occur at very low concentrations (Havel 1975a); these decrease rapidly with depth. Total P generally is under 100 ppm. The C:N ratio is relatively high, at about 30-50.

The occurrence of jarrah is not affected by altitude in the Darling Range, being found from near sea level to near the highest point, 582 m. Jarrah is replaced by *Eucalyptus patens, E. megacarpa* or *E. rudis* along streams in the western part of the Darling Range (Havel 1975b). Towards the eastern boundary *E. wandoo* begins to dominate broad valleys, and eventually jarrah is restricted to a residual lateritic mantle. Havel (1975b) provides an exhaustive study of the Jarrahdale area, and Mulcahy *et al.* (1972); McArthur *et al.* (1977) and Bettenay *et al.* (1980) provide detailed regional studies for the Mundaring-York, Dwellingup and Collie regions respectively.

Fire is a natural component of the mediterranean climate of south-western Australia. For example, 28 lightning fires were started around Dwellingup on the night of 10-11 January 1954 and 19 from two storms on the nights of 19 and 20 January 1961. Moreover, Aboriginals were present for the last 40 000 year (Pearce and Barbetti 1981); records of the earliest European settlers indicate Aboriginal firing of the south-west took place in summer and was probably frequent and of low to moderate intensity (reviewed in Abbott and Loneragan 1983b). According to Havel (personal communication*) the wide-spread incidence of fire in antiquity partly explains the dominance achieved by jarrah, which is more resistant to fire than the other eucalypt species in the jarrah forest.

The explanation of the dominance of jarrah on lateritic gravels is probably unrelated to its ability to cope with the low levels of fertility better than other tree species (Havel 1975b). Rather, jarrah is probably displaced by wandoo inland because the storage of soil moisture becomes inadequate for jarrah. Supporting data come from the fact that jarrah persists on shallow soils in the moister southern jarrah forest but not in the more arid northern forests, and from physiological characteristics of jarrah (see ch. 6, p. 26). In addition, high quality jarrah forest occurs in the high rainfall (western) sector of the Darling Plateau (Abbott and Loneragan 1983a).

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CHAPTER 5

Associations With Other Plant Species

The remarkable feature of the jarrah forest is its purity. Lane-Poole (n.d.) stated that the prime belt of jarrah forest is 'by far the least mixed eucalypt forest covering so wide an area in Australia'. Marri (*Eucalyptus calophylla*) occurs widely throughout the northern jarrah forest but is rarely as abundant as jarrah (See ch. 9 for details). Such a situation exemplifies a generalization first made by Pryor (1959) that in mixed stands of eucalypts the two species do not interbreed and are derived from different subgenera. In this case, jarrah belongs to the subgroup Monocalyptus and marri to the Corymbia.

Jarrah also occurs to a limited extent in association with several other species of eucalypts, *E. patens*, *E. megacarpa*, and *E. rudis*, near streams where the jarrah forest, for edaphic reasons, generally gives way to other vegetation types. In a similar fashion marri, wandoo (*E. wandoo*) and karri (*E. diversicolor*) mix with and then replace jarrah near different parts of the boundary of jarrah forest (see previous Chapter).

Before 1975, delimitation of forest types in the jarrah forest was very broad. Lane-Poole (n.d.) recognized six types: prime jarrah; marri predominant; sand plain type; wandoo type; a type found near Albany; and a karri-jarrah type. In 1938, Stoate and Helms classified most of the northern jarrah forest as 'Darling Range Jarrah' as distinct from 'Coastal Plain Jarrah' and 'Outlier Jarrah'.

The reason for this approach no doubt was a response to the uniformity of the eucalypt part of the forest. Stoate and Helms (1938) further developed a scheme of classifying forest sites on the basis of the total volume carried, stand basal area, and height of the stand. The forest sites were easily recognized on the basis of the amount and depth of rock and gravel on the upper slopes.

No further worthwhile studies were carried out until Speck (1958) classified the vegetation of the State. For the jarrah forest the relevant extract is: Formation: Forest; Subformation: High forest; Associations: *E. marginata; E. marginata-E. calophylla*; Alliance: *E. marginata-E. calophylla*. Speck approached this subject from a bio-geographic viewpoint on a state-wide basis. Consequently, all of the northern jarrah forest was within only two vegetation systems, the Darling and the Bannister. The treatment was very generalized.

In contrast, the whole of State Forest was classified by the Forests Department in the 1950s and 1960s from interpretation of aerial photographs, on a scale of 1:25 000. Stands were assessed in relation to stand structure, height and species' composition (Copies of these maps are held by the Mapping Branch, Department of Conservation and Land Management, Como).

An intensive study using plots located throughout the northern jarrah forest was tried (Havel 1975a). In this study chemical properties of the surface soils were determined and, together with selected physical properties of the topsoil, topo-graphical data, and the identity and cover of the perennial members of the understorey, a computer analysis was undertaken. The vegetation approximated a multi-dimensional continuum, which could be broken into 19 segments for the purpose of rapid use in the forest. Each segment was defined by edaphic conditions and could be recognized by the presence/absence of selected indicator species, both overstorey and understorey.

The usefulness of this scheme was demonstrated by mapping site-vegetation on four areas of forest 20-30 km^2 in area (Havel 1975b). A further development (Heddle *et al.* 1980) organized site-vegetation types into vegetation complexes. These were related to landform-soil units and rainfall zones. The Darling Plateau was thus subdivided into 28 vegetation complexes, defined and mapped in Heddle *et al.* (1980).

The basic site-vegetation units of Havel (1975a) were organized more broadly by Abbott and Loneragan (1983a) into two types of jarrah forest: high quality and low quality. However, we stressed in that paper that our procedure was only interim, resulting from insufficient growth plots in each of the site-vegetation types.

CHAPTER 6

Descriptive Features of Jarrah

This chapter summarizes descriptive detail about the size and shape of the jarrah tree and its bark, leaves, roots, lignotuber, reproductive organs, wood, physiological properties and the distribution of nutrients within the tree. We also describe the stages of development from seedling into tree.

Shape, Size and Mass

Jarrah shows a variety of growth forms, as evidenced by the number of stems arising from the lignotuber, and the length of the bole (the height of the stem below the crown). It grows as a mallee at Mt Lesueur, Tutanning, the Stirling Ranges and towards Cape Riche, as a short-boled tree amongst the woodland on the coastal plain between Wanneroo and Busselton, and as a true long-boled forest tree in the jarrah forest.

Many trees, however, do not have an umbrageous crown supported by a stem of perfect form (Fig. 4): much of the crown may be absent with large, dead branches, the lower part of the stem may bear a fire scar ('dry side') or be hollow ('hollowbutt'), and burrs may sometimes be present (Fig. 50 in Jacobs 1955). These are abnormal swellings present on the bole or branches caused by the accumulation of dormant buds (Kessell 1921a).

No detailed description of the structure and shape of the jarrah tree, along the lines of Holland (1969), has yet been attempted.

The height and d.o.b. attained by jarrah fall well short of those of many other tree species, according to data collated by Tiemann (1935). Ednie-Brown (1896) recorded that it

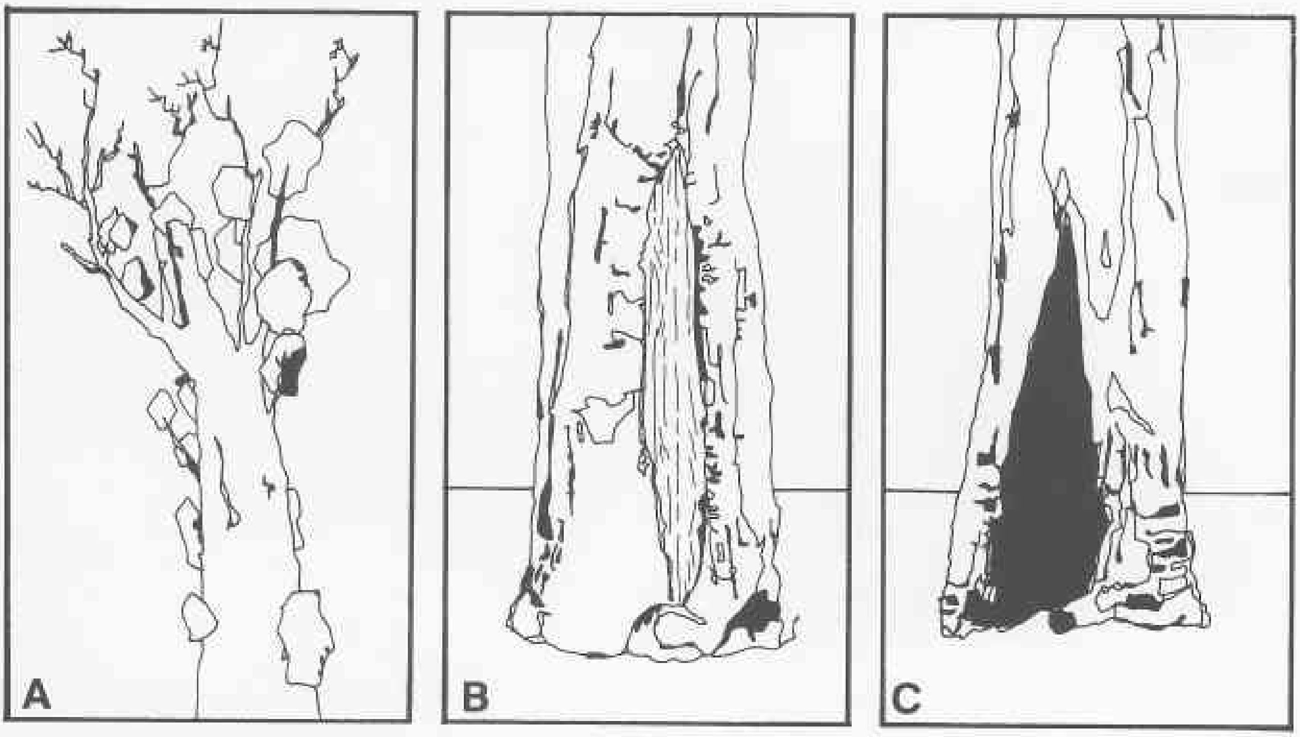

Figure 4
Examples of poor form shown by jarrah: A, unhealthy crown with many dead branches; B, fire scar; C, hollow butt.

was not uncommon to find considerable areas of first class forest where many of the mature trees attained total heights from 27 to 37 m, d.o.b.'s of 90–150 cm and boles from 15 to 18 m. Other authorities, by inadequately defining the sample, provide slightly different figures. Lane-Poole (1921) quoted (? average) height of 31-37 m, bole of 15-18 m, and d.o.b. of 180 cm. Later (n.d.) he stated that the tree attained a height of 46 m, averaging 21-31 m with a bole of 9-17 m. Harris (1956) stated that the maximum height attained is 46 m, averaging 27-40 m in prime forest, and that the bole may reach 24 m but is typically 8-11 m, that is about one quarter to one third of the height of the mature forest.

Table 1

Some characteristics of jarrah trees of exceptional size from throughout the jarrah forest. The order of trees is by diameter.

Locality (Generally Forest Block and Division)	Year measured	d.o.b. (cm)	height (m)	bole (m)
Hadfield, Harvey	1973 1981	317.7 319.3	36.3 –	21.3 –
23815, Manjimup	1975	279.7	35.4	18.9
National Park, Manjimup	1973	278.1	44.5	16.5
Sawyers, Mundaring	1981	259.2	28.0	7.0
Ellis Creek, Nannup	1973	257.8	42.1	25.0
Lowden, Collie	1972 1981	235.2 249.1 (*a*)	43.6 -	21.8 -
Kerr, Kirup	1971	242.5	–	[illegible]
Warner, Kirup	1981	238.4	45.8 (*b*) 41.2 (*c*)	-
Holmes, Dwellingup	1981	236.0	–	-
Chandler, Jarrahdale	1983	230.0 (*a*)	-	-
Plavins, Dwellingup	1981	- 229.6 (*d*)	-	-
Amphion, Dwellingup	1981	224.7 (*a*)	-	-
Ellis creek, Nannup	1973	223.1	39.0	21.0
Nanga, Dwellingup	1945 1958 1960 1981 1984	197.6 214.2 215.8 215.0 216.7	56.4 - 48.8 - 50.4	28.7 29.0 27.5 - 27.2
Mundlimup, Jarrahdale	1983	207.0 (*a*)	30.0	-
Gordon, Manjimup	1972 1979	174.4 169.0	55.8 50.4	30.8 30.0

(*a*) hollow butt, (*b*) dead tip, (*c*) green tip, (*d*) dry sided - not measured
Sources: Bednall and Hawkins (1945); Underwood (1965); Inventory and Planning Section, Manjimup; and our own measurements.

Trees of exceptional size have frequently been recorded: d.o.b. of 310 cm 1.53 m above ground level (von Mueller 1879), d.o.b. of 213 cm, also measured 1.53 m above the ground (Ednie-Brown 1896), and d.o.b. of 244 cm at the base of the tree (Hutchins 1916). The tallest tree recorded was 56.4 m high (Bednall and Hawkins 1945) though a later measurement was only 48.8 m (Underwood 1965). Trees with d.o.b. exceeding the arbitrary value of 200 cm have been called King Jarrahs by Abbott and Loneragan (1984a). The data available for a selected sample of these trees are summarized in Table 1.

Height and d.o.b. of these trees are not perfectly correlated. For example, the tree of largest d.o.b. is not the tallest. This observation was studied further and more generally with data of Helms[+] based on measurements of 1826 trees with d.o.b. ≥ 19.4 cm present in high quality virgin jarrah forest in Chalk Block, Harvey Division. The relationship between height and d.o.b. is not linear (Fig. 5).

Height and d.o.b. measurements from six other localities (also collected by Helms) were therefore fitted to an equation of the form $\ell n\ H = a + b\ \ell n\ D$ where H and D are respectively height and d.o.b., and a and b are constants.

The fit to this equation was always better for the samples from high quality forest (Table 2). In only one case was less than half the variation in height explained by d.o.b. These equations were then used to predict heights for d.o.b.'s of 20, 40, 80 and 120 cm. Differences in tree height between high and low quality forest are evident even for d.o.b. = 20 cm, and become more pronounced at larger d.o.b.'s (Table 2).

+. Forests Department file H.O. 1305/37.

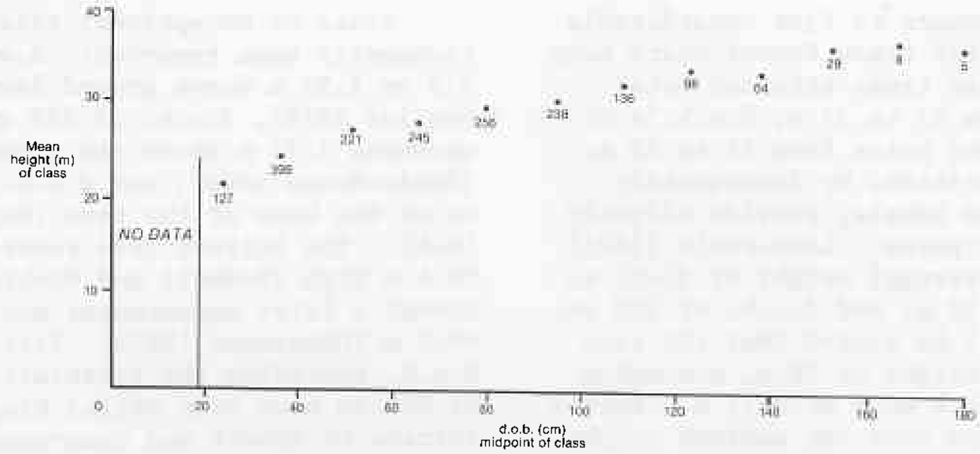

Figure 5
Relationship between mean height and d.o.b. for jarrah of d.o.b. $\geq$ 19.4 cm in high quality forest, Chalk block.

Table 2

Relation between height and d.o.b. for jarrah in high and low quality forest, using the equation ln Height = a + b ℓn d.o.b.

Locality	Site-vegetation type	a	b	r^2	N (a)	Calculated height (m) for d.o.b. (cm) 20	40	80	120
High quality forest									
Chalk	T	2.021	0.329	0.842	258	20.2	25.5	31.9	36.4
Ashendon	O	1.654	0.381	0.743	70	16.3	21.3	27.8	32.5
Holyoake	O	1.668	0.384	0.716	28	16.7	21.9	28.6	33.3
Low quality forest									
Clare	H/Z	1.821	0.294	0.417	34	14.9	18.3	22.4	25.3
Beraking	HZ	1.692	0.334	0.628	300	14.8	18.6	23.4	26.9
Coondle	HZ	1.197	0.378	0.620	263	10.3	13.4	17.4	20.2

(a) N = No. of trees of d.o.b. > 19.4 cm measured for d.o.b. and height.

The biomass of jarrah has rarely been determined, probably because of the effort and time required to cut up and weigh an adequate sample of trees. Hingston *et al.* (1980) did this for 10 trees in high quality forest near Dwellingup, deriving the following equation: ℓn (total dry weight) = 2.84 ℓn d.o.b. - 3.68 (r^2 = 0.99). However, traditional emphasis has been placed on determining the volume of the tree for forest inventory, planning and regulation of the cut.

The volume of a tree is the volume of all wood produced, including the branches. In practice, however, only the bole has value, whether as sawlog, power pole or jetty pile. Emphasis is therefore placed on calculating the volume of the bole, omitting the base which remains in the forest as a stump. Bole volume is calculated as bole length x b.a.o.b. x a coefficient called the form factor. This coefficient expresses the similarity of the bole to a cylinder of the same base and length (Kessell 1921a). Thus a form factor of 1 indicates a perfect cylinder.

Generally for jarrah the form factor is 0.72-0.81 (old growth or virgin jarrah, Lane-Poole n.d.) or less than 0.6 (regrowth jarrah, Loneragan, unpublished data). For whole tree volume (including that of the branches) Stoate and Helms (1938) used a value of 0.6. Related to form factor is taper, because for a given d.o.b. the longer the bole the narrower it becomes (See Harding 1939 for numerical data).

All these factors are taken into account when a volume table is constructed. This table gives the volume of trees on the basis of their d.o.b. and bole heights. The volume of wood contained in jarrah of d.o.b. 30-50 cm ranges from 0.1-2 m^3 depending on bole length (1-25 m). A tree of d.o.b. of 100 cm would have a bole volume of up to 9 m^3, and one of 200 cm d.o.b. a volume of up to 40 m^3 (Forests Department 1976). The volumes of King Jarrahs 1 and 5 in Table 1 are 61 and 60 m^3 respectively, the largest volumes known.

Bark

Jarrah (except as a sapling) has a rough, reddish-grey to brown bark. This is fibrous and flat with small fissures, and is persistent to the small branches (Hall *et al*. 1963; Hall *et al*. 1970; Wallace 1971). In the sapling stage, the bark near the apex is smooth and green and becomes reddish-brown and slightly fissured lower down. Farther down the stem the bark is brown, rough and flaky (Stoate and Wallace 1938). In 1879, von Mueller suggested that the Eastern Australian term 'stringybark' could be applied to jarrah, and it was so described by Lane-Poole (n.d.) and Gardner (1979). In contrast, both Maiden (1909) and Hall *et al*. (1963) assert that jarrah is not a true or typical stringybark.

Exfoliation of blackened bark is recorded as taking 15-20 years (Wallace 1966), though in 1983 we observed small amounts of charcoal still present on jarrah bark in compartments unburned since 1932 and 1937.

The thickness of the bark is an important characteristic. Up to the mid-1950s it was rarely recorded because it was too time consuming and because most of the high quality northern jarrah forest was protected from fire. D.o.b. was then sufficiently accurate to use for determining diameter growth rates. Once prescribed low intensity fires were put periodically through the forest, it was found that considerable errors in the estimates of growth rate were occurring because bark at breast height was lightly charred (Stoate 1951; Forests Department Circular 20/51). Since then, the thickness of the bark has been measured (on plots used for growth determination) with a bark gauge, usually at four places just above or below breast height, and these values then averaged. D.u.b. of each tree is calculated as d.o.b. - 2 x mean bark thickness. Bark thickness of jarrah should decline with height above ground, as occurs in other eucalypts (Grassia 1980). Because of the omission of bark thickness data from the earlier tree measurements (described by Abbott and Loneragan 1983b), we studied the bark thickness of jarrah trees in relation to d.o.b., number of years since the previous fire, and the intensity of fire. Stoate (1953) had remarked that bark thickness of trees of d.o.b. 45-90 cm (presumably protected from fire) was variable, averaging 3.0 cm. In the following, unless specified otherwise, all bark thicknesses were measured by O. Loneragan, thus eliminating variability resulting from different observers.

We examined the relationship between bark thickness and d.o.b. by regression analysis. For old growth jarrah (i.e. trees already present in the forest when logging took place), none of the regressions was significant, indicating that bark thickness does not vary in relation to d.o.b. The bark thickness attained six years after wildfire was no different from that reached 11 years after wildfire (2.8 cm, Table 3).

However, exclusion of fire from jarrah regrowth stands for 43-48 years leads to an increase in bark thickness (3.2-3.9 cm, Figs 6, 7). It is not certain when an equilibrium is attained between production and normal shedding of bark. Bark thickness measurements made by members of the Inventory and Planning Section of the Forests Department in two growth plots in a compartment in Chandler block unburnt since 1937 indicate no differences between the measurements of 1956 and 1972. Maximum bark thickness may therefore be attained at least 19 years after fire of low intensity.

Our analysis of second growth jarrah (i.e. trees regenerating after logging) revealed surprising differences from the old growth trees. In all but one case, there was a significant regression between thickness of the bark and d.o.b.

Table 3

Thickness of bark of old growth jarrah trees related to time since wildfire.

Block	Years since fire	d.o.b. range (cm)	N	Mean Bark thickness (cm)	Mean d.o.b. (cm)
Whittakers	0.3	49.7-101.4	24	2.1	64.1
Pindalup	2.6	49.3-111.1	30	2.5	70.5
Pindalup	4.2	50.3-123.2	33	2.6	66.7
Plavins	6.3	49.3-84.2	25	2.8	64.7
Holmes	8.5	50.7-147.1	22	2.8	79.2
Nowra	11.2	52.9-102.4	22	2.8	73.6

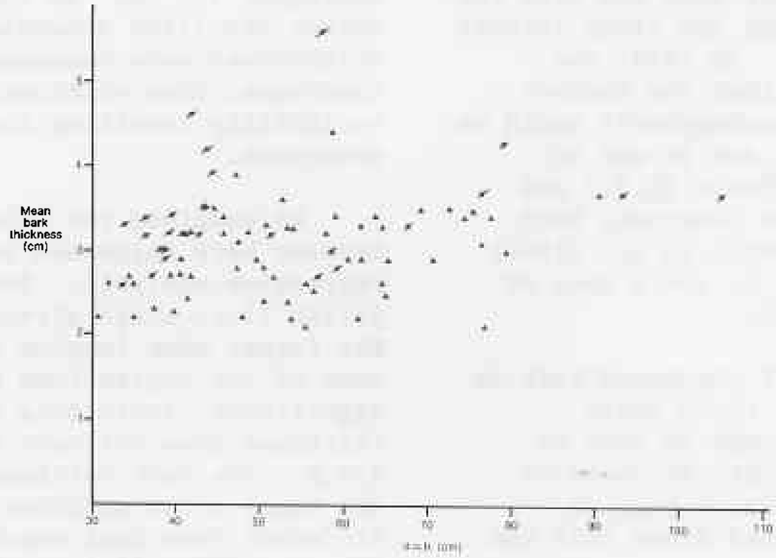

Figure 6
Bark thickness of jarrah in relation to d.o.b. in one stand unburnt for 43 years (⬈) and in another burnt periodically over the last 30 years (▲) [Site-vegetation type S (Havel 1975b)].

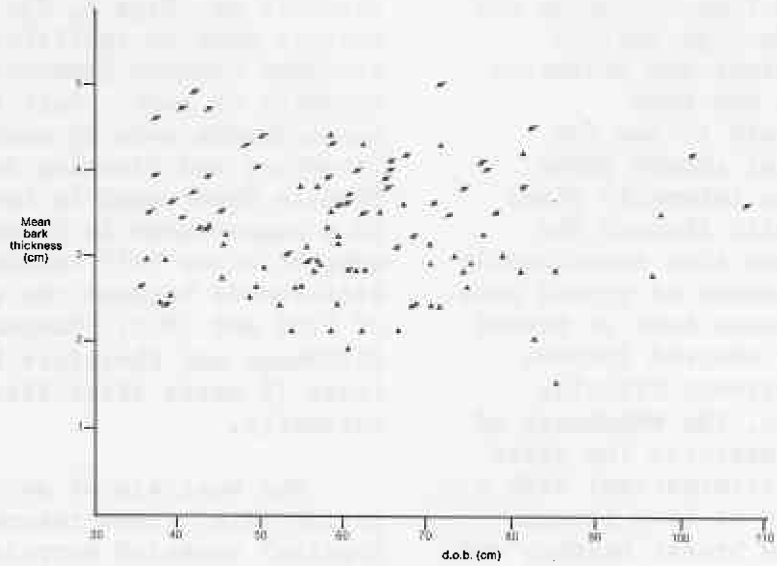

Figure 7
Bark thickness of jarrah in relation to d.o.b. in one stand unburnt for 48 years (⬈) and in another burnt periodically over the last 20 years (▲) [Site-vegetation type T (Havel 1975b)].

(Table 4). Bark thickness was still increasing 11 years after wildfire, unlike old growth (see Table 3). Other data (Table 5) in contrast show few differences in bark thickness of trees between stands protected from low intensity fire for 9-20 years.

Table 4

Thickness of bark of second growth jarrah trees related to time since wildfire.

Block	Years since fire	d.o.b. range	N	Mean Bark thickness (cm)	Mean d.o.b. (cm)	Regression Equation and significance (*a*)
Plavins	0.08	20.4-36.6	20	2.2	28.8	Y = 1.115 + 0.038X P <0.05
Whittakers	0.3	21.6-38.6	24	1.7	28.8	-
Pindalup	2.5	19.8-37.2	21	2.2	28.7	Y = 1.156 + 0.037X P <0.01
Pindalup	2.6	19.4-38.8	40	2.2	29.0	Y = 1.461 + 0.025X P <0.01
Plavins	3.0	19.4-33.5	28	1.5	26.8	Y = 0.274 + 0.047X P <0.01
Amphion	4.3	21.0-36.8	47	2.0	27.1	Y = 1.415 + 0.022X P <0.05
Plavins/ Inglehope	6.0	21.0-35.1	37	2.3	27.9	Y = 1.422 + 0.031X P <0.01
Holmes	8.4	19.4-38.0	28	2.5	28.8	Y = 0.998 + 0.050X P <0.01
Nowra	11.2	20.6-38.8	20	2.8	28.9	Y = 1.593 + 0.040X P <0.05

(*a*) Y, bark thickness; X, d.o.b.

Table 5

Effect of absence of low intensity fire on bark thickness of regrowth jarrah.

Block	No. years since fire	Mean Bark thickness (cm) in d.o.b. class (cm) (No. of trees measured in parenthese) 10-15	15-20	20-25	25-30	> 30	Site-vegetation type
Holmes	9	1.8(13)	2.2(37)	2.4(27)	2.6 (9)	3.0(15)	TS
Holmes	9	1.6(21)	2.0(27)	2.2(19)	2.3 (8)	2.8(10)	TS
Holyoake	20	-	2.2(15)	2.4(45)	2.7(25)	-	O
Holmes	20	-	2.3(23)	2.5(30)	2.6(23)	-	T
Holyoake	20	-	2.4(22)	2.6(34)	2.7(24)	-	O
Holmes	21	1.9(16)	2.1(26)	2.3(17)	2.5(10)	-	S
Holmes	21	2.1(35)	2.2(61)	2.7(27)	2.5(11)	2.8(16)	S

Bark thickness of jarrah in the long absence of fire appears to vary with site-vegetation type. For trees of d.o.b. ⩾ 30 cm, the site-vegetation type and mean bark thickness are as follows: T, 3.9 cm (Fig. 6); S, 3.2 cm (Fig. 7); Z, 2.3 cm (Fig. 8); H, 2.5 cm (Fig. 9). Mean bark thickness is less in low quality forest (Z and H) than in high quality forest (T, S).

<u>Leaves, Shoots, Branches and Crown</u>

The adult leaves were first described by Bentham (1866) and illustrated in some detail in von Mueller (1879, 1879-84). Later descriptions are to be found in, for example, Blakely (1965) and Hall *et al.* (1970). The mature leaves are oval-lanceolate or lanceolate, c. 10

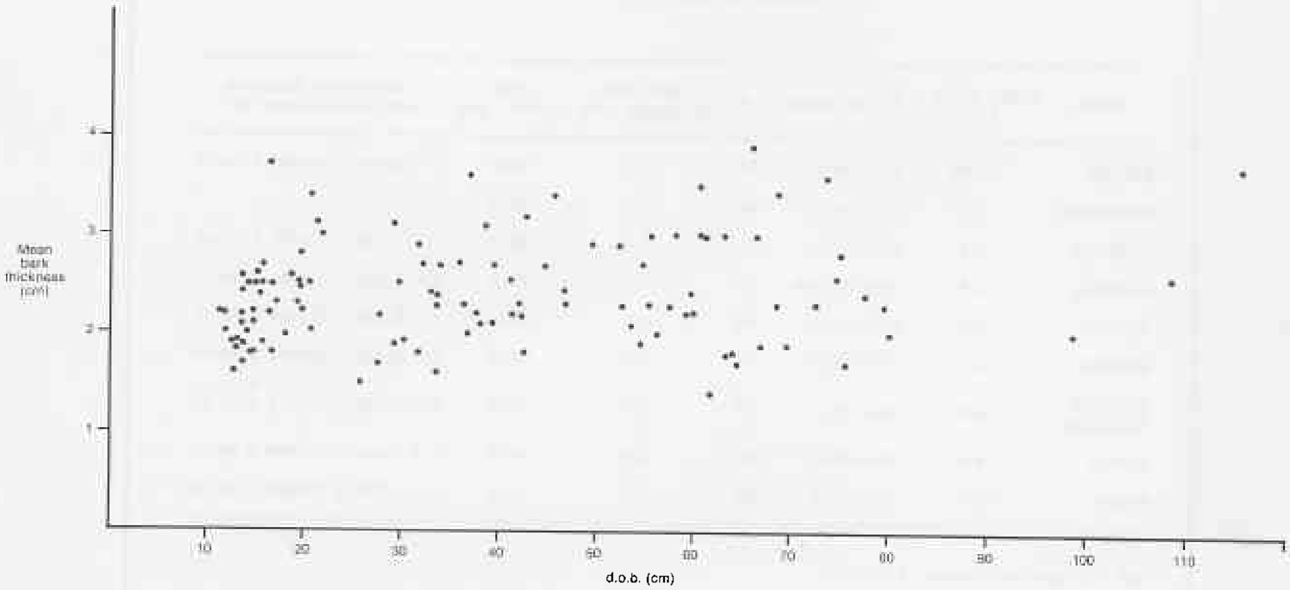

Figure 8
Bark thickness of jarrah in relation to d.o.b. in one stand unburnt for 25 years [Site-vegetation type Z (Havel 1975b)].

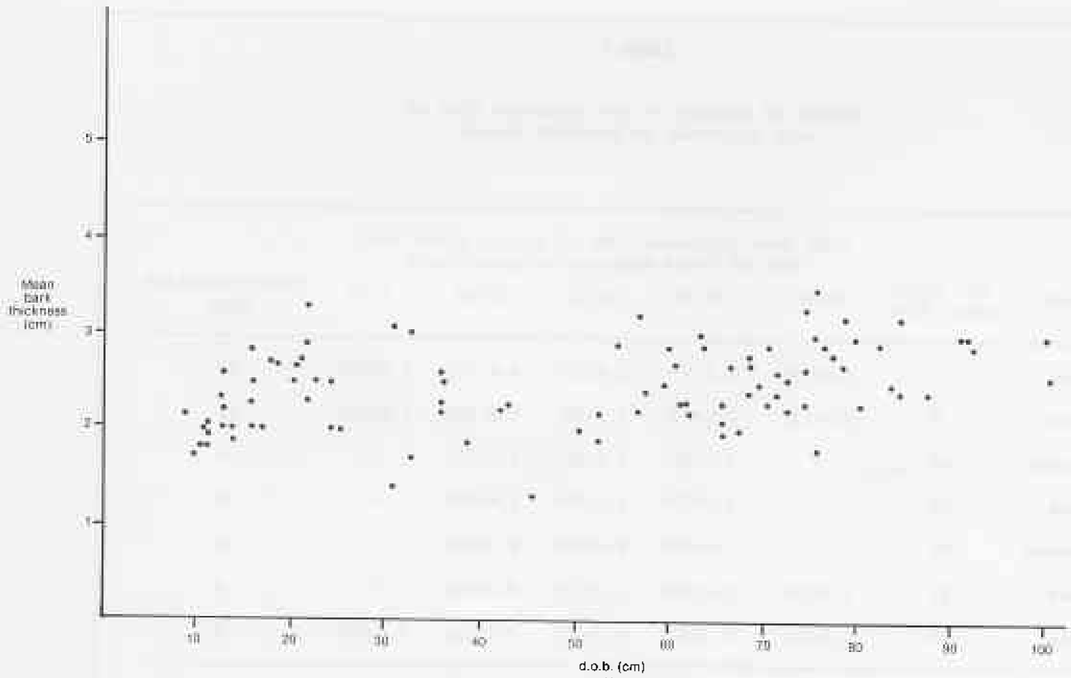

Figure 9
Bark thickness of jarrah in relation to d.o.b. in one stand unburnt for 25 years [Site-vegetation type H (Havel 1975b)].

cm long, slightly darker green above than below. A variant with glaucous leaves also occurs. The juvenile leaf is isobilateral in contrast to the dorsiventral condition of the adult leaf (Ridge 1980). The juvenile leaves were first described by Maiden (1911), and the cotyledons are described by Maiden (1909).

The leaves are typically sclerophyllous, with thick epidermis and strong development of mechanical tissues. Stomates are restricted to the lower surface (Grieve 1956). Stomatal frequency, the dimensions of the guard cells, epidermis and cuticle, and the proportion of the adult leaf occupied by the various cell types are given in detail by Ridge *et al.* (1984). There appears to be nothing unusual at all about the characteristics of the jarrah leaf.

There are four bud regions for producing the leafy shoots (Jacobs 1955). Three of these are signficant in the development of the branches and the crown. The leaves of jarrah, in common with other eucalypts, are produced by naked buds. Each new leaf unfolds from the naked bud in the axil of the mother leaf. Also located in the axil of each leaf is the meristemic region, which replaces the naked bud whenever it is destroyed. This is the accessory axillary bud, which is concealed in the node at the base of each leaf petiole and axillary naked bud.

While the naked bud continues growth, however, the accessory bud is inhibited and continues development in the cambium, as the meristematic strand, called the dormant bud. These buds have the same potential for growth as the original naked buds.

Shoots consist of a cluster of these growing tips. The apical growing tips tend to grow concurrently while the terminal tip continues the growth of the main axis of the shoot. Other shoots are produced from the growing tips to the side of the leading shoot. These develop into the short-lived branches or branchlets of the juvenile crown, into the long-lived branches, and also into the shaping branches of the primary or persistent crown.

The crown of the jarrah sapling has short-lived branchlets which bear leaves for four years and then die when about 1 cm in diameter and 1 m long (Stoate and Wallace 1938). These branchlets are cast off when the diameter of the stem at the base of the crown is about 6 cm. Three types of sapling crown recognized by Stoate and Wallace (1938) differ mainly in depth and shape (Fig. 10). Because the juvenile crown diameter tends to be constant (about 2 m) these differences are determined by height growth rates. As the sapling crown increases its height the leading shoots bifurcate and form competing branches. The ratio of the diameter

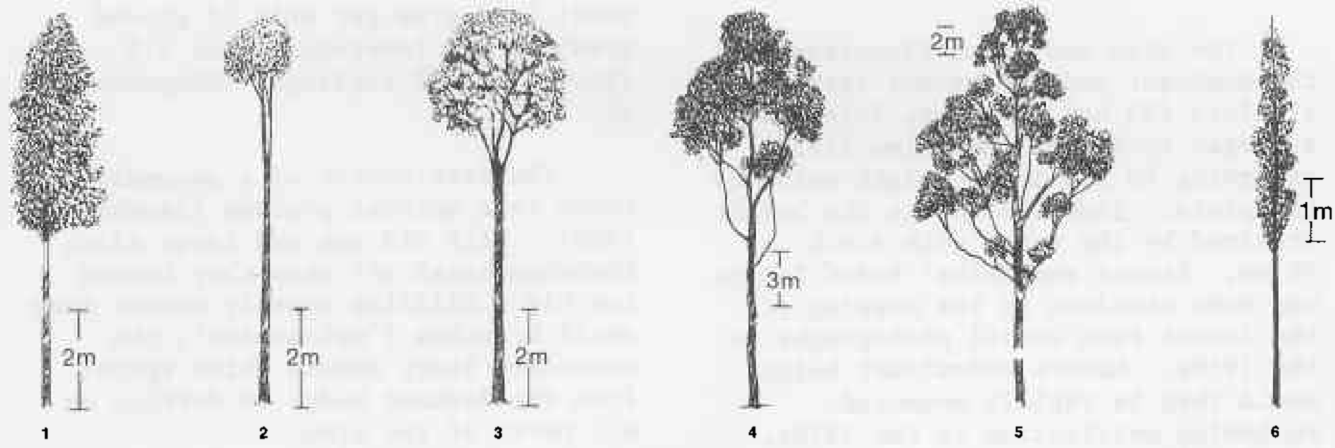

Figure 10
Crown structure of jarrah. 1-3 sapling (classes 1, 2 and 3 of Stoate and Wallace 1938), 4 pole, 5 pile, 6 epicormic crown of saplings after wildfire.

of the stem at the base of the crown to the diameter of these branches then decreases to less than 6:1. At d.o.b. of 14 or 15 cm the ratio of the rate of height growth to the rate of diameter growth falls abruptly from 112:1 to below 70:1 (Loneragan 1961). By increasing in diameter, the competing branches resist being shed.

The crowns of these branches, although relatively inconspicuous at the time of the main crown division, form the base of the persistent crown and promote diameter growth. After crown division, the shape of the sapling crown disappears, usually when the tree is about 20 m tall. The juvenile crown of the short-lived branches continues development and produces, at the reduced height growth rate, the branches of the persistent crown.

Crown depth varies from 2.1 to 6.1 m and crown spread varies from c. 1.2 to 3.4 m over the range for total height of 3.1-21.4 m (Stoate and Wallace 1938). Crown spread is an important characteristic of a crown-shy species like jarrah and is closely related to d.o.b. The so-called K:D ratio is crown spread divided by d.o.b. It steadily decreases with increase in d.o.b. (Stoate and Wallace 1938; Loneragan 1971). In regrowth stands with d.o.b. of 6 cm, K:D equals 25; 8 cm, 18; 16 cm, 13; 24 cm, 12. In old growth stands d.o.b. of 40-100 cm have K:D ratios of 16-13.

The stem and crown diameters of the dominant and codominant trees in 41 plots (83 ha) of virgin forest were arranged by Stoate and Helms (1938) according to the index height value of the plots. Index height is the height attained by the trees with d.o.b. of 76 cm. Stoate and Helms' index height was made obsolete by the mapping of the forest from aerial photographs in the 1950s. Mature codominant height could then be rapidly measured. Following metrication in the 1970s, height classes were rounded to the nearest 5 m. K:D ratios for the index height classes have been converted by us to mean mature codominant height, namely 21 m, K:D 17; 25 m, 16; 29 m, 15; 33 m, 14. However, because of the range of d.o.b.'s in any stand, it is generally sufficient to use a K:D ratio of 15 for high quality stands (with mature codominant height ≧ 27 m), and one of 18 for stands of lower height.

The crown of the jarrah tree is narrow but deep, with the first order branches generally developing at a point from the ground less than half the total height of the tree (Lane-Poole n.d.). The order of branching is determined by the number of angles of branching from the main stem, with the dominant arm having the higher order (Jacobs 1955). Leaves are clustered at the extremities of the branches, usually those of second and third order for saplings, and third, fourth and higher orders for taller trees. The total area of foliage appears small, so that the forest canopy is never dense. Having a 'crown-shy' character, the crowns of eucalypts will not interlock (Lane-Poole 1936). In the forest the ratio of the leaf area of an old growth stand of jarrah to the land surface is 0.57. In pole stands the ratio is 1.06 (Loneragan 1961). Leaf areas in old and young stands are respectively 4.45 m^2 kg^{-1} dry weight of the annual leaf fall and 5.18 m^2 kg^{-1}. The leaf area of jarrah in a pole stand near Dwellingup has been calculated to be 6.61 m^2 kg^{-1} dry weight and its leaf area index (the total leaf area per unit of ground area) as 2.7 (overstorey) or 2.9 (including all saplings) (Hingston *et al.* 1980).

The development of a secondary crown is a natural process (Jacobs 1955). With old age and large size, branches break off when they become too big. Wildfire usually causes many small branches ('epicormics', the secondary leafy shoots which sprout from the dormant buds) to develop on all parts of the stem ('feather-topping'). Wildfire is generally assumed to be responsible for the crowns of many trees in the jarrah forest being in an unthrifty condition (illustrated by Stoate 1953; see also Fig. 10). These crowns typically consist of a gaunt framework of limbs carrying relatively few leaves, in contrast to the dense crowns seen around towns and in pasture paddocks (Stoate 1953). The relative importance of insects, fungi, wildfire, and stand density in causing unthrifty crowns requires evaluation.

Lignotuber

The lignotuber is probably one of the critical factors in the success of jarrah on the Darling Plateau. It is a woody swelling of the stem initiated in the axils of the cotyledons and lower leaf nodes, that is, the fourth bud region for producing leafy shoots (Jacobs 1955). Because it has the same anatomy as the stem, it is properly considered part of the stem and not part of the root system (Bamber and Mullette 1978). Functionally, however, it is often better considered as part of the root system.

The main function of the lignotuber is to render the young plant virtually indestructible to fire, drought or grazing of the plant by mammals or insects. If the aerial portion of the plant is removed or damaged, the lignotuber produces rapid new growth. This is because of the many dormant buds and the nutrients stored in the lignotuber (Mullette and Bamber 1978). This dual role attributed to the lignotuber is controversial, because one school of thought stresses the food reserve aspect, and another the source of buds (see Lacey 1983, for review of early literature).

Lignotubers may be killed by high intensity fire in summer and autumn when the topsoil is dry (Underwood personal communication*).

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Roots

Jarrah possesses both a shallow widely spreading root system and a deeper penetrating one (Grieve 1956). A dense lateral and feeder root system is present in the top 1 m of soil, with a secondary dense layer of feeder roots at considerable depth (15-40 m) near the water table (Kimber 1974; Dell *et al.* 1983). The two systems are connected by vertical sinker roots with little branching. Sinker roots pass through fissures in the massive laterite layer and in the pallid zone. Otherwise the high bulk density of the clay (1.6 g cm^{-3}) would prevent root penetration. These fissures are permanent features of the profile and are of diameter 1 mm to 30 cm. Each jarrah tree has potential access to 100-200 channels, and each channel usually contains 2-3 roots (Dell *et al.* 1983).

Root diameter decreases with increasing depth (Dell *et al.* 1983), and the density of fine roots declines from 1.0 cm cm^{-3} in the bauxite horizon to 0.1 cm cm^{-3} in the pallid zone. Kimber's (1974) observation of a zone of proliferating fine roots above the water table does not appear to be a general feature (Dell *et al.* 1983). Most of the total root length of jarrah consists of fine roots, and much of the root system occurs in the topsoil (Carbon *et al.* 1980). For description of root types, see Dell and Wallace (1981), Malacjzuk and Hingston (1981) and Shea and Dell (1981).

In other eucalypt forests, the radial spread of lateral roots exceeds crown diameter by 2-4.5 times (Nambiar 1981). D.o.b. and lateral root spread are strongly correlated. Such findings should apply to jarrah.

Bud, Flower, Fruit and Seed

The flower buds, flowers, fruit and seeds were first illustrated in detail in von Mueller (1879), reproduced here as the Frontispiece. The fruit, as with other eucalypt species, is called a capsule but is technically a false fruit (see Cremer 1965). Each fruit has the potential to produce many seeds, but generally most are sterile. For a scanning electron micrograph of a fertile seed, see Boland *et al*. (1980).

In one stand of virgin jarrah forest, there were about 400 fruits per tree (Abbott 1984a), but this is probably not typical as the trees were decadent. There have been no studies of how fruit number varies with the dominance status of trees, but the generalizations of Jacobs (1955) should apply. Three batches of fruit each had an average of 1.2, 1.9 or 2.1 fertile seeds/fruit; 97 per cent of these were viable (Abbott 1984a). In other samples of fruit the number of viable seeds is 6-8 (Kimber personal communication*). Fertile seed is about 4.5 mm x 3.0 mm, with mean weight of 0.020 g.

The fertile seed has a terminal velocity of 2.6 m s^{-1}. For a tree 30 m tall with mean crown diameter of 26 m and a wind velocity of 2 km h^{-1}, the possible diameter of the seed shadow is about 39 m (Abbott 1984a).

Wood Properties

Hulme (1958) provides a useful bibliography of the wood properties of jarrah. Various characteristics of the stem wood of jarrah were summarised by Dadswell (1972). These include colour, density, vessels, rays, axial parenchyma, fibres and tracheids. Scanning electron micrograph studies of both stem and root wood were made by Ridge (1980), and Ridge *et al*. (1984). Fibres constituted the bulk of the wood. Other features are described by Shedley and Challis (1984) and chemical properties by Bland *et al*. (1949), Penford and Willis (1961) and Hillis and Carle (1962).

As noted by Dadswell (1972) for eucalypts in general, the sapwood is relatively narrow (< 2.5 cm width) and pale in colour. Cummins (1936) stated that this colour difference is not reliable, but McCaw (1983) noted that normally heartwood (truewood) is pink and sapwood cream.

Early descriptions of the timber properties of jarrah were enthusiastic (von Mueller 1879-84; Maiden 1889), but there were contradictory reports of its resistance to marine borer. Untreated jarrah piles in tropical waters are not resistant (Wickett 1970).

The 1887 Commission of Engineers concluded that the usefulness and desirability of jarrah timber depended on the locality where grown and the season of year in which felled. November to May/June was considered the best time to fell. This is when 'the sap is at the lowest ebb' (Maiden 1889). G. Simpson (quoted by Fraser 1882) recognized three varieties of jarrah wood. These observations are now considered unimportant.

Jarrah forms annual growth rings (Peet 1964, quoting Podger and Loneragan) but their clarity has often been questioned. For example, Lane-Poole (unpublished lecture notes 1917) stated that such rings are not discernible except in very young trees, and that false rings are common. (False rings do not extend around the stem; they are formed when diameter growth is interrupted and resumed during the same growing season - Kessell 1921a). Boas (1947) also reported growth rings as being poorly defined and Dadswell (1972) stated that they are vague or absent. Airey (1965) suggested that this was because of the narrow rings and the similar colour of dense and light wood; he provided a method of staining that enhances the clarity of growth rings by causing the dense wood to become darker. He counted complete rings only, as indicated by the commencement

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of each successive year's dense wood[+]. A densiometric study of these rings (based on variations in wood density) is given by Nichols (1974). We also have not experienced difficulty in identifying annual growth rings of jarrah. The ages of particular pole-sized trees have been determined by both counting rings and by examining Departmental logging maps. In all cases agreement between the two methods has been close.

Various faults in jarrah timber, including shakes, heartshakes and cupshakes, are described by Kessell (1921a). Basically these are cracks in timber; their cause is uncertain. They are often associated with the effects of wind sway and relief of growth stresses. Cracks give fungi access to the heart core. Physical damage to the tree cambium by fire and machines leads to development of dry patches. Cracks penetrating deep into the wood provide access to beetles, resulting in borer holes. Callus growth and gum veins are other defects developed by the tree in sealing off the damaged area and in repairing damage from the edges of wounds.

The true heartwood of jarrah is very durable timber. Only 5 per cent of creosoted posts (including sapwood) installed in the ground for 30 years failed (Tamblyn 1962). Pressure treatment with oil makes jarrah timber practically resistant to decay and termites.

Nutritional Characteristics

Nutritional studies of eucalypts are relatively scarce (Cremer *et al.* 1978). Four jarrah trees growing near Dwellingup were separated into bole wood, bole bark, dead wood, branches, twigs, leaves, flower-buds and fruit and analysed for elemental composition (Hingston *et al.* 1980). Those parts of the tree having the highest concentration of the nutrients studied were: N, leaves; P, K, Cl, buds and leaves; S, Ca, Mg, Mn, leaves; Na, fruit, buds and leaves; Cu, Zn, buds, twigs and leaves. Bole wood had the lowest (relative) concentration of each element. The leaves of the sample trees had greater Mg and lower P, Zn and Cu concentrations than is typical for eucalypts.

Some elements varied in their concentration within the tree. For example, N concentration was greater in the upper crown than in the lower crown, whereas Ca and Mg showed the reverse pattern. The concentration of Cl in bark increased with height above ground and the concentration of a few elements also varied with bark thickness (Hingston *et al.* 1980).

Comparisons of concentrations of selected nutrients in green leaves and leaf litter of jarrah are given by Wallace and Hatch (1952), Hatch (1964) and O'Connell *et al.* (1978). Concentrations of most elements are less even in freshly fallen leaf litter, indicating that the tree withdraws nutrients from leaves before shedding them. The major exception is Ca, which occurs in greater concentration in leaf litter than green leaves. This is consistent with the immobility of Ca in plants.

Few studies of how nutrients move within the jarrah tree have been made, although much research has been done on other eucalypt species (reviewed by McGrath unpublished data). The few glass or shade-house studies done specially on jarrah examine (among other matters) the effect of various fertilizers on the distribution of major nutrients within the seedling. This research may have little relevance to trees in the forest.

Most attention has been given to the mobile nutrients P and N, which should be transported quickly to parts of the plant where growth is greatest. In a pot experiment (Barrow 1977) jarrah seedlings responded to applied P within six weeks; this was not as soon as smaller-seeded species. With

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+. Forests Department file H.O. 779/63.

time, the concentration of P in the leaves of these seedlings decreased even though the P content of the plant increased. Ectomycorrhizae were first noted seven weeks after planting. The stem of the jarrah seedling is an important storage pool of P (Dell and Jones unpublished data): the concentration of P in the stem increases as P supply increases whereas that in the leaf responds only weakly. The amount of P in the stem may regulate the supply of P to the growing tips, being retained there until needed by the leaves (Dell and Jones unpublished data). As in the shoot, the concentration of P in the roots increases with increasing P supply but the concentration of P in the lignotuber remains unaffected.

The concentration of N in roots, lignotuber and stem increases with increasing N supply (Dell and Jones unpublished data). N concentration is always greatest in the stem (Dell and Jones unpublished data). The concentration of N in leaves of jarrah seedlings increases with increasing N supply (Mathie 1981).

In contrast, a field experiment testing blood and bone manure (250 kg ha^{-1}) against a control in Holyoak and Holmes blocks, Dwellingup, yielded no effect on the N content of jarrah leaves. Fertilizer had been applied each spring from 1952 to 1956. Leaves collected from the 1955 and 1956 crops gave the following concentrations of total N for the treatments respectively: 1955 0.868 per cent, 0.842 per cent; 1956 1.044 per cent, and 1.073 per cent (Hatch, unpublished data). The low levels of nutrient in the fertilizer were probably responsible for the lack of significant difference between treatments.

Fire sufficiently intense (900-2000 kW m^{-1}) to cause 80-100 per cent scorching of crowns reduces the concentrations of P and N in jarrah leaves (Glossop *et al*. 1980). Losses in the lower canopy were ascribed to volatilization, but those in the upper canopy may have resulted from nutrient withdrawal.

Physiological Characteristics

The most studied features of jarrah are those that help it cope with summer drought. Jarrah has evolved heavy dependence on an efficient root system and has leaf and stomatal physiology to match.

In winter, spring and early summer the surface roots are well supplied with water, but as the soil profile dries, water becomes unavailable near the surface irrespective of the many roots in that zone (Carbon *et al*. 1980). Wilting point is reached in the upper 0.5 m in late December and in the upper 5 m by late March (*Annual Report* 1970; Kimber 1974). More detailed studies by Butcher and Havel (1976) and Butcher (1977) show similar patterns of exhaustion of soil moisture on the nearby coastal plain. Yet, transpiration by jarrah persists in summer despite exhaustion of available water in the upper profile (Doley and Grieve 1966).

The reason that this inhospitable environment can support forest is that the deep root system of jarrah allows access to water supplies in the subsoil.

In summer water consumption by trees with d.o.b. of 23-38 cm ranges from 3350 to 11 000 L ha^{-1} (Doley and Grieve 1966). The rate of transpiration typically differs little between the high and low rainfall zones (Carbon *et al*. 1981). Jarrah shows an unexpectedly high rate of water loss in summer (Grieve 1956) probably because the stomates are often widely open. Although young jarrah leaves should take time to develop sclerophyllous attributes (Specht 1982), they transpire less water than mature leaves because of more effective stomatal closure (Doley 1967). Transpiration is greatest around noon in summer, but as the summer advances the stomates close earlier and for longer (Doley 1967). With rising temperatures and higher evaporation in mid summer, this mechanism keeps the water consumption of jarrah to a level similar to that before summer (Doley and Grieve 1966). Leaf resistance increases as air temperature rises by mid-afternoon; by the same time leaf water potential falls to its lowest value (Alcoa 1981).

Recent studies (Bartle personal communication*) have found that stomata rarely close completely even under extreme conditions. Also, the response to soil water deficits, observed by contrasting early summer and late summer transpiration under conditions of similar evaporative demand, is negligible.

After the very dry winter of 1976, Bartle and Shea (1978) showed that jarrah was susceptible to desiccation on shallow soil sites, suggesting that jarrah has a poorly developed adaptation to soil water deficit.

Minimum xylem pressure potential is usually about -1500 kPa (Carbon *et al.* 1981; Shea *et al.* 1982), and there is little seasonal variation in the daily extremes (Colquhoun *et al.* 1984). However, in the dry summer of 1978, an extremely low value of -3400 kPa was recorded (Bartle and Shea 1978).

Jarrah seedlings grown under drought conditions (watered on first day and then when wilting occurred) showed some anatomical differences from controls (watered every day). The area of bundle sheaths in the leaf was relatively less extensive, as was the area of reaction xylem in the stem. Stressed seedlings developed relatively more vessels in the roots (Ridge 1980). However, anatomical comparisons between several eucalypt species provide little evidence of anatomical correlation with physiological features (Ridge *et al.* 1984).

The second physiological factor that has been investigated is salt. The efficiency of jarrah (and other forest trees) in annually depleting water recharge results in the accumulation of salts (Bartle and Shea 1979). These salts arrive in rainfall, which governs the amount accumulated over geological time in these ancient soils. For example, for an average annual rainfall of 1200 mm, the total storage of salts is 10^4 kg ha^{-1}, and for 800 mm rainfall, > 10^6 kg ha^{-1}. Details are given by Batini and Selkirk (1978) and Herbert *et al.* (1978).

Experimental studies with jarrah seedlings indicate that jarrah is sensitive to salt (Scheltema 1982). Less than 0.2 g of Na Cl 100^{-1} g soil did not result in symptoms of stress. At 0.2 g of Na Cl 100^{-1} g, nearly half the seedlings died.

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CHAPTER 7

Growth

Stages of Development

The stages of development of jarrah, from seedling to tree, have been classified in several ways. The earliest scheme (Kessell 1921a) recognized seedling (germination to height of 1.5 m), sapling (height of 1.5 m to d.o.b. of 13 cm), pole (d.o.b. of 13 cm to when stand attains its full height) and tree (from the time the stems attain full height). One problem is that these four words are still in common use but not usually in Kessell's sense. To some extent such classification is mainly for convenience. Much research done in the 1960s was marred by the lack of careful definition of the early stages of the jarrah. Ironically, a very good classification had been devised by Stoate and Helms (1938) for describing the earlier stages of development.

These stages were defined, with slight modifications by us (Abbott and Loneragan 1984b), as follows (Fig. 11):

(1) Seedling - Less than one year old, usually with cotyledons present, and without obvious lignotuber. Height of shoot is not specified.

(2) Lignotuberous seedling - Older than one year, cotyledons absent (or if present, then dead), one stem with lignotuberous swelling.

(3) Seedling coppice - The lignotuber is obvious and remains so at least until stage (4) is reached. Arising from this are multiple shoots, restored after fire or other agent has damaged or killed the original shoot(s).

(4) Ground coppice - Two substages are recognized: incipient ground coppice lacks a definite leading stem, whereas dynamic ground coppice has a well defined leader

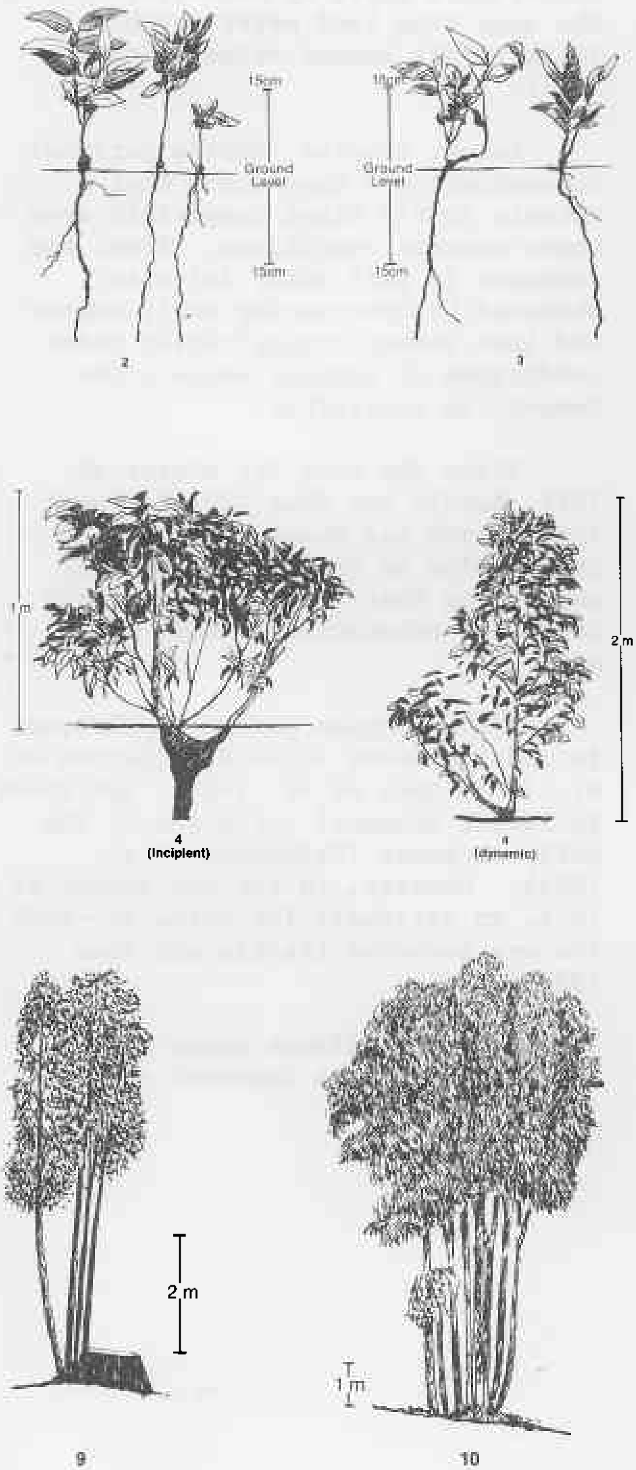


Figure 11

Early stages in the developent of jarrah; (2), lignotuberous seedling; (3), seedling coppice; (4), ground coppice; (9), stump coppice; (10), stool coppice.

among the surrounding multiple shoots. In both cases the length of the longest shoot is less than 1.5 m, and the length of the long axis of the lignotuber is less than 15 cm.

(5) Sapling - Height of the tallest stem exceeds 1.5 m but d.o.b. is less than 15 cm. The sapling has a juvenile crown, consisting of the leading shoot(s) and short-lived branchlets. From this stage, the lignotuber becomes so large and ill-defined that it is best regarded as a root-stock or caudex.

(6) Pole - d.o.b. ranges from 15 to 45 cm. The crown consists of the leading juvenile crown and crown units of the semi-persistent branches and persistent primary branches. These have reduced juvenile crown units which extend the lateral spread.

(7) Pile - d.o.b. ranges from 45 to 60 cm.

(8) Tree - d.o.b. exceeds 60 cm.

The d.o.b. limits specified for stages (6)-(8) are arbitrary and differ in relation to site quality (Fig. 12). It may be useful to subdivide stage (8) into immature, healthy mature and overmature tree though in practice recognition is subjective. Poles, piles and overmature trees may have a secondary growth of epicormic branches replacing the primary-shaping branches which have been broken from the trunk (Fig. 4).

Two other stages, developed from logging, are very common throughout the northern jarrah forest:

(9) Stump coppice - These are resprouts from stumps cut above ground level, normally during logging.

(10) Stool coppice - These resprout from stumps cut at ground level (mullinizing). This treatment

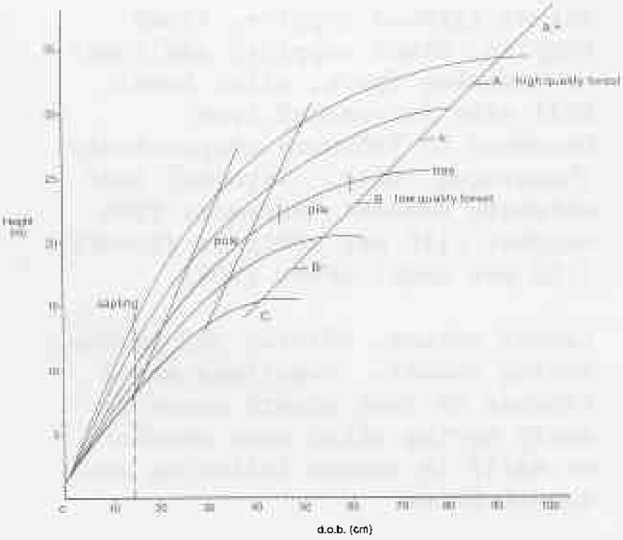


Figure 12

Stages in the development of jarrah subsequent to ground coppice (indicated by mean mature codominant height) in relation to site quality: A^+, > 33 m; A, 27-32 m; B^+, 21-26 m; B, 15-20 m; C,< 15 m.

was carried out extensively by the Forests Department during the 1930s.

The rate of transition through the above stages, and the factors responsible, are discussed in later chapters.

Seasonal Patterns of Growth

The seasonal cycle of plant growth in temperate Australia (with emphasis on mediterranean climates) may be summarized as follows (Specht 1975, 1982): in late spring to summer starch stored in stems and roots is hydrolysed, the canopy grows and leaves are shed. During this period the leaf area index remains more or less constant. Growth of the stem and roots occurs during autumn; canopy growth ceases then. There is cambial stem growth in winter. By late winter and spring, leaf litter begins to decompose, roots grow and starch is stored in the roots and stems.

Seasonal growth of jarrah is well understood for leaves and shoots, wood and roots.

(a) Leaves and Shoots
The leaves of jarrah start unfolding from the naked buds in

August (ground coppice, stump coppice, stool coppice, saplings) or November (pole, pile, tree). Full size is reached from December to February respectively (Loneragan 1961). Terminal leaf moisture content increases from October (110 per cent) to January (150 per cent) (Peet 1964).

Leaves mature, thicken and harden during summer. Sometimes small flushes of leaf growth occur in early spring after warm weather or early in autumn following good summer rains.

Leaves rarely live longer than two years; about half are shed after 12-15 months and nearly all after 24-27 months (Loneragan 1956, 1961). To a great extent, the life of the leaf varies with the degree of vigour and branch extension. Where extension growth is greatest, leaves may live for less than one year. On stagnant branchlets, they may survive for nearly three years. The age, vigour and position of the tree, season, and damage caused by insects, frost or fire are also important (Loneragan 1956). For example, the entire crown may hold no leaves older than six months when a favourable season follows an unfavourable one or a seed year. As expected, most height or shoot growth takes place in summer, when leaf production is greatest.

In December the old leaves become yellow to brown in colour and are then shed as the branchlets die throughout summer (Stoate and Wallace 1938). Most litter fall takes place in January, February and March (Wallace and Hatch 1952; Hatch 1955; 1964); this may exceed 650 kg ha^{-1} during some summers (Hatch 1964). The association between leaf fall and leaf flush is probably causal (Hatch 1964): the production of new leaves probably reduces the amount of water and nutrients available for older leaves. An abscission layer forms at the base of the petiole (and branchlet) during senescence, resulting in its shedding (Jacobs 1955).

There appears to be no marked effect of season on the resprouting of coppice from jarrah stumps. This may be compared with *E. occidentalis* plantations in Israel, where the proportion of stump regeneration from cutting during late spring/early summer is relatively low (Zohar *et al.* 1978).

(b) Cambium

Growth of the stem cambium begins in autumn, usually during April at the break of the season (Loneragan 1961). The wood produced then is dense, with a high ratio of fibres to small pores. Most growth occurs during winter, when a high ratio of fibres to large pores is produced. Growth usually stops in December; this is marked by a discontinuous ring of pores. The cambium does not grow in summer.

This information comes from three sources: the regular measurement by tape of a single tree over 10 years; short-term measurements using dendrometer bands; and studies of wood anatomy. The first two methods measure both cambial growth and shrinkage/expansion of bark. In winter bark is moist and expands, but in summer (and periodically during winter and spring) it dries and shrinks. This results in dendrometer bands recording negative increment. Useful data on the moisture content of wood throughout the year are given by Doley and Grieve (1966).

The d.o.b. of one tree at Willowdale was measured monthly with tape by J.M. Leeds (unpublished data) for 10 years. In March 1936 d.o.b. was 68.0 cm and in October 1946 it was 76.4 cm. Normally, a sample size so

Table 6

Monthly increment in d.o.b. of one jarrah tree at Willowdale, measured nearly every month from 1936-46.

Month	No. zero readings	No. readings	Mean d.o.b. increment (cm)
Dec./Jan	0	10	0
Jan./Feb.	0	10	0
Feb./Mar	0	10	0
Mar./Apr.	5	11	0.09
Apr./May	7	11	0.14
May/June	7	11	0.13
June/Jul.	9	11	0.15
Jul./Aug.	1	11	0.03
Aug./Sep.	3	11	0.05
Sep./Oct.	2	10	0.03
Oct./Nov.	3	10	0.06
Nov./Dec.	4	10	0.06

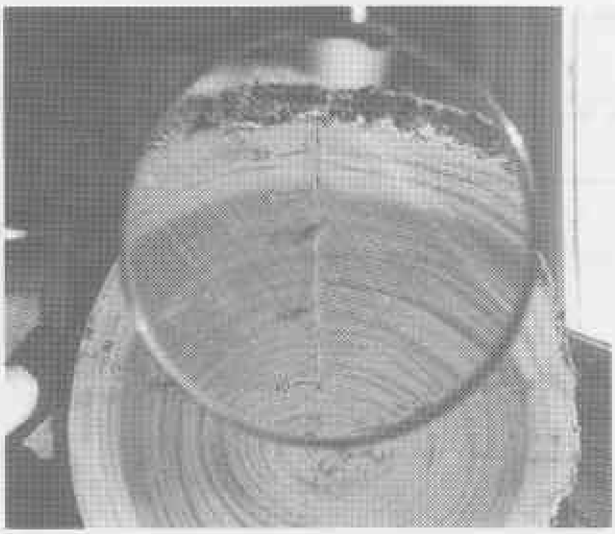
small would not be very useful, but the long period of measurement compensates for that deficiency. No growth was recorded during summer (Table 6). Most took place during autumn and winter, with 70 per cent of total increment between March and July.

Dendrometer growth studies show that d.o.b. growth of 150 jarrah poles is greatest in May and positive in all months except December (Peet 1964; McCormick n.d.). Flushes occur in spring (with a peak in October) and autumn (peak in May). Otherwise growth is maintained at a low level.

The original graphs (Peet and McCormick unpublished data) show that greatest positive increment occurred in April to May 1964, April to June 1965, February/March and May 1966, May and June 1967, and March, May, and June 1968. Negative increment was greatest in December and July but occurred also in January, February, August and September. Decrement recorded in winter may have resulted from low temperatures. Other dendrometer studies (November 1966, monthly measurements for one year, Kimber unpublished data; and monthly measurements over 40 months, Bartle and Shea 1978) yield similar results. A study from 1964 to 1970 found positive increment from February to November, with maximum growth in June and July (Nichols 1974).

The third approach is potentially more useful but is very laborious. Loneragan (1961) studied the surface of cross-sections (at ground level) of jarrah poles. Anatomical details were observed using a hand lens and binocular microscope. Stems from part of Amphion block burnt by wildfire in February 1940 and March 1952 helped confirm the growth ring pattern (Fig. 13). Pores are aligned in distinctive patterns allowing the recognition of growth rings (Fig. 14). Each growth ring is terminated in porous wood in a discontinous ring of pores in the spring wood. Dense wood begins abruptly in the adjacent growth rings in autumn and has the smallest pore sizes (abnormalities sometimes occur; these are discussed later).

Seasonal changes in wood growth are displayed by the arrangement of the pores (see Fig. 14).



A. Jarrah annual growth rings. Note the proventitious dormant bud strand capable of producing epicormic shoots (para. 1, Ch. 1).

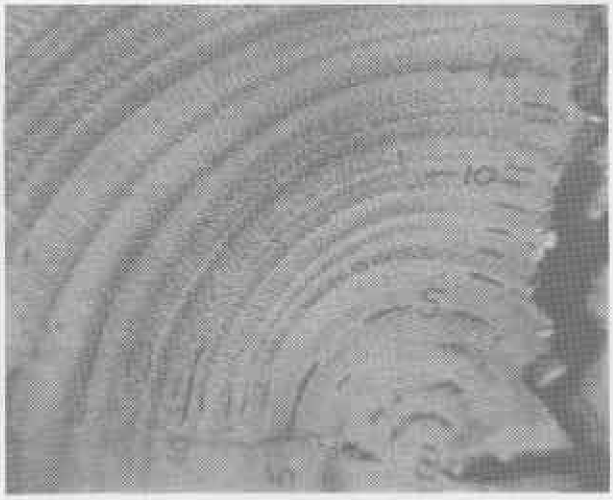


Figure 13

B. Section of the stem of a jarrah pole showing annual growth rings and the meristematic strand of the dormant leaf bud (jacobs 1955).

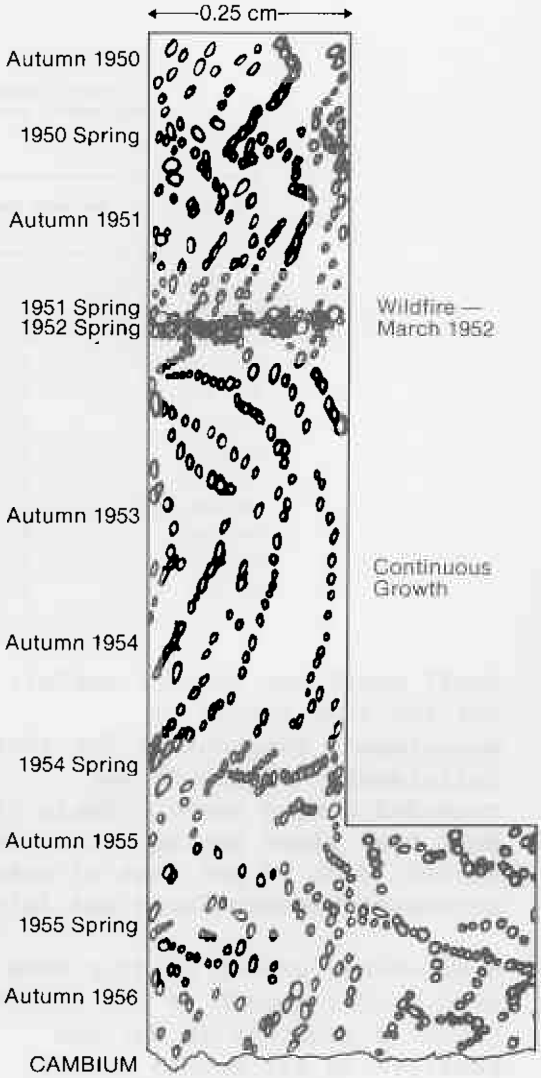


Figure 14

Anatomy of a section of jarrah wood, showing the formation of the annual growth rings before and after wildfire (after Loneragan 1961).

Pores arranged in radial lines across the growth ring show that growth was uniform, whereas pores oriented in curved lines indicate rapid growth, with rate of growth increasing then decreasing. Towards the end of the annual growth (in the spring wood cambium) pores appear closer together and terminate almost side by side in a discontinuous ring.

The seasonal sequence of growth, with dense wood in autumn and porous wood in spring, is typical of eucalypts in southern Australia. Because spring wood is found late in the growth sequence, it should not be called 'early wood'.

(c) Roots

The seasonal pattern of root growth is similar to that of cambium. Most growth occurs in May/June and September/October (Dell and Wallace 1983). Rainfall is important in initiating growth; rapid growth occurred within two days of an unseasonal storm in February. Much of the framework for fine feeder roots is built up after the autumn rains. There is little difference in growth periodicity of the various types of root (Dell and Wallace 1983).

The phenological patterns described for leaves, cambium and roots imply that starch is stored in the wood during winter and then in spring and summer is used for leaf growth.

Rate of Growth

(a) Height

Because height of trees is difficult to measure as accurately as d.o.b., there are few references to the rate of growth in height of jarrah. Most of these pertain to the smaller stages of development (< 1.3 m tall). Lane-Poole (n.d.) quoted an average height growth of 5 cm yr^{-1} for seedlings at Dwellingup; this was considered to be about twice that at Mundaring. Seedlings eight-months-old in the Ashendon virgin forest had grown 7-8 cm tall (Abbott 1984a). In Mundlimup block, seedlings nine and 21 months old had grown to average height of 3 and 5 cm respectively (Abbott and Loneragan 1984b). Other records (Abbott and Loneragan 1984b) include: 5.3 cm (six months, Ashendon block), 6.9 cm (2.5 yr, Young block) and 7.9 cm (6 yr, Plavins block - see also Table 7). These data come from stands with basal areas typical of the northern jarrah forest and do not include specialized conditions such as ashbeds or thinned stands, which are discussed later.

Development from the seedling coppice stage into the ground coppice stage takes many years, with height usually remaining at c. 1 m. There is continual renewal of multiple shoots from the lignotuber until a dynamic shoot is able to assume the sapling habit and continue height growth (Abbott and Loneragan 1984b). Three categories of height growth for saplings were recognized by Stoate and Helms (1938): 0.8-0.9, 0.5-0.6 or ≦ 0.3 m yr^{-1}. These result in crowns of saplings in these categories having different shapes. Saplings belonging to the fastest growth category achieved a height of 20 m in 23 years. Saplings in lower quality sites have slower growth rates and achieve lower final height of

Table 7

Height growth of jarrah seedlings in Plavins block, Dwellingup (unpublished data of P. Kimber).

Date measured	Age (months)	No. measured or alive	Mean height (cm)
May 1965	9-12	314	-
May 1966	21-24	242	-
August 1967	36-39	130	7.5
June 1968	46-49	84	-
May 1969	57-60	57	-
August 1970	72-75	45	7.9
June 1971	82-85	40	7.1

\- not measured

the crop trees. Growth rate is most rapid in the early years for healthy regeneration on all sites (Loneragan 1971; see Fig. 12). Height growth of stool coppice is about 1.2 m yr^{-1} for the first three years after cutting and thereafter decreases to about 0.6 m yr^{-1} (Chandler 1939). Height increment of the leading coppice shoot is most influenced by stump size.

There have been no studies of height increment of piles or trees.

Jarrah achieves its final stand height relatively early in its life cycle. For example, stool coppice eight years old has a height of c. 7 m (Bednall 1942), about one quarter of the final height. This is also illustrated (Table 8) by the similar height of regrowth stands 23 or 51 years old. These data also indicate that most height growth is achieved within 20 years after release of the ground coppice stage by regeneration treatments or clear-felling of the original overstorey.

Table 8

Mean height (m) of jarrah regrowth in relation to d.o.b. Measured in 1955.

Plot	Stand age (yr)	d.o.b. (cm) class 9.7-14.6	14.7-19.4	19.5-24.3	24.4-29.1	29.2-34.0
Reservoir 4	51 (*a*)	9.7	12.8	14.7	16.1	19.1
Reservoir 2	51 (*a*)	9.2	12.8	15.1	16.0	17.4
Reservoir 5	51 (*a*)	-	14.1	16.6	18.0	18.8
Reservoir 8	51 (*a*)	10.3	12.9	15.0	16.5	19.6
Sawyers 28	23 (*b*)	10.4	11.8	12.9	14.6	-

(*a*) After clearfelling in 1903 for Goldfields water supply.

(*b*) Following regeneration treatment of 1932.

\- Sample too small (<10).

The growth in height of pole-sized jarrah has been studied in Curara and Cornwall blocks (Wallace unpublished data), and Holmes and Dale blocks (O. Loneragan unpublished data). The Curara stand was referred to by Stoate and Wallace (1938). In 1934, the height range of this stand was 9.6-18.1 m (20 codominant trees). In 1981, this was 18.1-28.9 m. Mean height increment was calculated to be 0.19 m yr^{-1}. In Cornwall block, the range of heights was 12.8-22.6 m (for 12 pole sized trees) in 1940 and 19.5-24.9 m in 1954, yielding a mean height increment of 0.17 m yr^{-1}.

More information is available for the stand in Sawyers block. Mean height of the target coppice stem per stool (for the stool diameter class of 20-30 cm) was 5.5 m (age 5 yr), 10.4 m (15 yr) and 11.8 m (23 yr).

Height growth in various stands in Holmes block is 6.4 m (at 15 yr), 13.8 (24 yr), and 16.8 m (40 yr) [compartment 5]; 16.5 m (28 yr) [compartment 1]; and 19.4 m (32 yr), 20.9 m (38 yr) [compartment 10]. Final height in these compartments is 30-33 m.

In Dale block, where final (mature codominant) height does not exceed 24 m, heights attained are 3-4 m (age 5 yr), 8-12 m (20-25 yr) and 14.6 m (25 yr). Height growth eventually stops although diameter growth continues (Stoate and Bednall 1940). At the final height, secondary growth of the epicormic crown units fluctuates from year to year. Height probably decreases with overmature age as the crown dies back. For codominant trees, height is proportional to age until a certain diameter is attained (Stoate and Bednall 1940); that is, when the diameter (d.o.b., cm) is 2.6 times the height (m) (see Fig. 12).

(b) Diameter

Jarrah has long been recognized as a long-lived slow-growing tree (von Mueller 1879-84; Lane-Poole n.d.). Diameter growth was first quantified by Ednie-Brown (1896), who counted the growth rings of felled trees. His estimate was 1.2-1.5 cm yr^{-1} 'in good situations'. These early estimates have limited meaning because stand basal areas were not quoted. There is a strong negative correlation between stand basal area and diameter growth (Abbott and Loneragan 1983a). Rate of diameter growth was discussed extensively by witnesses to the 1903 Royal Commission but the information was based more on opinion than on measurements. The rates mentioned (pp. iv, 23, 86, 92, 93, 95, 111, 123, 141) averaged 1.4 cm yr^{-1}. Later information strongly implies that this figure is exaggerated or represents the growth of a small sample of healthy dominant trees.

Lane-Poole (n.d.) estimated diameter rate of growth as 0.6 cm yr^{-1}. Later, measurements for the first growth plots established in 1916 and 1917 became available (*Annual Report* 1922). The average d.o.b. increment ranged from 0.27 to 0.48 cm yr^{-1}, but again these are unreliable because the plots were burnt between measurements and the period of measurement was only 4-5 years. Diameter growth of 212 selected crop trees at Willowdale, Jarrahdale and Kirup was 0.35-0.51 cm yr^{-1} over a wide range of d.o.b.'s (Royal Commission 1951). McNamara and Campbell (c. 1956) quoted average diameter growth of prime jarrah as 0.2 cm yr^{-1} and of elite trees as 0.4 cm yr^{-1}.

All of the above estimates of diameter growth probably refer to fully stocked stands of high quality jarrah forest. The most recent authoritative estimate for such forest is 0.17 cm yr^{-1}, with a range of 0.09-0.25 cm yr^{-1} (Abbott and Loneragan 1983a). In contrast, diameter growth of coppice from stumps or stools is very rapid: initially it is 1.0 cm yr^{-1} (Abbott and Loneragan 1982); after about 10 years, the rate of growth declines to about 0.3 cm yr^{-1}.

(c) Basal Area

In high quality jarrah forest, b.a.u.b. growth (c.a.i.) averages 0.19 m^2 ha^{-1} yr^{-1} (Abbott and Loneragan 1983a).

(d) Volume

V.u.b. growth (c.a.i.) in high quality forest averages 1.2 m^3 ha^{-1} yr^{-1} (Abbott and Loneragan 1983a). The classic basal area or volume increment curves showing current annual increment (growth during the last year) and mean annual increment (cumulative growth divided by age) are not available for jarrah. However, it is likely that maximum increment (given by the intersection of the two curves) would occur at about 40 years (O. Loneragan unpublished data). This signifies that the rotation period for maximum volume production (to 10 cm top diameter) is about 40 years. At this age, of course, average tree d.o.b. in untreated stands is too small to be saleable as sawlogs.

(e) Lignotuber

The rate of growth in length of the long axis of the lignotuber is about 0.7 cm yr^{-1} over the first 20 years (Abbott and Loneragan 1984b).

(f) Comparisons of Jarrah with Softwood

Volume growth for eucalypt forest (selective logging) and softwood plantations are 0.5-3 and 14-25 $m^3\ ha^{-1}\ yr^{-1}$ respectively (Florence and Shepherd 1975). However, the comparison is inequitable, because pine forestry involves initial clearfelling, thinning at least once during the period of the rotation, and fertilization (except on red loam soils).

It is known that jarrah would respond to similar conditions. For example, in a measured plot at East Kirup, the m.a.i. of volume was 28 $m^3\ ha^{-1}\ yr^{-1}$. This is better than the average for plantation-grown *Pinus radiata* (20 $m^3\ ha^{-1}\ yr^{-1}$, Butcher, personal communication*). These jarrah trees were too small to be used for sawlogs. They also developed bad form by forking into multiple leaders. Exposure to frost and insect attack at the sapling stage were responsible.

By comparison, maximum increments for *Pinus pinaster* on the coastal plain near Perth are attained at about 5 yr (height) and 8 yr (d.o.b.). The m.a.i. of volume for *P. pinaster* averages 10 $m^3\ ha^{-1}\ yr^{-1}$ (Butcher, personal communication*).

The Effect of Site on Growth

'Site' is used to describe the integration of environmental factors, particularly climate and soil, in an area. It influences to a large degree the height, diameter size distribution, basal area and volume of the stand (Abbott and Loneragan 1983a, 1984a). Consequently, the rate of growth varies with site. In fully stocked high or low quality jarrah forest, average increments are: d.u.b. 0.2, 0.1 cm yr^{-1}; b.a.u.b. 0.19, 0.06 $m^2\ ha^{-1}\ yr^{-1}$; and v.u.b. 1.2, 0.2 $m^3\ ha^{-1}\ yr^{-1}$ respectively (Abbott and Loneragan 1983a). Surprisingly, site does not affect diameter growth of stump coppice (Abbott and Loneragan 1982). This suggests that the well established root system of stump coppice overcomes the problems of lower rainfall received by low quality forest.

The Effect of Provenance on Growth

Information on geographical variation in growth of jarrah comes from an experiment in Inglehope arboretum. Seedlings (grown from seed collected at various locations) were planted in freshly ploughed ground in winter 1969 at a wide spacing (3 m) and were fertilized. Each of the 11 provenances was represented by eight plants. A randomized complete block design was used (Kimber unpublished data).

The results of ten years' growth (Table 9) indicate some genetic differences between provenances. Seed from the two high quality sites attained the largest d.o.b. and that from the locality farthest inland the least. In contrast, the height data reveal much overlap between populations. However, the experiment is too small for realistic conclusions to be drawn from it.

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Table 9

D.o.b. and height growth of jarrah in relation to seed provenance, June 1969 to January 1979.

Locality of seed	Mean d.o.b. (*a*) (cm)	Mean height (*a*) (m)
High quality forest		
Cameron Block, Dwellingup	17.4	9.4
Shannon River	17.4	8.8
Low quality forest		
Julimar	13.3	6.9
Helena	13.1	6.7
E. Boddington	15.3	8.6
E. Collie	14.4	8.7
Coastal plain and sunklands		
E. Wanneroo	14.0	7.3
Yanchep	12.1	7.1
Myalup	13.8	7.7
Quilergup	12.5	6.1
Wheatbelt		
Jilakin	11.5	6.7

(a) Sample size varies from 6 to 8.

The Effect of Dominance Status, Crown Vigour, and Bole Diameter on Growth

These factors have an important influence on diameter growth (and hence basal area and volume growth); this is summarized by Abbott and Loneragan (1982, 1983c). Depending on the stand, codominant trees may grow up to 70 per cent faster than sub-dominant trees. Codominant stool coppice has grown nearly 40 per cent faster than sub-dominant coppice in the same stand.

The vigour of the crown rated subjectively shows that codominants with dense crowns have faster diameter growth than those with sparse crowns (Abbott and Loneragan 1983c). Crown vigour is also a good predictor of diameter growth: a study of pole-sized jarrah indicates that the possession of the deepest, widest and densest crown makes possible the greatest diameter increment recorded in unthinned jarrah forest, 0.9 cm yr^{-} (Abbott and Loneragan 1983c).

A codominant or dominant position of the crown in the canopy does not guarantee a rapid diameter growth. Competition among too many stems in regrowth stands forces the weaker ones into subordinate positions. Residual old growth trees, weakened by the vigour of competing regrowth, show reduction in leaf density. We searched the growth plot records of the Inventory and Planning Section of the Forest Department and found 20 trees with d.o.b. 100 cm when first measured. Diameter growth averaged 0.10 cm yr^{-}, ranging from 0 to 0.5 cm yr^{-}. Because mean d.u.b. is 114 cm, trees of this large size should be dominants or codominants. Although there is no information about the crown vigour of these trees, it is very likely that the variation in diameter growth reflects variation in crown vigour.

Diameter (an indication of size and age) has some influence on diameter growth. We investigated this using Walford's (1946) method of calculating a linear regression equation between d.u.b. at the second measurement (as dependent variable) and d.u.b. at the first measurement (as independent variable). These equations for 22 stands are presented in Table 10; several were graphed by Abbott and Loneragan (1983a). In relation to the line of no growth, $y = x$, these regression lines diverge at small diameters and converge at large diameters, indicating that trees of smaller diameters (e.g. poles) grow slightly more rapidly than trees of larger diameter. Because these data refer to mixed age stands with a wide range of diameter classes, the most likely explanation is that diameter gives an approximate measure of age. If this is so, younger trees are growing faster than older trees.

In several pole stands near Dwellingup we have measured d.u.b. growth as 0.3-0.4 cm yr^{-1}, but usually it is not this great (Table 11). In more or less even aged stands measured for d.o.b. down to 10 cm, the larger diameter classes show faster growth rates (Abbott and Loneragan 1983a), probably because smaller diameter trees are suppressed.

Table 10

Walford equations for cut-over jarrah stands

Forest block	Site-vegetation type	Equation *(a)*	r	Years when measured	N *(b)*	d.u.b. (cm) range at first measurement	b.a.o.b. at second measurement ($m^2\ ha^{-1}$)
<u>High quality forest</u>							
Mundlimup	TS	Y=12.48+0.86X	0.91	1953/80	55	33.0- 74.6	31
	S	Y=11.93+0.84X	0.88	1953/80	50	31.2- 73.6	42
Chandler	TS/S	Y= 9.67+0.90X	0.99	1950/80	26	19.7- 95.4	39
Chandler/Cobiac	TS/S	Y= 9.51+0.93X	0.99	1950/80	52	18.9- 78.3	38
Chandler	PS	Y= 7.52+0.92X	0.99	1949/82	53	15.4- 80.1	28
Serpentine	S	Y= 5.77+1.03X	0.96	1952/81	28	12.4- 40.3	38
Holyoake	T	Y=18.05+0.89X	0.90	1934/81	16	16.0- 66.9	33
	O	Y=25.19+0.69X	0.88	1934/81	18	14.8- 63.3	35
Amphion	T	Y=10.75+0.94X	0.99	1952/81	46	20.5-95.0	45
Amphion/Plavins	T	Y=13.33+0.89X	0.98	1952/81	55	21.3-86.8	37
Curara	OZ	Y= 8.04+0.90X	0.97	1951/81	19	4.3- 75.8	28
Curara	OZ	Y= 5.98+1.03X	0.97	1951/81	26	7.1- 73.4	28
Young	OW	Y= 7.05+0.93X	0.99	1952/81	34	15.0-104.8	44
Darrell	ORT	Y= 6.42+0.95X	0.98	1946/81	54	30.6- 68.6	29
Lennard	TO	Y=10.61+0.90X	0.98	1949/81	54	16.0- 81.5	24
<u>Low quality forest</u>							
Dale	H	Y= 6.38+0.94X	1.00	1951/81	65	16.6- 94.0	22
Beraking	Z	Y= 4.50+1.02X	0.96	1952/81	60	13.6- 52.0	19
Clare	HZ	Y= 5.15+0.99X	0.96	1935/82	41	14.8- 66.5	17
	Z/HZ	Y= 7.36+0.98X	0.98	1935/82	31	20.5- 84.3	26
Leona	Z	Y= 6.31+0.97X	0.99	1951/82	45	14.4-101.7	22
Cooke	ZP	Y= 5.23+0.94X	0.99	1951/81	57	14.4- 83.9	20

(a) Y = d.u.b. at second measurement, X = d.u.b. at first measurement.
(b) N = number of jarrah trees measured.

Table 11

Effect of d.o.b. on d.u.b. growth

Forest block	Site-vegetation type	d.o.b. (cm) range at first measurement	N *(a)*	Years when measured	d.u.b. increment cm yr^{-1}	b.a.o.b. at second measurement
<u>High quality forest</u>						
Mundlimup	TS	39.4- 49.7 50.1- 80.8	10 45	1953/80	0.22 0.18	31
Mundlimup	S	37.6- 49.3 50.1- 94.4	14 37	1953/80	0.19 0.13	42
Chandler	TS/S	19.7- 43.9 50.1- 95.4	19 6	1950/80	0.23 0.14	39
Cobiac	TS/S	18.9- 49.1 50.5-113.4	30 22	1950/80	0.24 0.17	38
Amphion	T	32.9- 49.7 50.9-102.8	22 23	1952/81	0.30 0.26	45
Plavins	T	28.5- 49.5 50.1- 94.6	20 33	1952/81	0.34 0.26	37
Young	OW	19.6- 44.5 51.5-110.6	20 14	1952/81	0.19 0.09	44
Adjacent to Bombala (virgin)	OZ	10.9- 44.9 54.4-119.8	33 25	1951/81	0.23 0.09	38
<u>Low quality forest</u>						
Cooke	ZP	19.4- 49.5 50.0- 89.7	25 32	1951/81	0.12 0.07	20
Dale	H	21.2- 44.4 50.0- 99.0	15 50	1951/81	0.16 0.08	22

(a) N = number of trees measured.

The Effect of Flowering and Seeding on Diameter Growth

Seeding reduces the diameter increment of pole-sized jarrah to 60-80 per cent of similar sized trees lacking fruit (Kimber 1978). In another experiment (Kimber unpublished data), the d.o.b. growth from July 1971 to January 1972 was measured on 150 pole-sized trees in different stages of reproduction (assessed with binoculars). Mean diameter increment was 0.38 cm for non-reproductive trees (N=32), 0.33 cm for trees with flowers, immature capsules, or both (N=89), and 0.28 cm for trees with mature capsules, flowers or both.

The Effect of Litter, Shade and Browsing by Kangaroos on Growth of Seedlings

Height growth of seedling jarrah to the middle of the first summer is reduced by the presence of litter of *Allocasuarina fraseriana* but is unaffected by kangaroo browsing (Abbott 1984a). An experiment assessing the importance of shade produced ambiguous results.

The Effect of Fire on Growth

Growth in length of the long axis of the lignotuber is more rapid after high intensity fire than low intensity fire (Abbott and Loneragan 1984b). All but the mildest fire kills the shoots of lignotuberous seedlings and ground coppice. New ones resprout from the lignotuber. For small lignotubers the rate of height growth of these shoots is little affected by the intensity of fire. At a lignotuber length of 6 cm, the increase in the length of the tallest shoot nearly 30 months after the fire is 38 per cent after low intensity fire and 170 per cent after high intensity fire.

Ashbeds have an important effect on the early growth of jarrah. These are formed by branches building up in patches on the ground, and by the accumulation of branches, stems and leaves after logging. Once dried, it will often burn completely to ash. The nutritional properties of ash (Hatch 1960) result in seedlings growing very rapidly in height of the shoot and size of the lignotuber (Abbott and Loneragan 1984b).

Frequent low intensity fire does not affect diameter growth of pole-sized jarrah. McCormick (n.d.; see also Peet and McCormick 1971) established 24 plots (5 trees/plot) near Dwellingup in 1963. Dendrometer bands were fitted to each tree. There were three treatments, each applied to six plots: a mild spring fire (November 1964); a mild autumn fire (April 1965); and controls (for each fire). One year before the fires, there was no significant difference in d.o.b. growth between treatments (range = 0.33-0.37 cm yr^{-1}). The same result was found one year after treatment (range = 0.34-0.41 cm yr^{-1}). The fires had no significant effect on d.o.b. growth.

A slightly longer-term study (Peet and McCormick 1971) examined d.o.b. growth one year before a spring fire in November 1964 and for four years after. This fire had no effect on diameter growth.

Exclusion of low intensity fires from jarrah forest for 30-50 years has no influence on d.u.b. growth (Abbott and Loneragan 1983b). In contrast, moderate to high intensity fires in some cases accelerate d.u.b. growth (Abbott and Loneragan 1983b), although Peet and McCormick (1971) did not demonstrate any difference between low and high intensity fires in their effect on growth. Their measurements were taken over bark, which may account for this conclusion.

However, Kimber (1978) also followed this procedure except that he scraped loose bark from the stem. He found that trees with scorched crowns increased their diameter more quickly than controls. This was attributed to both the replacement of the old leaves with a dense crown of young leaves and the prevention of seed development.

The stimulatory effect of a moderate to high intensity fire on diameter growth is shown clearly by analysis of growth rings (Loneragan 1961; Wallace 1966). Ring growth beginning in autumn lasts for 18 months instead of the usual eight months.

The death of the crown of jarrah saplings is directly related to fire intensity (Peet and McCormick 1971). Therefore, where such regeneration is to be the new crop in a particular area, fire is excluded, otherwise saplings will be damaged. When the cambium and dormant bud strands are killed in the crown and below the division of the crown, growth of epicormic shoots from the dormant buds produces the mis-shapened 'dog-leg' bole.

The Effect of Intraspecific Competition on Growth

Reducing root competition from surrounding trees in a trenching experiment increased the height growth of seedling jarrah by 20 per cent (Abbott 1984a).

significant even in fully stocked jarrah stands, as evidenced by the negative correlation between diameter growth rate and stand basal area (Abbott and Loneragan 1983a).

One of the important non-experimental sources of evidence that intraspecific competition curtails diameter growth of jarrah comes from the remeasurement of stands or selected trees over a long period.

Table 12

Walford equations for virgin jarrah stands

Forest block	Site-vegetation type	Equation (a)	r	Years when measured	N(b)	d.u.b. (cm) range at first measurement	b.a.o.b. at second measurement (m^2 ha^{-1})
High quality forest							
Bombala (adjoining)	OZ	Y=7.16+0.94X	1.00	1952/81	[illegible]	[illegible]	[illegible]
Teesdale	TO	Y=1.85+0.99X	1.00	1975/81	[illegible]	[illegible]	[illegible]
Low quality forest							
Dale	HZ	Y=3.37+0.97X	1.00	1952/81	58	18.6- 94.3	23
Duncan	HZ	Y=1.05+1.00X	1.00	1975/82	30	9.0- 90.0	16
Bell	ZM	Y=1.37+1.01X	1.00	1975/82	47	6.3-69.8	23
Yourdamung	F	Y=1.56+1.00X	1.00	1975/82	26	8.3-135.1	17
Surface	[illegible]	[illegible]	1.00	1975/82	37	7.2- 92.6	19

(a) Y = d.u.b. at second measurement, X = d.u.b. at first measurement.
(b) N = number of jarrah trees measured.

Lane-Poole (unpublished lecture notes 1917) noted that the trees in cut-over forest show faster diameter growth than trees in virgin forest. To him this was expected, because 'the cutting out of mature trees by the sawmiller acts as a very bad thinning, but a thinning nevertheless'. However, selective logging for sawlogs rarely reduces stand b.a.o.b. for very long. Our studies on stump coppice growth suggest that, within 10 years of logging, competition between trees is restored to the level obtained before the logging (Abbott and Loneragan 1982).

Using the Walford equations (Tables 10, 12), we calculated d.u.b./age curves for each stand on the assumption that a d.u.b. of 10 cm was attained in 10 years. Comparison of Figures 15 and 16 indicates little difference in the growth of jarrah in virgin or cutover stands, probably because both types of stand are overstocked and the crowns of trees in virgin stands are often sparse. Nevertheless, competition is

Thus, a pole stand in Holmes block was measured in 1943, 1947, 1953 and 1959 (Abbott and Loneragan 1983c). During this period the number of dominant and codominant trees, and the rate of growth in height, diameter basal area and volume declined.

Although the sample of tagged trees is small it is historically important: these trees provide the oldest direct indication of diameter growth. The most valuable samples are from high quality forest in Holyoake block (first measured in 1932) and Mundlimup block (first measured 1927). The Holyoake trees were selected (by B.H. Bednall) as representative of good growing stock about 18 years after the initial logging. In 1932, these poles were about 60 years old, determined by counting growth rings. The stand had been given a regeneration cleaning (ch. 11) in 1928 followed by a mild fire. No other fires occurred during the period of measurement.

Mean d.o.b. increment (cm yr^{-1})

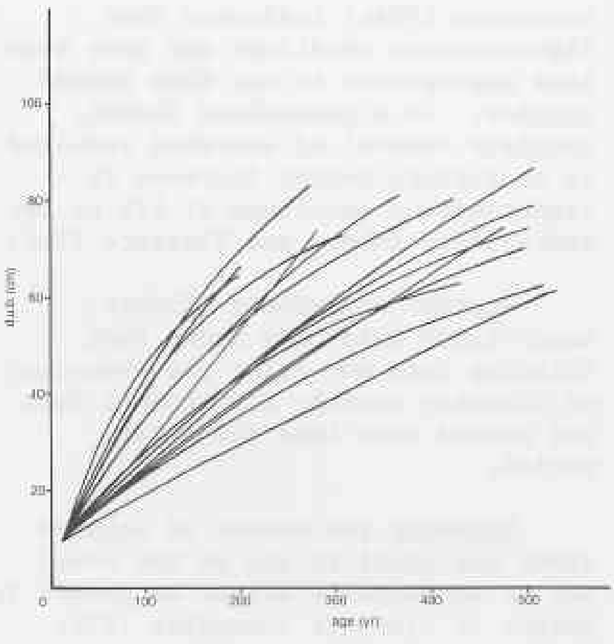

Figure 15
D.u.b. growth of jarrah in cut-over stands over time.

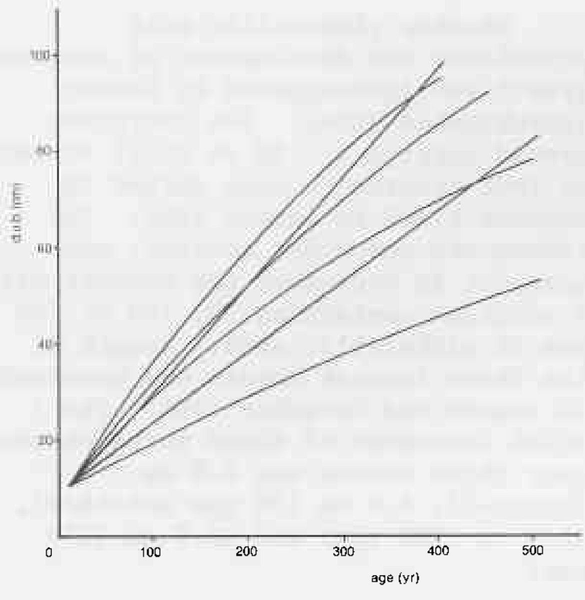

Figure 16
D.u.b. growth of jarrah in virgin stands over time.

declined as follows: 0.54 (1930-5); 0.42 (1935-40); 0.35 (1940-45); 0.31 (1945-50); 0.21 (1950-55); 0.10 (1955-60).

This indicates that the stand achieved full stocking within a few decades. In 1960 seven trees were codominant, two dominant and one sub-dominant.

The pole and pile-sized trees in Mundlimup were selected by Bednall from two adjacent compartments (No. 2 - 13 trees, No. 1 - 8 trees). All were then codominants. Both compartments were given a regeneration treatment in 1925 and a light crown thinning in 1928. For compartment 2, the mean d.u.b. growth in cm yr^{-1} from 1927 was as follows:

0.6 (1927-8); 1.2 (1928-9); 0.3 (1929-30); 0.4 (1930-1); 0.8 (1931-5); 0.4 (1935-6); 0.6 (1936-7); 0.5 (1937-8); 0.4 (1938-9); 0.5 (1939-40); 0.5 (1940-6); 0.4 (1946-9); 0.3 (1949-53); 0.2 (1953-7); 0.2 (1957-62); 0.1 (1962-82).

In compartment 1, mean d.u.b. growth in cm yr^{-1} was:

0.8 (1928-40); 0.5 (1940- 6); 0.5 (1946-9); 0.3 (1949-53); 0.4 (1953-7); 0.2 (1957-62); 0.2 (1962-83).

Several factors probably contribute to the initial rapid growth. The 1920s and 1930s experienced higher rainfall than the long term average, the light thinning of the 1920s temporarily reduced competition, and the trees were younger when first measured.

Provided that stump coppice is killed, thinning overcomes the gradual retardation in rate of growth demonstrated above. The experimental evidence for this has been collated and summarized by Abbott and Loneragan (1983c). A simple light thinning in more or less even aged stands involving a slight reduction in b.a.o.b. (e.g. of 5 m^2 ha^{-1}) produces only a modest increase in diameter growth.

Not until b.a.o.b. is reduced by more than half does basal area growth decrease markedly; however, this reduction in b.a.o.b. increases diameter growth the most (data of Kimber analysed by Abbott and

Loneragan 1983c). The benefit is that the rotation time is considerably shortened because growth is put onto fewer stems, and has greater value on these stems.

In contrast, in cut-over uneven-age stands in the northern jarrah forest, both basal area and volume growth are more influenced by number of stems per ha than initial basal area or initial volume (Abbott and Loneragan 1983a). This is because these regenerated cut-over jarrah stands are well-stocked, having an excessive number of regrowth stems.

Because logging of the northern jarrah forest generally followed the group selection scheme, the veteran trees remaining should have suppressed the regrowth jarrah. We assume that the conclusions established for karri (Rotheram 1983) should apply, suppression occurring within twice the crown radius of the veteran.

An experiment (Kimber unpublished data) designed to determine growth of lignotuberous jarrah under varying degrees of competition found no differences among treatments after six years. A split-plot factorial design, comprising four large plot treatments, two subplot treatments and five replicates, was set up in Plavins block in August 1964. The treatments were: large plots with four b.a.o.b. measurements - 35 (control), 23, 12 or 0 m^2 ha-1; and subplots with ground vegetation untouched (control) or uprooted annually. All stumps were poisoned to prevent coppicing. There were five blocks, each consisting of four 15-m square plots. Ten lignotuberous seedlings 2-3 years old were planted in each subplot.

Neither removal of ground vegetation nor thinning of overstorey influenced survival or height growth of the lignotuberous seedlings. Mean height (cm) in May 1970 was 7.7 cm (control), 7.2 cm (b.a.u.b. 23 m^2 ha^{-1}), 8.1 (12 m^2 ha^{-1}) and 10.0 cm (0 m^2 ha^{-1}). These differences are of no practical interest. However, subsequent knowledge (Abbott and Loneragan 1984b) indicates that lignotuberous seedlings may have been less appropriate to use than ground coppice. In a Queensland forest, complete removal of overwood resulted in an average height increase in lignotuberous seedlings of 120 cm two years later (Henry and Florence 1966).

Another experiment (Kimber, unpublished data) has shown that thinning does not alter the phenology of diameter growth; i.e. growth does not extend more into the summer period.

Thinning the number of coppice stems per stool to one or two stems has no appreciable effect on growth in height or diameter (Chandler 1939; Bednall 1942; Abbott and Loneragan 1982). This may be because most coppice is in overstocked stands.

The Effect of Gibberellic Acid on Growth

Whether gibberellic acid stimulates the development of advance growth was investigated by Kimber (unpublished data). Ten incipient ground coppice (c. 50 cm tall) in each of four treatments were marked in Amphion block in August 1964. The treatments comprised control, and spraying in September and October with a solution containing 50, 100 or 250 ppm of gibberellic acid. Length of the three longest shoots was measured in August and November 1964. The total increment of these three shoots over three months was 0.8 cm (control), 6.9 cm (50 ppm solution), 11.9 cm (100 ppm) and 19.8 cm (250 ppm).

The Effect of Fertilization on Growth

The use of fertilizers to increase growth of existing eucalypt forests is relatively recent; the treatise by Jacobs (1955) does not mention the subject. In Western Australia, however, interest in using fertilizers extends back to the 1930s. This was prompted by the personal research interests of T.N. Stoate and the extreme nutrient deficiencies of jarrah forest soils. This latter factor was one reason the forest was not cleared for agriculture last century.

(a) Early Research

Stoate (1953) reviewed the early research and concluded that fertilizer did not affect growth of jarrah trees in the forest. Unfortunately, it is difficult to explain this because most details, particularly the nutrient composition of the fertilizers, have been lost. It is a surprising conclusion in the light of subsequent research.

The first experiment (1937) tested Ca, P, N and K in Harvey and Kirup Divisions. The next experiment (ten trees in each of 14 paired plots, Samson block, 1944) examined the effect of adding superphosphate annually (250 kg ha^{-1}). D.o.b. increment (1947-54) averaged 0.27 and 0.26 cm yr^{-1} on the fertilized and control plots respectively. In the third experiment plots with a surround of 120 m x 120 m were pegged out in August 1952 in three stands of 40-year-old jarrah regrowth near Dwellingup. Each plot was divided into nine subplots 40 m x 40 m in area and a Latin Square design was used. Three treatments were applied in spring of 1952, 1953 and 1954: blood and bone manure (250 kg ha^{-1}), potato manure E (same rate), and control. Ten codominant trees were selected in each of the 27 plots, and their d.o.b.'s were measured in August 1952, January and August 1953, October 1955, and February and May 1956. Over the four-year period there were no significant differences among treatments in d.o.b. growth (stand 1: 0.18, 0.26, 0.16 cm yr^{-1} respectively; stand 2: all 0.15 cm yr^{-1}; stand 3: 0.18, 0.22, 0.18 cm yr^{-1}). The lack of response to P suggests that it was fixed in a relatively unavailable form by the lateritic gravels (Hatch unpublished data).

Between 1958 and the present many fertilizer experiments were established, but most of the results have not been written up. Emphasis has been on the response of seedlings, a subject more relevant to overcoming the resting stage of ground coppice and stimulating dynamic sapling growth than the response of pole and pile sized jarrah in forest management.

(b) Experiments with seedlings and lignotuberous seedlings

The first experiment on the nutrition of jarrah seedlings was done in a shade house at Dwellingup (van Noort unpublished data). The upper 15 cm of jarrah forest soil was used. Seed was sown in pots in December 1958, but only one seedling was retained in each pot. A randomized complete block design was used, with 12 treatments each replicated thrice in three blocks. Superphosphate and compost were mixed into the soil of the appropriate treatments before sowing. The light dressings of N and K were applied as 1.8 g/pot for the first four weeks after the development of the first pair of true leaves. Heavy dressings were given as 7.1 g/pot initially and then as 1.8 g for each of the four subsequent weeks. Seedlings were well watered throughout the experiment.

This experiment showed clearly (Table 13) that N and P have a positive interaction. Jarrah seedlings grew most rapidly when both N and P were applied. There was little response to N, NK or PK (the heavy dressings of N, P and K were evidently toxic, as seedlings either died or showed no growth response). The major deficiency of this experiment is that no explanation was given of the quantities of fertilizer added.

The second experiment (Kimber, unpublished data) was more ambitious, but the above deficiency applied again. Topsoil (0-30 cm depth) from Holyoake block was passed through a 12 mm sieve. Ten jarrah seeds were sown in late August 1967 directly into pots (15 cm top diameter), and covered with a 6 mm layer of vermiculite. Six weeks later seedlings were thinned to

Table 13

Effect of fertilizer on survival and growth of jarrah seedlings in pot experiment.

Treatment	Survival after 3 days (%)	Survival after 6 months (%)	Mean height (cm) after 6 months
N_1	100	100	16.5
N_1P_1	100	56	30.5
$N_1P_1K_1$	100	56	25.4
N_1K_1	100	100	17.8
P_1K_1	100	100	16.5
N_2	78	78	11.4
N_2P_2	0	0	-
$N_2P_2K_2$	0	0	-
N_2K_2	33	0	-
P_2K_2	89	56	12.7
Compost	100	100	25.4
Control	100	100	10.2

N_1 = 7.1 g $NaNO_3$, P_1 = 14.2 g superphosphate, K_1 = 7.1 g K_2SO_4/pot

N_2 = 14.2 g $NaNO_3$, P_2 = 56.8 g superphosphate, K_2 = 14.2 g K_2SO_4/pot

Compost = 113.6 g of a mixture containing dry hay, superphosphate, K_2SO_3, urea and lime in the ratio of 100:2:2:3:5.

3/pot. Fertilizers were applied as top dressings eight weeks after germination. Sufficient water was applied from above to ensure entry of the fertilizer to soil but not to leach the fertilizer.

A factorial design was used, testing N, P, K and a trace element mixture at two levels (present or absent). Four replications were used. Plants were harvested 14 weeks after the fertilizer application and their total height and oven dry shoot and root weights measured. Fertilizers used were:

N 0.75 g NH_4NO_3 (34 per cent N) per pot

P 1.15 g $Ca(H_2PO_4)_2.2H_2O$ (23 per cent P) per pot

K 0.6 g K_2SO_4 (45 per cent K) per pot

Trace elements applied were: 0.1 g/pot of a mixture of magnesium sulphate (70 per cent), manganese sulphate (10 per cent), zinc sulphate (10 per cent), copper sulphate (4 per cent), cobalt chloride (2 per cent), sodium borate (2 per cent) and sodium molybdate (2 per cent). These quantities were chosen on the basis that they would certainly elicit growth responses (Kimber personal communication*).

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*. P.C. Kimber - Department of CALM, Como.

Table 14

Effect of fertilizer on growth of jarrah seedlings in pots in a shadehouse.

Fertilizer Treatment	d.f.	Mean height (cm)	Significance	Total weight (g)	Significance	Root weight as % of total weight
Control	-	10.4	-	1.89	-	31
N	1	9.7	***	3.16	***	31
P	1	8.5	***	1.43	***	27
K	1	10.3	NS	2.60	***	31
T (*a*)	1	10.9	NS	1.93	***	26
Blocks	3	-	NS	-	**	-
NP	1	46.7	***	16.37	***	11
NK	1	11.6	NS	3.60	NS	34
NT (*a*)	1	9.7	NS	2.82	***	30
PK	1	9.5	NS	1.78	NS	31
PT (*a*)	1	8.9	NS	1.81	***	38
KT (*a*)	1	10.1	NS	2.35	NS	45
NPK	1	52.6	***	17.06	***	11
NPT (*a*)	1	52.5	***	19.39	***	11
NKT (*a*)	1	10.6	NS	3.80	NS	35
PKT (*a*)	1	9.4	NS	1.81	NS	36
NPKT (*a*)	1	54.6	***	21.15	***	17
Error	45	-	-	-	-	-
Total	63	-	-	-	-	-

(*a*) T = trace element mixture present

NS, **, *** indicate the probability of a significant difference from the control as $P > 0.05$, $0.01 > P > 0.001$, $P < 0.001$ respectively.

There was an overwhelming growth response to N and P (Table 14). Most of this growth was in the shoot and not the roots. N by itself depressed height growth but increased total seedling weight; P by itself depressed both height and total weight. The NK interaction was of minor importance when compared with the NP interaction. There was little response to trace elements.

However, this is expected because N and P were limiting. If the experiment were repeated with adequate levels of P and N, a response in growth to trace elements may become obvious.

Kimber (unpublished data) then examined the ratio of N:P giving maximum growth of jarrah seedlings. Most of the methods were as described above. N and P were applied each at five levels: 1, 2, 4, 8 or 16 units. One unit of N = 0.05 g of NH_4NO_3/pot (0.017 g N) and one unit of P = 0.075 g $Ca(H_2PO_4)_2 \cdot 2H_2O$ (0.018 g P). A factorial design with each combination replicated three times was used. Seedlings were sown in August 1968, fertilizer was applied in October 1968 and the seedlings were harvested 12 weeks after fertilization.

Plant response (Table 15) to either element was generally greater at the higher levels of the second element. Growth depression at a constant P level to increasing N concentration was also sometimes evident.

In the last decade the study of seedling growth under glasshouse conditions has been refined (Wallace 1978; Mathie 1981; Dell and Jones unpublished data). A growth response curve to applied P was worked out by Wallace (1978), using six levels of P (P_0, 0; P_1, 0.26; P_2, 0.53; P_3, 0.79; P_4, 1.06; P_5, 2.11; P_6, 3.17 g of P/pot). Maximum growth of stem + leaves occurred at P_5; P_6 depressed growth.

N applied as NH_4NO_3 at three rates increased the weight, height, number of leaves and leaf area of jarrah seedlings (Mathie 1981). Shoots grew relatively more than roots. Subsequently, Dell and Jones (unpublished data) studied the effect of P and the effect of N (separately) on growth (dry weight) of the shoot, lignotuber and roots of jarrah seedlings. At a constant supply of N, the shoot, lignotuber and roots increased with increasing levels of P. In contrast, at constant P, only the shoot increased in dry weight with increasing N supply. Growth of the lignotuber and roots became less rapid at greater levels of N. These three recent studies confirm and extend the early finding that jarrah seedlings do respond to fertilizer.

Table 15

Growth of jarrah seedlings in pots in shadehouse at various N:P ratios.

Mean oven-dry weight (g)

	P_1	P_2	P_4	P_8	P_{16}
N_1	2.20	1.45	2.75	2.10	2.36
N_2	2.63	3.15	2.60	1.38	2.79
N_4	2.43	2.45	3.01	4.55	4.88
N_8	3.09	5.53	5.90	6.25	9.37
N_{16}	2.79	2.25	4.43	9.98	10.83

ANOVA

factor	d.f.	significance
N	4	< 0.001
P	4	< 0.001
blocks	2	> 0.05
N x P	16	< 0.001
N x P x blocks	48	> 0.05
Total	74	

Probably one of the most relevant fertilizer experiments yet tried for jarrah examined whether the long resting lignotuberous stage could be bypassed upon the application of fertilizer and grow directly into the sapling stage (Kimber unpublished data). The seven treatments (Table 16) were each replicated five times, with ten plants per treatment. The NPK ratios refer to quantities, by weight, of $(NH_4)_2\ SO_4$ (20 per cent N), 'single superphosphate (20 per cent P_2O_5)', and K Cl. Fertilizer was applied (28 g/plant) within a 30 cm radius of each lignotuberous seedling in June 1965. Growth was measured in June 1967.

Table 16

Effect of NPK fertilization on shoot growth of the jarrah lignotuberous seedling.

Treatment (N:P:K)	Total length of three longest stems (cm) after two years	Plants with dominant shoot (%)
1. 1:6:½	78.7 (N *(a)* =40)	83
2. 2:6:½	78.0 (40)	83
3. 3:6:½	80.0 (36)	84
4. 3:6:1	76.7 (33)	69
5. 3:6:2	81.0 (44)	92
6. 3:6:½	79.5 (35)	71
7. Control	55.6 (29)	69

(a) In all cases the number of plants per treatment was originally 50.

N:P:K ratios are weights in ounces (1 ounce = 28.4 g).

Varying the levels of N (first three treatments) or K (treatments 4-6) did not produce any useful growth response (Table 16), with all fertilizer treatments showing an increment of about one-third more than the control. Only fertilizer treatment No. 5 led to the development of a greater proportion of dominant shoots than the control ($P < 0.05$, χ^2 test). The fertilizer may have had more effect on lignotuber and root growth rather than on shoot growth (Chapin 1980), but these features were not studied.

The effect of P and N on lignotuber size of eucalypts does not appear to be consistent between species, with some increasing and others decreasing in size after fertilization (reviewed by Jahnke *et al.* 1983). In jarrah seedlings, increasing N in the presence of P, or increasing P in the presence of N increases lignotuber growth (Dell and Jones unpublished data).

(c) <u>Experiments in pole stands</u>

From the point of view of forest management, the most useful experiments (Kimber unpublished data) were performed on high quality stands of pole-sized jarrah. In the first experiment, NPK fertilizer was applied to thinned and unthinned stands, and in the second the period of response to NPK fertilizer was assessed annually for up to four years after fertilization.

An even-aged regrowth stand c. 35-45 yr old and of codominant height 20-25 m was selected for study in Holyoake block. Single trees were treated as plots, matched for d.o.b., leaf and floral development and separated by at least 12 m. Fertilizer (NPK) was spread evenly within a 4 m radius of the base. A 2^3 factorial design was used, with six replications, giving a sample size of 48 trees per treatment. D.o.b. ranged from 17.8 to 45.3 cm, with mean of 30.7 cm. The study was done in two stands, one control with b.a.o.b. of 33.0 $m^2\ ha^{-1}$ and the other thinned to b.a.o.b. of 13.2 $m^2\ ha^{-1}$. Details of fertilizer levels are: N, 0 or 560 kg ha^{-1} $(NH_4)_2\ SO_4$ (21 per cent N equivalent to 112 kg ha^{-1} N); P, 0 or 1120 kg ha^{-1} superphosphate (112 kg ha^{-1} P); and K, 0 or 187 kg ha^{-1} K_2SO_4 (78 kg ha^{-1} K).

D.o.b. of trees was measured first in August 1966, and fertilizer was added in August 1967. The b.a.o.b. increments have been adjusted according to the mean b.a. of the stands (Table 17). Crown density was rated visually in September 1970 by five observers. Crowns were scored as 1 (dense), 2 (medium), 3 (sparse). These scores were summed for all trees per treatment.

None of the unthinned trees showed increased b.a.o.b. growth (Table 18). In the thinned stand, only the treatments N, NP and NK showed increased growth. In both stands, the NP and NK treatments had the densest crowns, but the N treatments were rated little differently from the control. Most importantly, however, nitrogen (whether in treatment N, NP or NK) was the only element increasing b.a.o.b. growth. D.o.b. increment of trees with or without nitrogen fertilizer for each year from 1966 to 1974 (Fig. 17) shows that the response to N is greatest two to three years after fertilization.

The differences in growth response with thinning are probably related to increases in water availability after thinning. Several lines of evidence support this inference. First, watering jarrah seedlings every day leads to a threefold increase in dry weight over seedlings watered the first day and later only after wilting (Ridge 1980). Second, on the Swan coastal plain the growth of *Pinus pinaster* over summer is governed largely by stand density,

Table 17

Growth response of jarrah poles to NP (1:1) fertilizer.

Treatment	b.a.o.b. growth (*a*) (m^2 ha^{-1}) 1969-71	Increase over control (%)	b.a.o.b. growth (a) (m^2 ha^{-1}) 1969-73	Increase over control (%)
1. Control	0.653	-	1.386	-
2. 67 kg ha^{-1} urea + 175 kg ha^{-1} double superphosphate	0.720	10.3	1.471	6.2
3. 134 " " 350 " " "	0.910	39.3	1.762	27.1
4. 269 " " 700 " " "	1.025	57.0	1.903	37.3
5. 538 " " 1400 " " "	1.272	94.8	2.582	86.9
6. 1075 " " 2800 " " "	1.586	142.9	3.234	133.4
7. 2150 " " 5600 " " "	1.351	106.9	3.332	140.4

(*a*) adjusted as follows: (measured b.a.i. x mean plot b.a./individual plot b.a.)

Table 18

Effect of fertilizer on basal area growth and crown density of jarrah poles.

Fertilizer treatment	Mean b.a.o.b. growth (m^2) per tree (over 4 years)		Crown density rating (*b*)	
	Thinned trees	Unthinned trees	Thinned trees	Unthinned trees
Control	0.0081	0.0047	23	27
N	0.0111 (*a*)	0.0069	23	30
P	0.0073	0.0062	33	21
K	0.0066	0.0041	35	34
NP	0.0115 (*a*)	0.0070	13	10
NK	0.0128 (*a*)	0.0071	8	11
PK	0.0075	0.0060	29	29
NPK	0.0090	0.0076	16	18

(*a*) lsd = 0.0025 (P = 0.05).
(*b*) the lower the rating, the denser the crown.

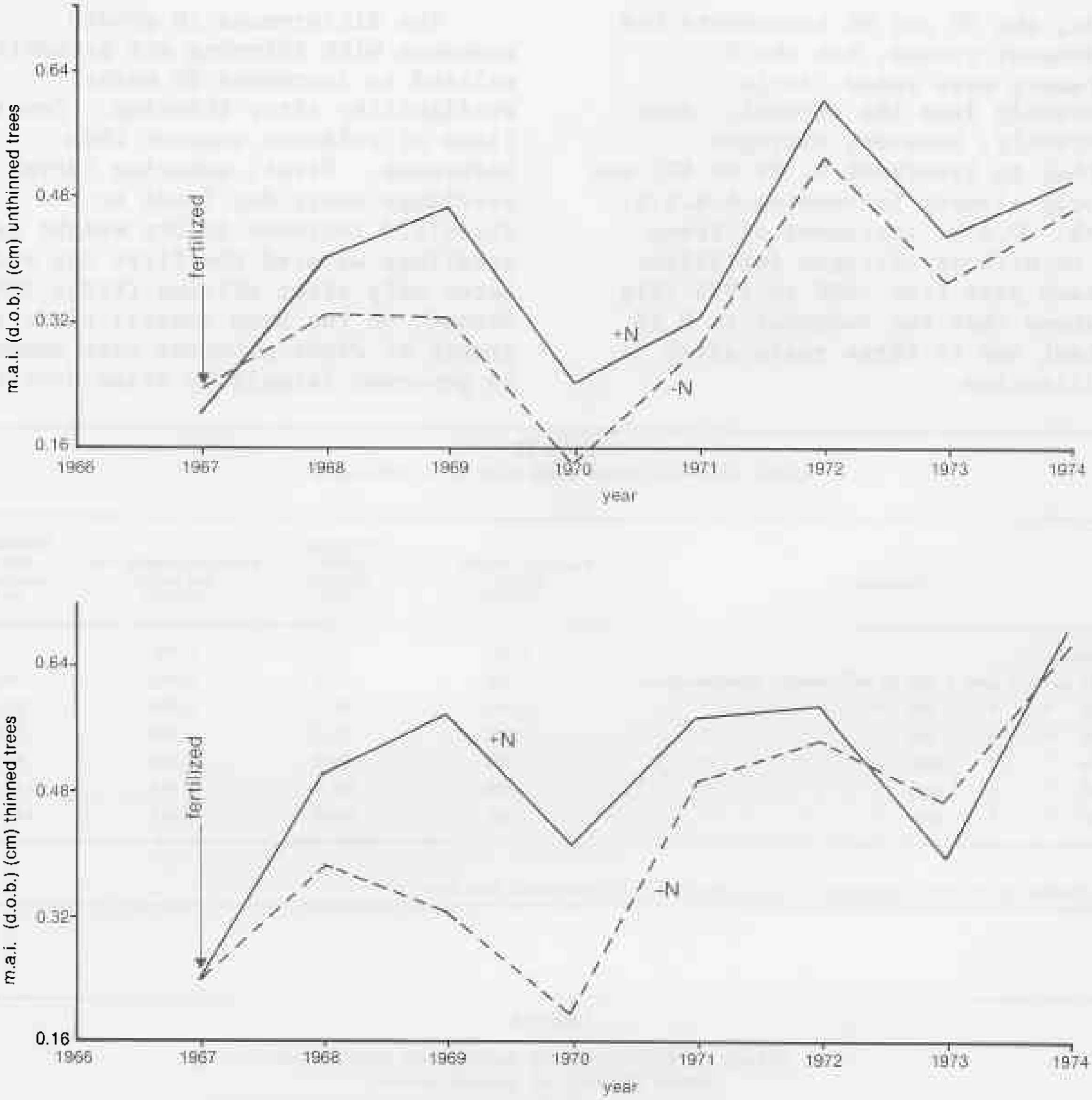

Figure 17
D.o.b. growth of fertilized and unfertilized jarrah in unthinned and thinned stands over eight years.

which controls the rate of exhaustion of stored water (Butcher 1977; Butcher and Havel 1976). Once the limiting factor of water is alleviated through thinning, the next factor most limiting, the supply of N, comes into play.

The nature of the response curve of jarrah poles to NP was investigated next (Kimber unpublished data). Twenty one plots (0.16 ha) were marked out in August 1969, and a randomized complete block design of seven treatments each replicated thrice was used. A stand of 45-year-old jarrah poles, thinned in 1965 to 15.8 m^2 ha^{-1} was selected. D.o.b. of trees was measured in a central 0.04 ha area of each plot. N was added as urea (46 per cent N), and P as double superphosphate (17 per cent P), such that the N:P ratio was 1:1.

Two years after fertilization, basal area growth increased with increasing fertilizer application, except at the highest rate (Table 17). After four years, in contrast, basal area growth increased with increasing level of fertilizer, though the rate of growth became less rapid at the highest rate tested. Maximal b.a.o.b. growth could therefore be obtained with a mixture of urea and double superphosphate applied at 1075 kg ha^{-1}

Table 19

D.o.b. (cm) increment of jarrah poles after fertilizer (mean of 3 blocks).

Treatment (see Table 17)	Period 1969-70	1970-1	1971-2	1972-3	Total	m.a.i.
1	0.36	0.32	0.37	0.36	1.42	0.36
2	0.28	0.30	0.34	0.24	1.16	0.29
3	0.38	0.40	0.40	0.32	1.50	0.37
4	0.36	0.44	0.39	0.26	1.45	0.36
5	0.43	0.73	0.70	0.40	2.26	0.57
6	0.51	0.88	0.79	0.53	2.72	0.68
7	0.44	0.61	0.83	0.65	2.54	0.64

and 2800 kg ha^{-1} respectively. In all but treatment 1, d.o.b. growth rate declined rapidly four years after fertilizing (Table 19).

The final experiment (Kimber unpublished data) aimed to determine how much P is required with N fertilizer to obtain an N x P interaction, and how much K is required with N fertilizer to obtain an N x K interaction. The existence of the N x P and N x K interactions was established in an earlier experiment. A randomized complete block design was used, with ten treatments. Each treatment consisted of 15 trees stratified so that each contained equal representation of the range of d.o.b.'s. Each tree was a codominant pole, at least 12 m from the next selected tree, in a thinned pole stand in Plavins block. Fertilizer (Table 20) was added in August 1971.

Trees in four of the treatments grew significantly faster in d.o.b. than the control (Table 20): these treatments were N alone, and three of the four NK combinations. There was no significant N x P interaction, possibly because the quantity of P added was insufficient after becoming fixed in the lateritic soil.

The above experiments indicate that nitrogen is the nutrient most limiting productivity of the jarrah forest. This conclusion accords with other studies (Beaton 1973; Miller and Cooper 1973; Weetman and Hill 1973; Keay *et al.* 1968; Ballard 1979). Yet,

Table 20

D.o.b. growth of jarrah poles fertilized at constant N level but at various levels of P or K.

Treatment *(a)*	d.o.b. increment (cm), July 1971-February 1975
Control	5.16
N_{448}	7.09 *(b)*
N_{448} P_{56}	5.77
N_{448} P_{112}	6.78
N_{448} P_{224}	6.60
N_{448} P_{448}	6.25
N_{448} K_{56}	7.29 *(b)*
N_{448} K_{112}	6.27
N_{448} K_{224}	7.54 *(b)*
N_{448} K_{448}	7.37 *(b)*

(a) N_{448} = 448 kg ha^{-1} of urea.

(a) P_{56} = 56 kg ha^{-1} of double superphosphate.

(b) Significantly different from control (Duncan's multiple range test).

it is surprising that N is more limiting than P even though the soils of the jarrah forest are extremely deficient in P. Although the annual litter fall is in the order of 2000-3500 kg ha^{-1}, the average return of N, P and K to the forest floor is only about 13, 0.7 and 6 kg ha^{-1} yr^{-1} respectively (Hatch 1964). Thus the low natural growth rate of jarrah is probably an important trait which reduces the annual nutrient requirement (Chapin 1980).

The effects of N fertilizer on jarrah are not greatly different from those described for other species (Russell 1973). Plant species will only make efficient use of N fertilizer if the supply of water is adequate. A thinning of forest is effectively an irrigation. N promotes leaf growth and hence the size of the crown, thereby increasing the surface area available for photosynthesis, and reducing the root/shoot ratio of the plant. Fertilization should reduce stem taper as a result of increased wood production below the crown. In contrast, trees in thinned stands generally increase in taper. However, no specific information about these treatments on taper of jarrah is available.

The efficacy of a combined thinning and fertilizing of jarrah forest agrees with other forest studies. Fertilization without amelioration of any non-nutritional limiting factor results in little growth response (Ballard 1979). The short term growth response of jarrah to N fertilizer also conforms with worldwide experience (Auchmoody and Filip 1973).

Any operational use should therefore comprise frequent, small applications. At present, routine use of N fertilizer in the jarrah forest is considered uneconomic (Hingston *et al*. 1982). Recent emphasis is on improving the biological fixation of N_2 (with *Acacia* species) and the re-cycling of N (Grove and Malajczuk 1980).

Growth Potential of Jarrah

This section collates several examples of jarrah growing under specialized conditions, particularly with no overstorey competition or restriction in growing space. When the railway was extended from Pinjarra to Dwellingup in 1910, some jarrah forest in Holmes block was cleared and part of the soil was used to ballast the line. Presumably soon after, seed dispersed from adjacent forest and germinated. In 1981 we measured the d.o.b. of a sample of trees. Mean d.o.b. of ten codominant trees was 25.8 cm (range 17.9-33.5) and of two dominant trees 38.8. The m.a.i. of these two classes is 0.36 and 0.55 cm yr^{-1} respectively.

The d.o.b. of a large tree (dominant, free-growing) in the park between the railway line and Divisional Forestry Headquarters at Dwellingup was measured in 1948, 1956 and 1983. C.a.i. was calculated as 1.1 cm yr^{-1} (1948-56) and 1.0 cm yr^{-1} (1956-83).

A large tree (d.o.b. 115.0 cm) growing in pasture near Pinjarra showed c.a.i. in diameter of 1.5 cm yr^{-1} (Stoate 1953).

Jarrah planted with *E. microcorys* in the Jarrahdale No. 2 minesite in 1971 attained mean height of 13.5 m and mean d.o.b. of 19.0 cm by 1983 (J. Kaye personal communication*). Jarrah has also been grown in the Inglehope arboretum, where it was planted as one-year-old seedlings about 40 cm tall at 2 m spacing in June 1965 and fertilized with NPK 3:6:0.5.

We remeasured all trees in 1983 except those in the outer two rows, and found the following mean d.o.b.'s: dominant (23.0 cm, one tree),

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codominant (19.7 cm, five trees) and sub-dominant (15.9 cm, eight trees). Mean codominant height after 18 years was 13.8 m. Most trees had poor form.

In another planting (in Teesdale block), one-year-old seedlings (mean height 18 cm) were planted in June 1966 and fertilized in August. Mean height in July 1967 and 1968 was 39 cm and 1.2 m. Sixty jarrah seedlings at the age of one-year transplanted in 1941 from forest into the East Kirup nursery when 8 cm tall, attained a height of 1.5 m and dynamic sapling habit within three years. These plants were manured and watered regularly, and were spaced at 2 m intervals. The height growth (m) of the two most rapidly growing trees was as follows:

	1943	1944	1945	1946	1956	1961
Tree 1	1.5	2.6	3.3	3.7	15.9	20.4
Tree 2	1.2	2.0	3.5	4.1	15.6	18.9

At the age of 21 years in 1961, the d.o.b. of these trees was 42.1 cm and 27.7 cm respectively.

The data presented above indicate that under optimal conditions jarrah can grow in diameter at a rate of 1-2 cm per year. It would therefore take about 35-70 years for a tree of 70 cm d.o.b. to be grown. In the high quality forest, without any special silvicultural treatment, it takes an average jarrah some 400 years to attain this d.o.b. (Abbott and Loneragan 1983a). If faster growing trees only are considered, this d.o.b. is reached after 200 years' growth. If pole stands (with average d.o.b. of 30 cm) are thinned, d.o.b. of 70 cm would be attained after about 100 years (Abbott and Loneragan 1983c).

We draw attention to the lack of information available on the timber properties of jarrah grown at different growth rates (and from different provenances).

CHAPTER 8

Reproduction and Stand Establishment

Flowering, Fruit and Seed Fall

The primordia of the flower buds appear in the axils of the new leaves following leaf maturity about January. Most of these buds are cast off while immature between the annual growth flushes. Annual replacement takes place. Every four to six years conditions favour the retention and development of the primordia. In such cases, flowering occurs in spring or early summer some ten months after formation of the buds (Stoate and Wallace 1938; Loneragan 1961).

In the forest, flowering does not occur until the sapling stage is achieved. Not surprisingly, under artifical conditions of cultivation and fertilization, flowering may occur within three years after planting one-year-old seedlings (O. Loneragan personal observation).

Published records of the flowering period are few. This was recorded as October to December (von Mueller 1879-84), October (Lane-Poole n.d.), September to December (Harris 1956), and September to January (Smith 1969). We examined the specimens of jarrah held in the Western Australian Herbarium, and found that buds or flowers were present as follows: June, 1 case; July, 1; August, 3; September, 5; October, 6; November, 6; December, 6; January, 1; April, 1. The period of flowering varies from district to district (Stoate 1953). We have observed flowering on the coastal plain in September and October, whereas in the Darling Range it is generally later (November and December). Most trees in a district flower at the same time.

Pollination has not been studied, but presumably is effected by insects.

The flowers develop into fruits (Frontispiece) during the following year. The seed ripens over the winter, being immature but viable the following April, and mature by September, that is about one year after flowering (Kimber 1983). According to Lane-Poole (n.d.), no general seed years occur in the jarrah forest; this is typical of many eucalypts. Jarrah seeds about every four years by district (Lane-Poole n.d.), at least every three years (*Annual Report* 1925), every five to six years (Meachem 1962), or every four to seven years (Stoate 1953). Heavy seeding is associated with loss of leaves from the crown. During one year of heavy flowering, one tree in four was recorded as carrying abundant blossom (Loneragan 1956).

Mature stands, as would be expected, produce a greater proportion of floral litter (opercula, buds, stamens, fruit and seed) than younger stands (Hatch 1964).

The main branches, which continue leafy growth, retain capsules for several years before shedding the seed. Otherwise seed is shed naturally in the summer two years after initiation of the flower buds, but can be induced by fire to fall earlier (in late spring). The seed falls shortly before all leaves are shed from the branchlets to which the fruits are attached (Stoate and Wallace 1938).

The phenology of reproduction in jarrah was investigated by both van Noort (unpublished data) and Kimber (unpublished data). Three traps (0.9 m x 0.9 m) were fixed into position beneath jarrah forest near Dwellingup (van Noort unpublished data). Each tree in the stand carried a good crop of fruit from the 1958 flowering. The

Table 21

Mean number (mean of three traps) of floral parts of jarrah in traps, November 1959 to July 1960.

	1959 Nov.	Dec.	Jan.	Feb.	1960 March	Apr.	May	Jun.	Jul.
Seeds	3.7	3.3	5.3	5.0	5.3	3.3	0.7	0	0
Capsules	1.0	0	1.3	0.7	2.0	0	1.0	1.7	1.0
Flowers + immature fruit	11.7	51.7	12.0	1.3	0	1.0	0	0	2.0
Opercula	20.3	12.7	0	0	0	0.7	0	0	2.7
Buds	35.0	2.3	0.7	1.0	219.7	94.7	44.3	62.0	56.7

Table 22

Seed fall (1964-1969) in three stands of jarrah forest near Dwellingup.

Locality	Year (August-May)	Mean number of sound seed in capsules	Mean number of sound seed falling to ground (thousands ha^{-1})	SE	Fire history
Plavins	1964-5	19.1	322.7	108.6	scorching fire 1965
	65-6	0	40.2	34.3	
	66-7	0	443.7	149.9	
	67-8	0	564.7	155.6	spring 1967
	68-9	0	33.6	34.1	
Banksiadale	1964-5	13.6	100.7	44.9	
	65-6	13.6	114.3	105.9	
	66-7	0	114.3	57.5	spring 1966
	67-8	0	20.2	8.9	
Amphion	1964-5	32.7	121.0	40.0	
	65-6	0	141.2	91.9	spring 1965
	66-7	5.4	833.6	508.4	
	67-8	0	383.2	127.9	
	68-9	0	282.5	151.4	spring 1968

seed was determined to be viable in September 1959, ten months after flowering.

Most seed fall occurred from January to March (Table 21). The peak of the 1959 flowering season was in December. The large number of aborted buds from the 1960 season, shed mostly in March and April, indicated that the 1960 flowering season was to be a sparse one.

A more detailed study (Kimber unpublished data) examined seed fall in three stands (plot size = 2.0 ha). Four transportable seed traps (0.6 m x 0.6 m) were re-sited randomly within each plot at monthly intervals. Because the study by van Noort (above) showed that seed fall was negligible from May to August, the traps were removed then. The stands were chosen to reflect differences in structure. The one at Banksiadale consisted largely of veteran trees with few poles. The Plavins stand was a 40-year-old pole stand with a low density of veterans (< 10 ha^{-1}). An all-aged stand, consisting of poles, piles and veterans, was selected at Amphion.

Over the period of study, the amount of seed fall varied from 20 000 to 850 000 sound seed ha^{-1} (Table 22). The vast majority of seed was released from the capsules, and did not fall to the ground while still within the capsule.

The effect of fire on seed fall was studied by van Noort. In Teesdale block, the crowns of three jarrah trees were scorched by fire. For two of these, seed shed began only four days after the fire although most was retained until 25-30 days after the fire. The other tree shed few seeds. Another tree whose crown was not scorched also shed few seeds. The control tree (no fire) shed no seeds. Similar results were found from a study in Banksiadale block. Foresters have always used fire to initiate seed shed in regeneration burning (Underwood personal communication*).

Although the mechanism of seed release has not been studied in jarrah (see Cremer 1965), drying out of the capsule is implicated by the effect of fire.

Little precise information is available about the direction and distance of seed dispersal. Lane-Poole (n.d.) asserted that seed reaches a distance along the ground equal to the height of the tree. An experiment with an isolated jarrah tree 24 m tall in a paddock (van Noort unpublished data) comprised seven trays set out along the ground for a distance three times the height of the tree. Unfortunately little seed fell, but seed did disperse at least as far as the height of the tree.

Important factors affecting seed yield included tree age, crown size, weather, and seed-destroying insects (Boland *et al.* 1980). With jarrah, seed production may be related to age (*Annual Report* 1970), with the mean annual production of seed ha^{-1} over five years being 280 000 (55-year-old pole stand), 353 000 (uneven aged stands) and 90 000 (stand with veterans but few poles). Although there are no data specific to jarrah, the dominant and codominant trees should produce much more seed than suppressed trees (Jacobs 1955). Unseasonal cool weather should decrease the effectiveness of pollinators. The importance of insects as destroyers of jarrah seed has also not been studied.

<u>Fate of Seed after Seed Fall</u>

The usual experience with eucalypts having small seed is that only 0.1 per cent of the viable seeds will produce established seedlings (Jacobs 1955).

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Table 23

Loss of viability of jarrah seed under various conditions of exposure.

Placement of seed	Mean No. of sound seeds remaining out of 100 original seeds (*a*)	(Range)
Under canopy, on bare ground (*b*)	49.7	(38-59)
" " , on 3-yr-old litter	61.7	(56-69)
In the open, on bare ground	82.3	(77-86)
" " " , on 3 yr old litter	73.7	(52-85)

(*a*) 3 replicates. Seed was placed in forest in flywire envelopes from January to April 1966.

(*b*) Burnt by fire the previous spring.

Does jarrah seed lose viability between seed fall and germination? Kimber (unpublished data) collected seed from trees in Teesdale block in August 1965 and extracted the seed by drying the fruit in the sun. Some 93 per cent of a sample of 380 seeds was sound, as evidenced by presence of endosperm. Samples of this seed were placed under various conditions in the forest from January until April 1966. When the seed was examined, 93 per cent was still sound (Table 23). Hence exposure does not diminish viability of the seed of jarrah.

The most efficient way to establish the fate of jarrah seed after seed fall is to put known numbers of seed in various treatments and score the germination. Such experiments are also helpful in elucidating the critical factors promoting germination and seedling establishment. Basically, viable seed on the ground can either germinate when conditions become suitable or be eaten or damaged by animals or fungi. Kimber (unpublished data) investigated this by placing seed on the forest floor (1) in flywire envelopes, (2) in bird-wire cages with a flywire base to allow entry of insects but not of mammals, or (3) laid on a flywire tray, otherwise unprotected. One hundred sound seed were placed in each of four replicates per treatment on 4 January 1966. The number of seeds remaining was counted on 19 April 1966; the mean being found to be least (0.6) in treatment (2), intermediate (18.5) in treatment (3), and greatest (66.9) in the control (treatment (1)). This experiment showed that seed predation is important, but implied that ants and mammals may compete for seed as ants removed more seed in the absence of mammals.

Experiments by Majer (1982) indicate that 50 per cent of jarrah seed placed in seed depots on the forest floor is removed by ants within 24 hours. The principal species involved is *Rhytidoponera inornata* (Sochacki 1978). Other experimental studies (Abbott and Van Heurck 1985) show that about half of the jarrah seeds on the forest floor may be eaten by animals, with ants consuming more than mammals.

Germination

Germination under artificial conditions is generally rapid, taking 12 days (Lane-Poole n.d.). An experiment done in a shadehouse at Dwellingup (van Noort unpublished data) comprised six replicates, with 50 seeds per replicate. Seeds were sown on 24 August 1965. The first germination (at least 6 mm of radicle visible) was observed on 6 September 1965. Cumulative germination was 21 per cent (16 September), 57 per cent (22 September), 83 per cent (4 October) and 85 per cent (18 October). Other germination tests (van Noort unpublished data) investigated the timing of collection. Seeds were kept in the dark and moist but there was no temperature control. One lot was stratified at 2.8-4.4°C for 25 days. Total germination was not affected by month of seed collection: September 1959 collection 85 per cent, October 1959 collection 73 per cent. Stratification did not affect germination (September sample: 96 per cent stratified; 85 per cent control. October sample: 83 per cent stratified; 73 per cent control). Both experiments were begun on 2 February 1960.

Laboratory trials (O. Loneragan unpublished data) with constant light and constant temperature of either 20° or 25°C produced germination over 28 days of 47 per cent and 69 per cent respectively. In both cases the seeds were soaked in water for one day before the experiment. Most germination took place within 14 days. A more ambitious experiment compared six treatments:
(1) 20°C; (2) 25°C; (3) seed soaked for one day, 20°C; (4) seed soaked for one day, 25°C; (5) seed soaked and stratified for 5 weeks, 20°C; (6) seed soaked and stratified for 5 weeks, 25°C. Although final germination ranged from 20 to 60 per cent, none of the treatments differed significantly from the control.

For routine seed testing, Boland *et al.* (1980) recommended a constant temperature of 15° or 20°C, with first and last counts after 10 and 21 days respectively.

None of the above reports hints at any evidence of seed dormancy. However, Glossop *et al.* (1982) found differences in percentage of germination after 21 days among three treatments: control 42 per cent, soaking in water for 48 hours (19 per cent), and seed scarification (3 per cent). An earlier experiment studied the breaking of dormancy in seed of jarrah (Kimber unpublished data). There were six treatments, in which seed was soaked for 24 hours before sowing. Both initial and final germination increased with increasing gibberellic acid concentration (χ^2_5 = 41 and 13 respectively, Table 24).

Table 24

Effect of gibberellic acid (GA) on germination of jarrah seed. Seeds sown 6 January 1967 (*a*) under glasshouse conditions.

	Mean Germination (%)						
Treatment	3 Feb.	27 Feb.	2 Mar.	5 Mar.	20 Mar.	3 Apr.	28 Apr.
(1) Distilled water	9	51	53	55	58	64	68
(2) 5 ppm GA in dist. water	12	65	67	69	70	72	77
(3) 10 " "	16	65	65	65	67	70	71
(4) 50 " "	18	72	75	75	75	77	77
(5) 100 " "	25	77	79	80	81	81	82
(6) 500 " "	30	75	75	75	76	76	77

(*a*) Each treatment comprises 4 replicates, each of 50 seeds.

In the forest, seeds germinate from May to August (Abbott 1984a). This follows a drop in temperature and the start of the winter rains (Lane-Poole n.d.). Germination occurs virtually anywhere - on ant heaps, old stumps, tops of dead *Xanthorrhoea preissii*, forks of trees to name a few of the more bizarre (Lane-Poole n.d.).

Factors that are potentially important in affecting germination of jarrah seed include the nature of the seed bed (litter depth, soil type, amount of shade), fungi, competition from plants in the forest, and adverse weather conditions. The part that these factors play can be investigated only in the forest. In the first experiment (Kimber unpublished data) three treatments were replicated seven times. Each plot was 0.91 m x 0.91 m. The treatments were: litter removed by control burn in Spring 1965; two-year-old litter; five-year-old litter. On 25 April 1966 15 mg of jarrah seed (c. 300 seeds) was sown on each plot.

The total number of germinants present on 24 November 1966 was 267, 277 and 46 on no litter, 2-year-old litter and 5-year-old litter, respectively. Although this result indicates that fire facilitates germination, the experiment was not well designed because it confounded fire history with location differences.

A later experiment examined litter type and depth, shading, and root competition (Abbott 1984a). None of these factors significantly affected germination of jarrah seeds.

Seedling Establishment

Germination is only the first step in the regeneration of a forest. Next in importance is the establishment and growth of the seedlings. The observation (*Annual Report* 1922) that natural regeneration of jarrah is better developed among unburnt undergrowth than in forest where patches of mineral soil are exposed is difficult to explain in the light of later research. Although germination was conceded to be more plentiful on exposed soil, mortality during the first summer was observed to be higher than where there was cover of scrub and debris. Top-dispersal burning creates the ashbeds which provide the best conditions for establishment and growth. The effect of frost on seedling establishment does not appear to have been studied.

An early study (van Noort unpublished data) used one-year-old seedlings raised in pots. These were planted in four localities in openings in recently cut-over forest around Dwellingup. Each study area was divided into 20 milacre plots separated by buffer strips. Five seedlings were planted in each milacre plot and two types of treatments were applied.

Three major treatments were distributed randomly over the 20 plots as follows: cultivated (cultivated by hand using a mattock before planting and also the following spring) - four plots; cultivated and fertilized (cultivated as above and fertilized with compost and a 56 g dressing of potato manure E five weeks after planting) - eight plots; control - eight plots. The minor treatments were applied to a portion of the trial: partial shading (with a screen) - four plots; trenching (to depth of 46 cm or rock) and watering (every third week during the first summer) - eight plots; and spraying with insecticide (in the first spring) - four plots.

The minor treatments were ineffectual. At Clinton, most plants were defoliated by insects. Cultivation enhanced the survival of one-year-old jarrah seedlings by the end of both summers (Table 25). Fertilized seedlings grew faster than cultivated or control seedlings.

Root competition from trees in the forest does not affect the survival of jarrah seedlings, though it reduces the height attained.

Table 25
Establishment and growth of jarrah seedlings in relation to cultivation and fertilizing.

Locality	Cultivated survival (%)	Cultivated height (cm)	Cultivated + fertilized survival (%)	Cultivated + fertilized height (cm)	Control survival (%)	Control height (cm)
At end of first summer						
Teesdale	80	30.5	67	38.1	30	20.3
Taree	70	25.4	37	30.5	55	22.9
Duncan	95	33.0	85	33.0	65	25.4
Clinton	80	27.9	10	20.3	35	15.2
At end of second summer						
Teesdale	80	39.4	67	66.0	27	30.5
Taree	65	36.8	35	55.9	42	30.5
Duncan	95	41.9	82	52.1	57	27.9
Clinton	75	41.9	5	34.3	35	17.8

Browsing by kangaroos or grazing by insects does not significantly affect height growth. Shading and the type and depth of litter present do not affect survival. Height growth is least for jarrah seedlings growing among leaf litter of *Allocasuarina fraseriana* (Abbott 1984a).

Mortality of jarrah seedlings should be greatest in their first year of life because the lignotuber has only begun to develop. From then on survival is high (Abbott and Loneragan 1984b). Because jarrah is a lignotuberous species, it does not depend solely on seed fall at the time of regeneration. However, if seed trees are not numerous, blanks in regeneration will occur (Lane-Poole n.d.).

When jarrah forest is logged, the natural regeneration - lignotuberous seedlings, seedling coppice, ground coppice, saplings and poles - is irregularly present on the forest floor (van Noort 1960; Abbott and Loneragan 1984b). What appear to be seedlings a few years old could be decades old, a situation similar to that described for oaks (Merz and Boyce 1956). As in many other eucalypts the aerial parts of jarrah grow slowly in contrast to its roots. Once the tap root has penetrated to a depth where moisture is available all year, the plant ceases to be dormant and is then capable of developing into a sapling (Kimber 1983). Stump coppice and sometimes stool coppice develop rapidly after logging. In addition disturbance to the soil surface and the advance burn prepare a soil surface well suited to a seedbed.

The problem with most jarrah forest is that where there is no regeneration there can be a long delay between seeding and commencement of sapling growth. In contrast, under conditions suitable for regeneration there may be over 1.2×10^6 jarrah plants per hectare (Meachem 1962). The second growth forest consequently becomes overstocked soon after logging. The probable significance of this large number of plants is that it ensures that some survive adverse factors such as fire, drought and frost.

The main factor influencing the establishment of trees in cut-over forest is the amount and type of advanced reproduction present. The origin and density of this probably depends on many factors, including density of seed-bearing trees, frequency of seed production, seed theft, stand density, understorey type and density, and soil type. Some of these factors could affect seed survival, seedling establishment and eventual development of the lignotuber (Abbott 1984b).

In the southern jarrah forest there is considerable site variation in germination and development of jarrah to the early lignotuberous stages (Ritson* unpublished data). There have been no comparable studies in the northern jarrah forest.

Artificial Regeneration

Because of its cost, artificial regeneration was considered by the Forests Department (1927) to be a last resort, to be used only where the natural regeneration secured was insufficient to fully stock an area of forest. In the 1920s the method used was 'spot sowing', involving sowing 3-6 seeds/spot (c. 20 cm x 20 cm x 10 cm deep) within three months of fire. Spots were spaced c. 3 m apart. Many compartments of jarrah forest were then routinely spot sown with jarrah seed; this was quickly found to be a waste of time because of the abundant natural regeneration. This procedure may have been adopted because the development of the early stages of jarrah was not understood at that time.

During the last three or four decades, little artificial regeneration of jarrah forest has been attempted. Replanting of dieback-affected areas has been with resistant eucalypt species. However, in the 1970s, jarrah was planted after mining for bauxite near Jarrahdale. The procedure used was to plough the lateritic soil and plant one-year-old seedlings grown in a nursery. Fertilization ensures that most develop a dynamic shoot within 2-5 years (Kimber 1983). Few of these jarrah are of good form, conforming with our observations of jarrah in arboreta at Grimwade and Inglehope.

In the future, micropropagation methods using tissue culture (Bennett and McComb 1982) will probably supersede the technique described above. These jarrah will be genetically resistant to *Phytophthora cinnamomi*.

Jarrah in Plantations

Jarrah has been grown in plantations in Chile and the Congo (Penfold and Willis 1961), South Africa, Trinidad and India (FAO 1979), in California and Kenya (Zacharin 1978) and in Tanzania (Kimber personal communication*). It has usually failed (FAO 1979), though in the Congo it was stated to have given 'the best results' (Penfold and Willis 1961). No quantitative details are available, except that mean height of 16 m was attained at age 8 years in Tanzania (Kimber personal communication*). However, more than half of the trees had been killed by the fungus *Armillaria* sp.

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CHAPTER 9

Stand Description

The descriptive features of selected stands of jarrah forest include the number of stems of jarrah and marri present per hectare, the frequency of the various d.o.b. classes and the basal area and merchantable volume standing. Both virgin (unlogged) and cut-over stands are considered, particularly those studied by Stoate and Helms (1938) near Coondle, Beraking, Ashendon, Holyoake, Inglehope, Tallanalla, Chalk Brook and Treesville. In addition, less extensive information available on biomass, crown cover, log length, position of trees in terms of the canopy, crown vigour and mean codominant height is presented here and integrated later in our discussion of stand development (ch. 11).

The northern jarrah forest is almost a pure forest of one tree species, which develops into a large tree in spite of infertile soil and a harsh climate. The virgin forest is an open one of 50-70 per cent crown cover over a ground layer of shrubby growth < 1 m tall. Most of the overstorey is physically mature or overmature. There is generally understocking of the younger classes. These are scattered throughout the forest in small patches replacing the fire-killed veteran trees. This structure results from centuries of fire succession.

Height of the forest canopy ranges from 20-35 m, with some dominant trees being c. 6 m above the level of the mature codominant trees. Harris and Wallace (1959) noted that crowns of the codominants were rarely damaged from fires running through the relatively light litter and ground cover. Most of the canopy is occupied by jarrah with stems ranging from c. 60-120 cm d.o.b. with the occasional very large tree of d.o.b. > 200 cm.

Trees suffer little overlapping of crowns, so that the canopy is easily penetrated by light. Yet, despite its openness, the total number of trees is high for a eucalypt forest (Lane-Poole n.d.).

For a profile diagram of jarrah forest, see Speck (1958).

According to Havel (1975a), the site-vegetation types with a significant, if not dominant, component of jarrah are B, D, E, F, P, S, T, U, Z and O. The highest quality stands are T, S, U, O and P.

<u>Number of Stems per Hectare</u>

Stands in the northern jarrah forest are composed almost entirely of jarrah (Tables 26, 27; Gray 1938), with the proportion of marri stems rarely exceeding 20 per cent. The proportion tends to increase with a decrease in depth of the laterite horizon (Stoate and Helms 1938; Havel 1975a). Small patches of pure marri are found occasionally in gullies. Comparison of Tables 26 and 27 shows that in the northern jarrah forest marri does not increase in relative abundance in the second growth forest after jarrah has been logged.

Marri tends to be patchily distributed in the northern jarrah forest, as evidenced by considerable variation shown in eight plots within one compartment of Holmes block, Dwellingup (see Table 27; see also Abbott 1984b). In the southern jarrah forest, the proportion of marri may be quite high and may increase after logging of jarrah (Ritson* unpublished

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data). Stoate (1939) stated that such forest was termed jarrah forest until marri comprised 90 per cent of the stems, an arbitrary concept criticized by Gray (1939). More recently, the A.P.I. type maps produced by the Forests Department classify forest as marri when more than 50 per cent of stems are of this species.

The number of stems per hectare in a stand depends on which d.o.b. classes are included. Considering all stems with d.o.b. > 10 cm, Abbott and Loneragan (1983a) found a range of 80 to 749 stems ha^{-1} in cut-over forest.

Table 26

Average composition of the overstorey of old growth northern jarrah forest stands, based on all stems of d.o.b. > 19.4 cm. Summarized from Stoate and Helms (1938). All stands are of high quality as defined in Chapter 3.

Height index of Stoate and Helms	Equivalent mature codominant height (m)	Mean no. of stems ha^{-1}		% of Marri Stems	% of Marri b.a.o.b.	% of Marri v.o.b.
100-110	31-35	Virgin (11 plots)	127.0	11.8	5.7	5.3
		Cut-over (2 plots)	264.9	9.5	8.0	5.0
90-100	27-31	Virgin (19 plots)	127.7	12.1	9.1	8.3
		Cut-over (3 plots)	94.7	9.0	7.7	7.0
80- 90	23-27	Virgin (3 plots)	83.8	14.0	13.3	13.7
		Cut-over (6 plots)	90.5	13.8	9.5	9.0
70- 80	19-23	Cut-over (3 plots)	123.5	16.7	20.7	20.0

Table 27

Composition of the overstorey (omitting rare residual veteran trees) of regrowth stands in the northern jarrah forest. Unpublished data of O. Loneragan.

Forest block	Total stems ha^{-1}	% Marri	Stand age (yr)
Holmes (compt. 10) (*a*)	634.6	6.6	40
" "	488.9	18.2	40
" "	627.2	7.1	40
" "	730.9	10.8	40
" "	466.7	6.9	40
" "	600.0	4.5	40
" "	535.8	5.5	40
" "	503.7	17.6	40
Reservoir (compt. 2) (*b*)	975.3	5.3	51
" " 4 (*b*)	538.3	10.6	51
" " 5 (*b*)	496.3	6.5	51
" " 8 (*b*)	496.3	10.9	51
Sawyers (compt. 3) (*b*)	469.1	10.5	51
" " 28) (*b*)	901.2	2.5	23

(*a*) Including all trees of d.o.b. > 14.6 cm

(*b*) Including all trees of d.o.b. > 9.7 cm

Stand Tables

Stand tables, giving the frequency distribution of the various d.o.b. classes in a stand, are summarized in Tables 28-33 (See also Stoate 1941, 1943). The single feature in common is that trees of large diameter are less frequent than trees of smaller diameter; this is irrespective of whether logging has occurred or not. Site quality influences the d.o.b.'s attained. Big trees (i.e. those of d.o.b. > 100 cm) are less well represented in low quality forest than in high quality forest (Abbott and Loneragan 1984a; see also Table 30). Trees with d.o.b. exceeding 200 cm have never been recorded in low quality forest. Jarrah on the coastal plain and at Jilakin Rock attains maximum d.o.b. comparable to low quality forest on the Darling Plateau (Stoate 1940; Abbott 1984c).

Table 28

D.o.b. frequency distributions for jarrah in various cut-over stands in Ashendon block (data of Stoate and Helms, 1938).

% of jarrah stems in d.o.b. (cm) class								
19-38	38-64	64-89	89-114	114-140	140-165	165-190	N (*a*)	No. ha^{-1}
24	30	26	4	14	2	0	50	56.8
25	44	25	6	0	0	0	96	106.4
23	51	17	5	2	0	2	57	74.1
24	39	21	11	4	1	0	78	83.0
25	36	26	9	3	1	0	271	85.7
29	31	21	13	3	3	0	159	86.4
20	40	23	11	3	3	0	174	85.2
47	43	49	1	0	0	0	79	134.8
27	13	31	23	4	2	0	52	61.2
2	37	34	19	8	0	0	59	82.0
37	33	18	10	<1	<1	<1	123	73.6
37	38	18	6	1	0	0	276	102.5

Although all plots were cut-over, stumps are included in the table.

(*a*) N = the number of trees measured for d.o.b.

Table 29

D.o.b. frequency distributions for jarrah in 36 plots in virgin stands of Chalk Block. (Data of Stoate and Helms, 1938).

% of jarrah stems in d.o.b. (cm) class									
19-44	44-73	73-101	101-131	131-160	160-189	189-218	218-247	N	No. ha^{-1}
28	27	28	13	3	1	0	0	141	69.9
49	14	23	11	2	1	0	0	147	72.6
30	20	30	10	9	2	0	0	126	62.2
26	22	32	17	3	1	0	0	113	55.8
41	22	18	14	5	0	0	0	182	89.9
48	28	12	5	6	0	1	0	161	79.5
52	25	15	6	2	0	0	0	162	80.0
56	17	17	9	1	<1	0	0	219	108.1
50	29	13	5	3	<1	0	0	191	94.3
23	27	35	11	4	0	0	0	144	76.1
39	27	18	7	8	1	0	0	195	96.3
29	26	25	16	3	1	0	0	177	87.4
20	28	26	15	9	1	1	0	138	68.1
32	26	23	13	4	2	0	0	163	80.5
53	18	15	8	3	2	0	<1	216	106.7
55	19	8	11	5	1	1	0	214	105.7
44	17	23	11	4	1	0	0	185	91.4
73	14	7	5	2	0	0	0	378	186.7
79	9	8	4	1	0	0	0	333	164.4
44	29	16	8	3	<1	0	0	252	124.4
73	12	10	3	2	0	0	0	389	192.1
26	38	28	6	2	<1	0	0	183	90.4
43	33	19	5	<1	0	0	0	231	114.1
63	12	6	2	<1	0	0	0	417	205.9
53	26	17	3	<1	0	<1	0	262	129.4
54	24	14	7	<1	<1	0	0	292	144.2
64	18	13	5	0	0	0	0	165	163.0
73	13	8	6	0	0	0	0	438	216.3
39	39	16	5	1	0	0	0	247	122.0
27	38	24	4	4	3	0	0	78	38.5
41	39	15	5	1	0	0	0	173	85.4
62	31	6	1	0	0	0	0	201	165.2
35	26	28	7	1	2	1	0	121	59.8
34	31	17	10	7	<1	0	0	141	69.6
42	33	19	4	2	<1	0	0	188	92.8
62	22	14	2	0	0	0	0	203	100.2

Table 30

D.o.b. frequency distribution for jarrah in 197.5 ha of virgin forest near Dwellingup (data of Gray 1938).

% of jarrah in d.o.b. (cm) class													
25.4-35.6	35.6-45.7	45.7-55.9	55.9-66.0	66.0-76.2	76.2-86.4	86.4-96.5	96.5-106.7	106.7-116.8	116.8-127.0	127.0-137.2	137.2-147.3	147.3-157.5	157.5+
15.9	11.6	9.5	9.1	10.8	11.6	9.1	7.8	6.0	4.3	2.6	1.3	1.3	0.9

Mean number of jarrah stems ha^{-1} = 57.3

Table 31

D.o.b. frequency distribution for jarrah in virgin stands.

Plot	Site-type	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150	Stand N	No. /ha^{-1}
		% of jarrah in d.o.b. (cm) class																
High quality forest																		
Ashendon	SR	64	17	7	4	3	1	<1	<1	<1	<1	<1	<1	<1	0	<1	562	703
Amphion	TO	48	29	8	0	0	0	6	2	3	0	2	0	2	0	2	63	315
Curara	OZ	-	42	4	3	5	7	9	14	8	3	1	4	1	0	0	77	110
Chalk	O	14	11	21	18	8	8	8	11	3	0	0	0	0	0	0	33	21
Tallanalla (a)	T	-	-	18	9	7	8	12	11	10	9	6	4	2	1	<1	360	89
Low quality forest																		
Coondle	HZ	-	-	30	19	15	15	[illegible]	6	[illegible]	<1	<1	<1	<1	<1	[illegible]	352	87
Beraking	HZ	-	-	28	13	16	14	[illegible]	9	[illegible]	[illegible]	[illegible]	[illegible]	<1	<1	[illegible]	398	98
Beraking	Z	-	-	54	21	11	3	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	75	183
Dale	HZ	-	-	29	18	13	8	[illegible]	13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	38	93
Dale	HZ	-	-	30	36	25	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	44	107
Cooke	ZP	-	-	22	22	24	7	12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	41	100
Leona	Z	-	-	63	20	7	5	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	41	100
Clare	Z/HZ	-	-	12	14	18	20	14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	<1	[illegible]	<1	229	87
Bell	ZM	-	51	14	11	5	3	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	0	37	185
Surface	Z	-	8	4	10	19	10	29	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	0	48	120
Yourdamung	F	-	19	19	0	9	9	9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	3	32	80

- Indicates this d.o.b. class was not assessed.

(a) D.o.b. classes 150-160, 170-180 and 210-220 also represented, but <1%.

Table 32

D.o.b. frequency distribution for jarrah in regrowth stands (omitting rare veteran trees).

Forest block		9.7-14.6	14.6-19.4	19.4-24.3	24.3-29.1	29.1-33.9	33.9-38.8	38.8-43.6	43.6-48.5	48.5-53.3	53.5-58.2	Stand N
		% of jarrah in d.o.b. (cm) class										
Holmes (a)	(compt. 10)	-	44.6	22.9	16.3	10.0	5.8	0.4				240
"	"	-	41.4	21.0	21.0	11.1	3.1	2.5				162
"	"	-	44.1	22.0	16.5	11.9	4.7	0.8				236
"	"	-	41.3	24.2	18.9	11.7	2.3	1.5				264
"	"	-	44.3	22.2	22.2	8.5	2.3	0.6				176
"	"	-	35.3	29.3	15.9	13.4	3.9	2.2				232
"	"	-	34.1	27.3	18.5	9.8	4.9	1.5				205
"	"	-	26.2	23.8	23.2	19.0	4.8	3.0				168
Reservoir (b)	(compt. 2)	19.9	32.0	28.8	11.3	4.8	2.2	0.8	0.3			372
"	" 4	17.9	30.8	22.6	10.3	11.3	3.6	2.6	1.0			195
"	" 5	13.3	26.6	23.9	17.0	11.1	4.3	1.6	1.6	0.5		188
"	" 8	34.6	15.6	15.1	10.6	12.8	7.8	2.8	0.6			179
Sawyers (c)	(compt. 3)	27.6	31.2	12.4	9.4	3.5	7.6	3.5	1.8	0.6		170
" (d)	" 28	47.4	40.2	11.2	0.8	0.3						356

(*a*) Consisting of 40-year-old regrowth
(*b*) Consisting of 51-year-old regrowth
(*c*) Compt. 3 consists of 51- and 80-year-old regrowth
(*d*) Compt. 28 in addition has regrowth 23 years old.

Table 33

D.o.b. frequency distribution for jarrah in cut-over stands.

Forest block	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150	150-160	160-170	Stand N
	% of jarrah in d.o.b. (cm) class																	
Mundlimup (*a*)	30	38	9	8	5	7	1	<1	1	<1	0	0	0	0	0	0	0	107
Amphion (*b*)	33	34	15	6	2	4	0	0	<1	2	0	1	1	1	0	0	1	89

(*a*) First logged 1872, wildfire 1975, regeneration treatment 1928. No live veteran trees remain in the stand.

(*b*) First logged 1924, regeneration treatment c. 1932. It is likely that trees with d.o.b. >60 cm represent veterans.

The picture in terms of the smaller diameter classes is less sharp. Stands in the same forest block can vary dramatically in representation of particular d.o.b. classes of trees (Tables 28, 29). This reflects the time since disturbance, perhaps by wildfire or logging, or the degree of senescence of the overstorey (Abbott 1984b).

Regrowth stands resulting from very heavy logging typically show predominance of one or two of the smaller d.o.b. classes (see Tables 32, 33). The resulting stand is never as uniform as that resulting from clear-felling, because a considerable amount of advance growth poles remains: not all regeneration comes from the dynamic development of the incipient ground coppice. It is thus not always correct to refer to regrowth jarrah stands as even-aged. Virgin forest or forest cut over under a selection scheme can be all-aged.

There have been no formal studies of the frequency distribution of ages of trees in a stand; rather it is usually assumed that the d.o.b. frequency distributions reflect to a large extent the underlying age distribution (Stoate 1939, 1940).

Spatial Pattern of Trees

Jarrah tends to have an aggregated distribution over small areas (several m^2) and a more random one over larger areas. This is irrespective of whether the stand is virgin or cut-over. The nearest neighbour of a jarrah (i.e. > 1.3 m tall) will be another jarrah (> 1.3 m tall), and both will be less than 3 m apart (Abbott 1984b). These clumps of jarrah (height of individual plants > 1.3 m) tend to be less than 4 m^2 in area. Adjacent trees are often of the same d.o.b., suggesting that they are of the same age, having been released most likely in veteran stands as advance growth following some disturbance. It is very likely that many of these clumps have grown on ashbeds. In some cases, expression of dominance has led to substantial differences between d.o.b. of stems of the same age (Meachem 1962). Ultimately neighbouring trees are probably derived from seed dispersed from a related reproductive tree. Groups of trees may be uneven aged (Meachem 1962).

That jarrah occurs in groups of even-aged trees was recognized by Stoate (1923). In the sapling stage, with the plants only several centimetres apart, these groups are obvious. At the pole stage, they have thinned out naturally to a distance of 1.5-3 m apart but the group is still distinguishable (Stoate 1923). Later when trees have attained d.o.b. of 70 cm and are separated from similar sized trees by distances of 6-12 m, the boundaries of the original groups become obscured. Often trees of smaller d.o.b. are found between and below the larger trees. While appearing to represent a later crop, such trees are actually the same age as the larger trees but have been out-competed by them (Stoate 1923).

Basal Area of Jarrah Stands

Stoate and Helms (1938) quote b.a.o.b. figures of 42.6 m^2 ha^{-1} and 25.2 m^2 ha^{-1} for good and poor quality jarrah forest respectively. All but about 2-6 m^2 ha^{-1} is contributed by jarrah. Their extensive tabulations for northern jarrah stands show that for mature codominant height class of 33 m b.a.o.b. ranges from 34-45 m^2 ha^{-1}. At height class intervals of 29 m, 25 m and 21 m, b.a.o.b. ranges from 25-44, 19-37 and 27-35 m^2 ha^{-1} respectively. These figures are not particularly high for a virgin forest (Jacobs 1955), but are impressive given the large proportion of sound wood.

A study of 112 plots in the northern jarrah forest (Kimber, n.d.) showed that nearly half of the plots had b.a.o.b. exceeding 32 m^2 ha^{-1}. The maximum was 49 m^2 ha^{-1} although only about 8 per cent of the plots exceeded 40 m^2 ha^{-1}. The average maximum b.a.o.b. attainable in the northern jarrah forest may be taken as 40 m^2 ha^{-1}.

Mean b.a.o.b. varies in relation to site-vegetation types (Havel 1975a) as follows: T (35 m^2 ha^{-1}), S 39 m^2 ha^{-1}), P (40 m^2 ha^{-1}), Z (29 m^2 ha^{-1}) and H (25 m^2 ha^{-1}). These figures have been summarized from computer print-out provided by J. Havel. In essence these data show little difference in b.a.o.b. of types T, S and P, and of Z and H. These two groups have been formally recognized as high and low quality jarrah forest respectively (Abbott and Loneragan 1983a).

Earlier, Stoate and Helms (1938) had successfully ranked jarrah stands in Chalk Block in relation to soil type. The greatest stand basal areas occurred where lateritic rock outcropped on upper slopes and on the sandy gravelly loams of lower slopes. However, unlike Havel (1975a), they had no information on chemical properties of these soil types.

B.a.o.b. varies from stand to stand, probably reflecting the extent of sheet laterite and silvicultural history. B.a.o.b. does not significantly correlate with number of stems per ha in high quality forest (Abbott and Loneragan 1983a). Often there is little difference in b.a.o.b. between virgin and cut-over stands (see Table 42), because maximum basal area production occurs at an early age. In the Ashendon, Chalk and Amphion virgin stands (see Table 31), b.a.o.b. are 37.8, 32.0 and 37.4 m^2 ha^{-1} respectively. These are about one-third greater than the average of 22.2 m^2 ha^{-1} for cut-over stands in the northern jarrah forest (Abbott and Loneragan 1983a). Logging initially reduces b.a.o.b., but the rapid growth of stump coppice and ground coppice in the northern jarrah forest restores b.a.o.b. to about half of its original value within ten years (Abbott and Loneragan 1982, 1984b). After this initial spurt of growth, basal area increment in high quality forest decreases to about 0.2 m^2 ha^{-1} yr^{-1} (Abbott and Loneragan 1983a). The m.a.i. of b.a.o.b. growth can be calculated from data for regrowth stands (Table 34).

Table 34

B.a.o.b. and v.u.b. of regrowth stands in Mundaring Division.

Block and compartment		b.a.o.b. *(a)* m^2 ha^{-1}	v.u.b. *(b)* m^3 ha^{-1}	Period since most recent cutting (yr)
Reservoir	2	33.1	117.3	51
"	4	25.2	84.4	51
"	5	23.4	103.0	51
"	8	20.3	84.1	51
Sawyers	3	20.2	92.9	51
"	28	17.7	40.8	23

(a) jarrah and marri combined

(b) jarrah only

Volume of Jarrah Stands

Total volume of all eucalypt trees present in high quality cut-over jarrah forest averages 194 m^3 ha^{-1}, with a range of 111 to 281 m^3 ha^{-1} in the plots studied (Abbott and Loneragan 1983a).

Before the Forests Act of 1919, estimates of volume of merchantable timber were hazy and optimistic (Barrett 1949). The Royal Commission of 1951 noted marked variation in merchantable volume per hectare. On exceptional areas, up to 140 m^3 ha^{-1} of logs were available compared with an average yield of c. 30 m^3 ha^{-1} in high quality jarrah forest. It should be noted that 'merchantable' varies with mill and market. Much wood that is now marketable was not so even ten years ago.

In virgin forest, the total volume of wood (not necessarily merchantable) varies from 630 to 868 m^3 ha^{-1} in stands with mature codominant height of 33 m (Index height 100-110, Stoate and Helms 1938). In poorer quality stands, with mature codominant heights of 29 m, 25 m and 21 m, volumes are 398-765 m^3 ha^{-1}, 305-573 m^3 ha^{-1}, and 325-492 m^3 ha^{-1} respectively. These total volumes (including branchwood) were calculated by Stoate and Helms (1938) as mean stand b.a.o.b. x mean height of dominant trees x 0.6.

Over a range of site qualities log volume is more influenced by diameter and bole length than by number of stems per ha or b.a.o.b.. Within one height class volumes are closely proportional to b.a.o.b.. As with b.a.o.b., most total volume growth occurs early in the life of the stand (see Table 34). Virgin forest is regarded as a static reserve of timber volume (Meachem 1962). The nett increment of merchantable material is nil as growth is balanced by death and decay. Wildfire can lead to negative increment.

Height of Jarrah Stands

Stand height is generally the mean height of the crop trees. Codominant height rather than height of the dominants is taken as the general top level of the canopy.

Mean mature codominant height is sometimes called the final height of the stand. Because this varies consistently with site-type with less variation than b.a.o.b., it is the best index of crop quality (Stoate and Bednall 1940; Barrett 1949).

V.u.b. is less reliable because of considerable variation between stands of the same site quality (Barrett 1949). Although Stoate (1953) considered that volume is the true measure of site quality, a uniformity trial (Stoate and Helms 1938) showed that a minimum plot size of 4 ha is required to obtain a coefficient of variation < 10 per cent.

Early research (Stoate and Helms 1938) did not use mature codominant height. Instead, an index height corresponding to mean d.o.b. of 76 cm was used to provide a basis for comparing heights of small samples of stands. These authors considered that the ideal would be to determine stand height at a selected age, but it is not possible to achieve this in the jarrah forest.

Unpublished data of Havel show that the height of the tallest trees on the plots in his study of site-vegetation types were: T, 33 m; S, 30 m; P, 29 m; Z, 24 m;, H, 25 m. The classification of jarrah stands by height adopted in the 1950s by the Inventory and Planning Section of the Forests Department is: A^+, > 33 m; A, 27-33 m; B^+, 21-27 m; B, 15-21 m; and C, < 15 m (metricated after Nunn 1959). Subsequent changes to the limits are provided by Rayner and Williamson (unpublished data).

Proportion of Crop Trees in Jarrah Stands

Trees in the jarrah forest may be classified by the position of their crowns relative to the canopy (Stoate and Bednall 1940). Dominants are trees growing above the general level of the canopy (codominants). Sub-dominants fail to reach the canopy level but are still favoured by free overhead space.

Dominated and suppressed trees are completely overtopped by other trees in the stand and form part of the understorey of the forest.

Dominants, dominated and suppressed trees tend to be very scarce in low quality forest (Table 35). In most stands, irrespective of site quality, codominant trees constitute the most frequent class of tree. Codominant jarrah in the Reservoir and Sawyers plots contribute 51-61 per cent of stand (jarrah) b.a.o.b. Generally, there is a difference of 3-5 m in height between each class of trees (Table 36). Mean d.o.b. of classes may differ by up to 30 cm (see Table 36).

Table 35

Classification of trees in jarrah stands by the position of their crowns in relation to the forest canopy.

Stand		N	Dominant	Codominant	Sub-dominant	Dominated + Suppressed
			% representation			
High quality forest						
Tallanalla (a)		258	20.0	38.8	18.6	23.7
Ashendon		67	13.4	26.9	34.3	25.4
Reservoir (b)	2	162	2.3	35.2	21.5	41.0
"	4	218	6.0	33.9	24.3	35.8
"	5	201	3.5	39.3	26.4	30.8
"	8	201	4.0	34.3	23.4	38.3
Sawyers (b)	3	190	5.3	26.8	28.4	39.5
"	28	366	7.7	42.6	30.1	19.7
Low quality forest						
Clare		34		67.6	32.4	
Clare		69	1.4	56.5	40.6	1.4
Beraking (a)		300	0.3	83.0	15.0	1.7
Coondle (a)		261		95.8	3.4	0.8

(a) virgin forest

(b) Minimum d.o.b. = 19.4 cm for old growth and 9.7 cm for regrowth Reservoir and Sawyers plots.

Table 36

Mean height and mean d.o.b. of dominant, codominant, sub-dominant, dominated and suppressed trees in old growth jarrah stands.

Sample sizes in parentheses.

Stand	Dominant	Codominant	Sub-dominant	Dominated	Suppressed
		Height (m)			
High quality forest					
Tallanalla	36.9 (47)	31.5 (100)	27.0 (48)	23.7 (42)	20.8 (19)
Ashendon	28.3 (7)	25.2 (18)	21.2 (23)	19.3 (16)	-
Low quality forest					
Clare		21.5 (23)	16.2 (11)		
Clare		23.7 (39)	20.2 (28)		
Beraking		20.8 (249)	15.9 (45)		
Coondle		14.1 (250)	10.9 (9)		
		d.o.b. (cm)			
High quality forest					
Tallanalla	107.9 (47)	81.5 (100)	53.8 (48)	32.6 (42)	24.5 (19)
Ashendon		68.7 (7)	61.7 (18)	43.1 (23)	37.8 (16)
Low quality forest					
Clare		59.2 (23)	40.9 (11)		
Clare		61.3 (39)	41.6 (28)		
Beraking		55.5 (249)	33.0 (45)		
Coondle		47.1 (250)	30.5 (9)		

Source: Field books of A.D. Helms, held in Archives, Institute of Forest Research, Department of CALM, Como.

Crown Vigour

Crown vigour was rated subjectively for several stands as well-formed, medium, or poor (Table 37). Few trees had well-formed crowns, i.e. deep, wide, and with dense leaf area. In high quality forest most codominant trees had medium crowns. Sub-dominant trees in high quality stands and both codominants and sub-dominants in low quality forest tended to have poor crowns.

Log Length in Jarrah Stands

Although log length is always less than bole length, to a great extent log length should reflect the length of the bole. Thus, because dominant trees are tallest, they produce the longest logs. In high quality forest, codominants contribute log lengths 3.7-12.2 m (Table 38). Most logs from sub-dominants are 3.7-7.6 m in length. Most logs from low quality forest are 3.7-7.6 m in length. The ratio of length of log to height of tree varies with site quality (Stoate and Helms 1938). For tree height of 28 m, the ratio is 0.33. Ratio varies ±0.02 for each ±5 m change in height. Thus, in high quality forest (33 m height) the ratio is 0.35 and average log length is 11.6 m. In low quality forest (23 m in height) the ratio is 0.31 and average log length is 7.1 m.

Table 37

Crown vigour in relation to dominance status of jarrah trees in old growth stands. N is the sample size.

Stand	Crown	Dominance status (% of trees) Dom.	Codom.	Sub-dom.	Dominated	Suppr.
Tallanalla	Well-formed	28	4			
	Medium	57	50	42	21	11
	Poor	15	46	48	79	90
	N	47	100	48	42	19
Ashendon	Well-formed	14		4		
	Medium	86	78	52	6	
	Poor		22	44	94	
	N	7	18	23	16	
Clare	Medium		4			
	Poor		96	100		
	N		23	11		
Clare	Medium		3			
	Poor		97	100		
	N		39	28		
Beraking	Medium		5	2		
	Poor		95	98		
	N		249	45		
Coondle	Medium		3			
	Poor		97	100		
	N		250	9		

Source: Field books of A.D. Helms, held in archives, Institute of Forest Research, Department of CALM, Como.

Table 38

Log length in relation to dominance status of jarrah trees in old growth stands.

Stand	Log length (m)	Dominance status (% of trees) Dom.	Codom.	Sub-dom.	Dominated	Suppr.
Tallanalla	>12.2	49	15	8		
	7.6-12.2	34	43	25	10	
	3.7- 7.6	6	32	40	7	
	< 3.7	11	10	27	83	100
	N	47	100	48	42	19
Ashendon	>12.2		6			
	7.6-12.2		11	22	13	
	3.7- 7.6		44	30	13	
	< 3.7		39	48	75	
	N		18	23	16	
Clare	7.6-12.2		9			
	3.7- 7.6		17			
	< 3.7		74	100		
	N		23	11		
Clare	7.6-12.2		13			
	3.7- 7.6		39	18		
	< 3.7		49	82		
	N		39	28		
Beraking	7.6-12.2		8			
	3.7- 7.6		48	13		
	< 3.7		44	87		
	N		249	45		
Coondle	7.6-12.2		<1			
	3.7- 7.6		15			
	< 3.7		85	100		
	N		250	9		

Source: Field books of A.D. Helms, held in Archives, Institute of Forest Research, Department of CALM, Como.

Table 39

Comparison of the b.a.o.b. and v.u.b. of jarrah trees in high and low quality forest, for selected bole lengths and d.o.b. F is the artificial form factor.

Mature codominant height (m)	Bole length (m)	d.o.b. (cm)	F (a)	b.a.o.b. (m^2)	v.u.b. (a) (m^3)
High quality forest					
33	11.6	15	.29	.018	.06
		45	.45	.159	.83
		60	.53	.283	1.74
		75	.61	.442	3.13
		90	.66	.636	4.87
Low quality forest					
23	7.1	15	.35	.018	.04
		45	.50	.159	.56
		60	.58	.283	1.17
		75	.66	.442	2.07

(a) based on Forests Department (1976).

Artificial Form Factor and the Calculation of Class and Stand Volumes

As explained in Chapter 6, the form factor expresses the similarity of the bole to a cylinder of the same base. An artificial form factor (F) is related to bole length (L), v.u.b. and b.a.o.b. of the bole by the equation v.u.b. = b.a.o.b. x L x F. Class volumes may then be calculated as either number of trees x b.a.o.b. of the mean tree x L x F or as number of trees x v.u.b. per class. Examples in terms of site quality are given in Table 39.

It is useful to stratify the forest into height, diameter, b.a.o.b. and crown cover classes. Stand b.a.o.b. may be measured in the forest by wedge prism, or the crown cover may be estimated from aerial photographs, and the b.a.o.b. calculated from percentage crown cover. Stand volume is estimated then as in the examples of stratification given in Table 40. On the A.P.I. maps the two stands were symbolized as JA 6/60 and JB 20/50, indicating the codominant height class (A and B site qualities) crown cover class of the overstorey and whole stand respectively in 10 per cent classes. Also, average crown diameters of healthy trees could be measured on aerial photographs on the basis of height and d.o.b. classes (Table 41) as a more accurate aid for separating site qualities than height alone.

Crown Cover and Crown Area

Crown cover, the area covered by tree crowns but not including obscured crowns or overlap, has been mapped from aerial photography for the whole of the State forest. Crown area of a stand is the sum of the crown areas including the overlap not seen on aerial photographs. An average value for crown cover for jarrah forest near Dwellingup, of which most is cut-over, is 60-70 per cent (Kimber 1970).

Determining the spatial arrangement of crowns in a stand is a laborious task because it involves mapping on the ground the position of each stem and the margin of its crown. Crown plans for three stands so mapped are reproduced as Figures 18-20. The very minor extent of overlap between codominants is evident, further proof of the 'crown shy' nature of jarrah. In the past, crown area has been calculated for each d.o.b. class from the crown ratio of the stand (e.g. Bednall 1939; Stoate 1941).

Jarrah stands may be classified as tall open forest if final height is > 30 m or open forest if final height is < 30 m, according to criteria of Specht *et al.* (1974).

Table 40

Calculation of stand volumes in terms of stratified d.o.b. classes, bole length (L), artificial form factor (F), and stocking (b.a.o.b. estimates were obtained by wedge prism in the forest or calculated from percentage crown cover on aerial photographs).

d.o.b. (cm)	L x F (m)	Crown cover (%)	b.a.o.b. (m^2 ha^{-1})	v.u.b. (m^3 ha^{-1})
<u>High quality forest</u> (*a*)				
15-45	4	-	-	-
45-60	6	48	16.8	101
60	8	12	4.2	34
<u>Low quality forest</u> (*b*)				
15-45	3	-	-	-
45-60	4	25	6.0	24
60	5	25	6.0	30

(*a*) A quality on A.P.I. type maps.

(*b*) B quality on A.P.I. type maps.

\- Not recorded on A.P.I. type maps.

Table 41

Separation of d.o.b. classes on aerial photographs by crown diameter and height intervals in high and low quality forest (after Loneragan 1971).

Stand	d.o.b. class (cm) 15-28	29-48	49-72	≥ 73
<u>High quality forest</u>				
Height (*a*) (m)	17±6	23±5	27±5	30±3
Crown diameter (*b*) (mm)	0.014	0.032	0.050	0.057
<u>Low quality forest</u>				
Height (*a*) (m)	14±5	20±5	23±4	-
Crown diameter (*b*) (mm)	0.015	0.036	0.060	-

(*a*) Read off from Figure 12.

(*b*) Measured from aerial photograph, scale 1: 20 000.

Figure 18
Crown plan for young jarrah pole stand (0.61 ha, Holmes block).

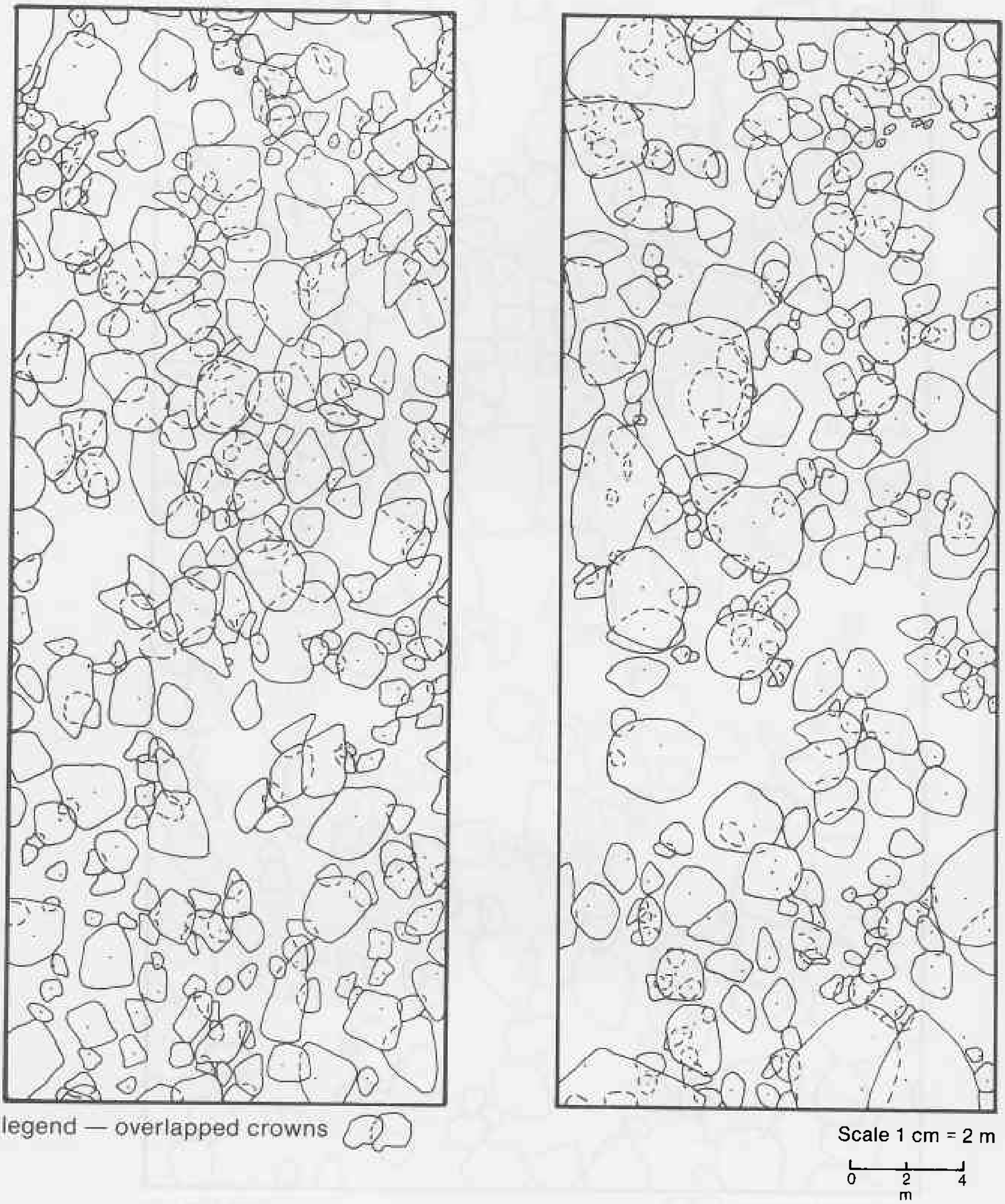

Figure 19
Crown plan for jarrah pole stand (0.81 ha, Holmes block).

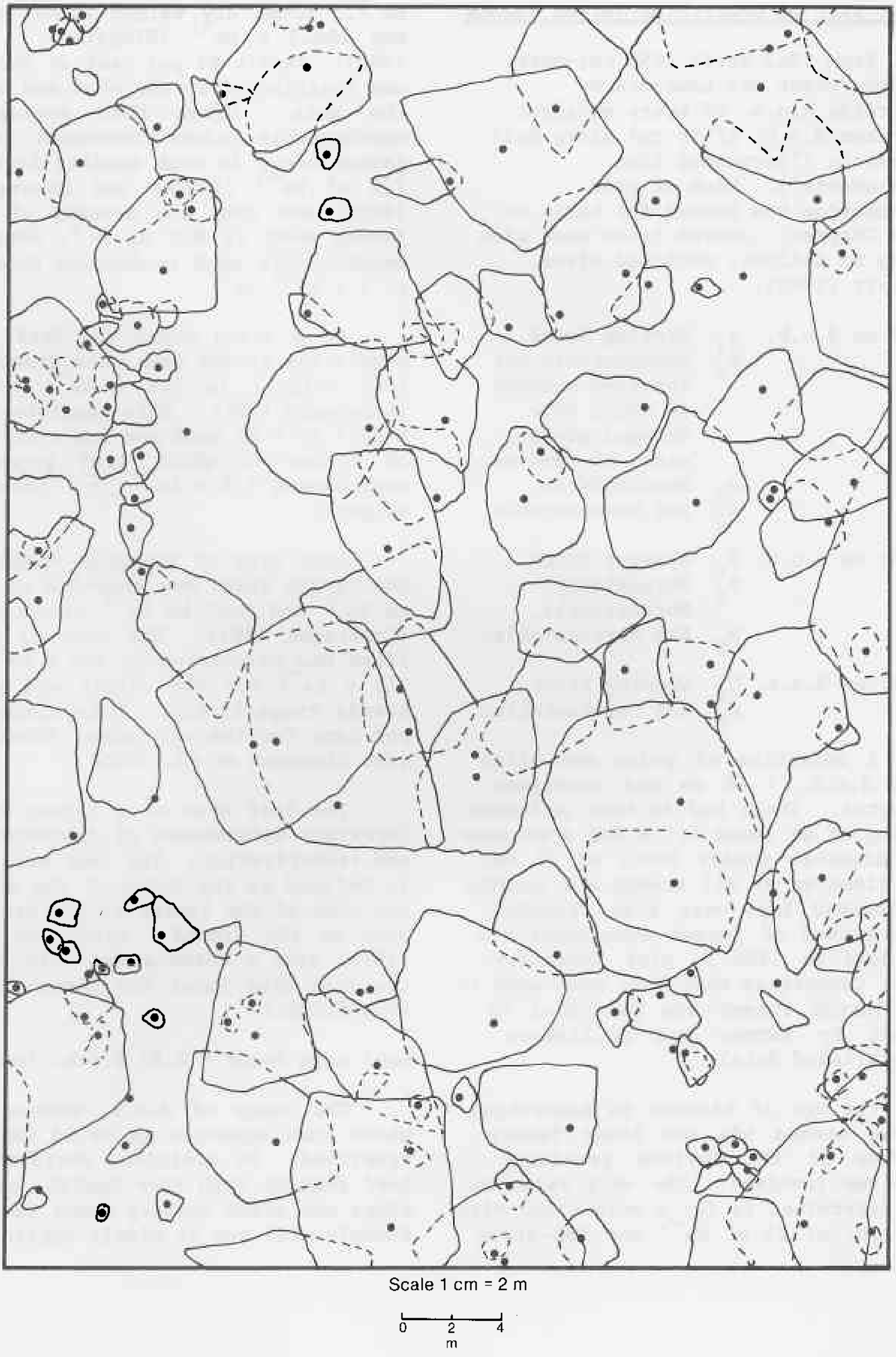

Figure 20
Crown plan for virgin jarrah stand (0.71 ha, Location A4596, adjacent to Amphion and Bombala blocks).

Other Ways of Describing Jarrah Stands

From 1942 until 1956 cut-over jarrah forest was assessed by recording d.o.b. of every eucalypt (minimum d.o.b. of 48 cm) along belt transects ('permanent line assessments'). Much of this information has formed the basis of this Chapter. Jarrah trees were also coded as follows, modified after Barrett (1949).

≥ 73 cm d.o.b.	A_1	Growing Stock.
	A_2	Merchantable but retained because it would have damaged growing stock if removed.
	A_3	Merchantable.
	A_4	Not Merchantable.
58-72 cm d.o.b.	B_1	Growing Stock.
	B_2	Potentially Merchantable.
	B_3	Not Merchantable.
48-57 cm d.o.b.	C_1	Growing Stock.
	C_2	Not Merchantable.

A selection of poles and piles with d.o.b. < 48 cm was sometimes measured. These had to have a length of log of at least 6.1 m and a minimum top diameter (under bark) of 15 cm. The diameter of all stumps and lengths of removed logs were also recorded. This method of forest assessment was replaced in 1956 by plot inventory. Other techniques that have been used in the jarrah forest are described in detail by Rayner and Williamson (unpublished data).

The use of biomass in describing jarrah stands has not found favour because of the obvious practical problems involved. The only value so far determined is for a pole stand with b.a.o.b. of 26 m^2 ha^{-1} and 356 stems ha^{-1}. Total dry weight above ground was 206.3 t ha^{-1} (Hingston 1980). Nearly 85 per cent of this mass was contributed by the wood and bark of the bole. Given that average merchantable volume increment for a jarrah stand in high quality forest is 1.2 m^3 ha^{-1} (Abbott and Loneragan 1983b) and that the density of dry jarrah wood is 820 kg m^{-3}, average merchantable wood production should be c. 1 t ha^{-1} yr^{-1}.

In a stand where the leaf area equals the ground area, the growth mass (dry weight) is 5.9 t ha^{-1} yr^{-1} (Loneragan 1961). This consists of 2.7 t ha^{-1} yr^{-1} of wood and 3.2 t ha^{-1} yr^{-1} of litter to which leaf growth contributes 1.9 t ha^{-1} yr^{-1} (oven dry weight).

Leaf area of two pole stands and one virgin stand was recorded as 1.056 ha ha^{-1} and 0.57 ha ha^{-1} respectively (Loneragan 1961). The mass of wood fibre was calculated as 258 t ha^{-1} and 115 t ha^{-1} for the virgin and pole stands respectively. This allows 15 per cent for the persistent branchwood (see Hingston *et al.* 1980).

The leaf area of a forest is an important determinant of photosynthesis and transpiration. The leaf area index is defined as the ratio of the area of one side of the leaves to the projected area on the ground. Carbon *et al.* (1979) give a formula for calculating the leaf area index for jarrah forest from d.o.b.:

Leaf area index = 2.87 d.o.b. (cm) - 33

The range of d.o.b. values for which this equation is valid was not specified. In addition, variation in leaf density with tree health, seeding stage and stand density means that this formula will not be widely applicable.

CHAPTER 10

Exploitation of Jarrah

Exploitation is used here to refer to the way commercial enterprises have perceived and extracted the timber resource. This section therefore examines the history of logging, particularly the questions of where, when and why.

Logging of jarrah forest has produced nothing like the deforestation around the Mediterranean (Thirgood 1981). South-western Australia has experienced no wars or invasions, and until after the 1939-45 war industry had been rudimentary. The relatively small population, the presence of a large coal resource, and the lack of a major ship building industry have minimized the local need for timber.

The major cause of the reduction in the extent of jarrah forest (ch. 3) has been agriculture. Most of the existing high quality forest was not converted to agriculture because it was located on ironstone gravelly soils, except for relatively small areas used for fruit-growing in the more fertile valleys close to towns. Little progress was made in dedicating State Forest in the first decade after the proclamation of the Forests Act in 1919. A substantial portion of the eastern fringe of jarrah forest/wandoo woodland was cleared for sheep and wheat farming in the period 1850-1950. Most jarrah forest soils were considered to be too rocky or infertile to plough or farm.

Forest exploitation can be classified into four periods (Nunn 1957). In the pioneering era of 1829-1880, the total volume of timber cut was insignificant.

The era of timber concessions and leases followed by 1880-1900, during which the sole rights to remove, sell or export timber were granted at a nominal rent. Later eras included early permit control (1900-1919) under the Land Act, and the present one of forests management (since 1919).

The year 1919 was when the Forests Act became law. Before then, logging of the forests was virtually unsupervised by Government. R.T. Robinson (Western Australian Parliament 1918a) noted the following:

> 'Since 1836 Western Australia has been engaged in mining her forests, that is to say she has striven, regardless of the future, to get as much as she possibly could out of the areas of timber country that be scattered within her borders. Timber men have been encouraged to take up forests for saw-milling purposes, and the terms under which concessions have been granted were of the most advantageous character. The object of each successive Government has been to exploit as much timber as possible in the shortest time'.

Almost all high quality stands in the northern jarrah forest were logged before 1919. The source of timber was still seen as inexhaustible and there was little attempt at regeneration.

The jarrah forests of the Darling Plateau were discovered in 1829 and their worth was soon recognized (H. Trigg in Ogle 1839). The influential Surveyor-General noted near Collie

> 'the splendid straight mahogany or jarrah trees, growing within 3 or 6 feet of each other, reaching to the height of 50 and 80 feet without a brand or blemish, and apparently quite sound'. (Roe 1852).

The forests remained unlogged until the 1870s because of a lack of markets and transport (Ireland 1962). Local consumption and limited export could be satisfied by logging jarrah in the *Banksia* woodlands of the coastal plain near Perth. Roads to the Darling Plateau were poorly developed and there was no government-built railway connecting the forests to port until the 1880s.

Although timber was first exported in 1836, its value did not exceed ₤5000 until 1853 (Battye 1924). In the 1870s the Government granted concessions of large areas of jarrah forest (one exceeded 100 000 ha) to private enterprise, capitalized mainly from Britain. There was no real attempt to police the regulations (as listed in Fraser 1882) governing these concessions because of lack of staff. In 1874 exports of timber first exceeded local consumption (Robertson 1956).

Details of when and where sawmills were established in the northern jarrah forest are given by Fraser (1882) and Ednie-Brown (1896, 1899). Further information is available in the Annual Reports of the Forests Department from 1897 to 1929. Recent local histories serve to show the importance of timber-getting in the early development of the south-west of Western Australia. These include Eliot 1983 (Mundaring Shire); Fall 1972a, b, 1979 (Jarrahdale area); Slee 1979 (Kalamunda area); Popham 1980 (Karragullen area); Richards 1978 (Murray Shire); and Staples 1979 (Harvey Shire). Other historical details are supplied by Thomas (1929), Carron (1980) and Stewart (n.d.).

The method of logging involved the selection and cutting of the largest sound trees for sawmilling. Witnesses to the 1903 Royal Commission stated that 7-25 trees were logged per ha.

The average volume of merchantable timber per tree was 4 m^3, with the most profitable having d.o.b. of 80-140 cm. Until the introduction of steam-driven machinery in the 1870s, logs were sawn up in the forest using the ancient technique of pit sawing (Calder 1980; Gabbedy 1981). Later those logs were hauled to the mill by horse or bullock teams. Once stands close to mills were cut, light railways were constructed by each timber company to provide access to more distant stands.

Given the extensive area of virgin forest, the high standard of log required, and the easy access dictated by the gentle undulating nature of the Darling Plateau, cutting tended to be light. The forests were cut-over rather than cut out (Royal Commission 1903). However, stands close to mill sites or log depots alongside the railway tended to be cut more uniformly. All fellings were unregulated in the sense that there were no silvicultural controls. For example little consideration was given to the extent of damage to immature trees during logging. There was also much wastage of timber in removing the log from the felled tree and in its conversion to sawn timber at the mill (Lane-Poole n.d.). The lack of royalty payments also induced waste (Hutchins 1916). Expansion of the railway system between 1880 and 1920 resulted in the need for large numbers of sleepers (Robertson 1956). These were required by the Government to be hewn and not sawn (Royal Commission 1903), resulting in even more waste.

The result of such unregulated selection of the best and largest trees was that the smaller, weaker and more defective trees were left. The forest was then regarded by foresters as grossly overworked and in poor condition (Meachem 1962).

Accumulation of lop and top debris on the forest floor together with lightning strikes and fires escaping from farms adjacent to forest resulted in many wildfires sweeping the forest from the 1870s. The timber resource became degraded and the regrowth damaged (ch. 12), resulting in malformed and defective trees.

A Woods and Forests Department was founded in 1895 and headed by a professional forester (J. Ednie-Brown) who died four years later. The chief regulation at this time was that only trees of d.o.b. c. 50 cm could be legally cut. There was insufficient staff to police this in the forests.

Concern about the above matters resulted in the Royal Commission of 1903-1904 investigating how long the forests would last given the rate of cutting. However, the Commission could not call any witness to provide an authoritative value of the annual d.o.b. growth rate of jarrah. The Commission found that there was no difference in quality between hewn and sawn sleepers, and that in sleepers, scantling, pickets and paving blocks hewing obtained about 60 per cent of the timber in a log against about 70 per cent from sawmilling. Hewers should therefore not be allowed to precede sawmillers in the cutting of virgin forest. A minimum d.o.b. of 76 cm was recommended for cutting. A minimum of 73 cm was adopted by Government in 1905 in order to reserve for the future trees of smaller d.o.b. (the growing stock).

The Commission also recommended the foundation of a Forests Department and the disposal of timber by royalty only, but nothing effective was done until the appointment of Lane-Poole as Conservator of Forests in 1916. The result of this delay was that large numbers of poles and piles were removed illegally, greatly depleting the stocking of the younger age classes (Harris 1956). With the implementation of the Forests Act of 1919, the jarrah forest was no longer unmanaged. Commercial cutting was by the harvesting of small groups of trees rather than individual trees. The object of this procedure was to create openings in the forest for natural regeneration.

The use of a minimum d.o.b. to restrict cutting of stands was criticized. Vested interests claimed that it added to the expense of working a forest (W.G. Pickering, Western Australian Parliament 1918b). Lane-Poole (1921) regarded it as a faulty selection system when applied to virgin forest because the selection of trees rested with the sawmiller instead of the forester. Most of the volume in virgin jarrah forest is in the mature and overmature trees of large d.o.b. The first trees removed should be the unsound overmature trees which have ceased to grow (the static volume of the forest). Deformed undersized trees should also be removed then. Such a procedure results in a more productive growing stock, capable of growing logs in a shorter time. Furthermore, the proportion of useful volume removed under the minimum d.o.b. criterion jeopardized the future of the sawmilling industry (Jacobs 1955). Because of the high cost of removing cull (overmature, useless) trees it has not been economic to follow this ideal procedure.

Major achievements of the Forests Department in the 1920s included the classification and dedication of State Forest, inventory of the forest, introduction of royalties, the preparation of working plans designed to reduce overcutting and increase the life of mill towns, and the abolition of the minimum d.o.b. regulation (Robertson 1956). Trees to be removed and their direction of fall were marked by Forests Department personnel. This avoids damaging the trees retained (and hence preserves the dynamic volume of the forest) and ensures that the untilizable part of the bole is not wasted. Surprisingly, outside the Forests Department the idea that a forest is 'a mine of timber to be worked out and then deserted' still persisted (Kessell 1928). The 1929 working plan for jarrah attempted to place the timber industry on the basis of a regulated-yield. Previously, the volume of timber cut was controlled only by the number and size of the mills which happened to be established at any particular time. Nunn (1957) noted that

> 'it has been possible during four decades of active forestry to bring a eucalypt forest of between four and five million acres to a fairly satisfactory condition of forest management under working plans'.

A large part of the northern jarrah forest has now been cut-over two or three times, mainly under the Australian group selection scheme described above (Jacobs 1955). The reasons for this less intensive approach were outlined by Stoate (1923):

> 'If conditions here were as in some other countries, where forest management has been practised over long periods, and density of population has rendered a closer utilisation possible of all kinds and classes of wood, the treatment which would be followed to achieve the best results for a light-demanding species like jarrah would be clear-felling, followed by even-aged crops. This means that the whole of the timber standing on a specified area of forest may be sold each year without restriction as to girth, method of felling, or cleaning up, making the supervision of the bush of minor consequence'.

Haulage of logs by bullocks and horses to depots along the railway lines continued until the 1930s when tractors were introduced (Stewart n.d.). The great mass of logs (up to 15 t) and low recovery (usually < 35 per cent) at the mill dictated short haulage distances to mills (average 20 km) and minimum handling (Hartley 1946). By the end of the 1939-45 war, trucks began to replace the use of locomotives and railways (O'Brien 1938; Robertson 1956). For illustrations of early logging activities, see Ednie-Brown (1896, 1899); the *Australian Forestry Journal* (vol. 1, pp 18-25, 1918); and Forests Department (1969). Since the late 1940s the axe and cross cut saw have been replaced by power saw and then the chain saw for the felling of trees.

Originally the jarrah forest produced trees of 150 cm d.o.b. over an estimated physiological rotation of 800 to 1000 years. Under management, the forests have been changed with the object of providing trees of d.o.b. c. 70 cm within 90 to 120 years (Kessell and Stoate 1937). The proportion of useable volume in the managed forest is considerably more than in the virgin jarrah forest. The great boles of long length which gave the virgin forest such a large volume of wood are unlikely to be grown again, other than in areas of the northern jarrah forest set aside from future timber production.

CHAPTER 11

Stand Development, Treatment and Productivity

In this chapter we integrate information from Chapters 7 (Growth), 8 (Stand Establishment) and 9 (Stand Description). We also discuss stand dynamics and productivity in relation to past, present and future forest management.

In the jarrah forest, private enterprise removes the valuable parts of the stand and Government (through the Department of CALM) is responsible for all siliviculture, protection from wildfire and dieback (*Phytophthora cinnamomi*) hygiene. In order to secure adequate regeneration, the Department of CALM controls the cut; otherwise large worthless trees would be left to overtop promising groups of poles or to occupy ground which might support new growth (Stoate 1923).

The basis of all silvicultural work in the jarrah forest is that the regeneration is the result of the fellings themselves (Nunn 1957). This is effected in two ways: immature growing stock is retained and protected during logging operations, and a controlled fire in advance of logging and subsequent disposal burning of lop and top provides ashbeds for germination of seed dispersed from the trees remaining and removes debris which may later damage crop trees. The use of the Australian group selection scheme, involving the removal of single trees or groups of trees (Jacobs 1955), results in openings in the stand which release dormant advance growth (van Noort 1960). The openings as such are not as important as the reduction in competition from other trees.

The goal of the forest manager in tending jarrah forests is to discover the essential requirements of jarrah and provide the best conditions for growth. The difficulty in the early days was that forest management could not wait for the results of experimental studies of silvicultural problems (Kessell 1943). A very large timber industry was extant before the Forests Department came into existence.

Historical

Before 1919, no silviculture was practised in the jarrah forest. The forest regenerated naturally as trees aged and died. Logging simply accelerated regeneration in space and time. Uncontrolled fires resulting from the accumulation of logging debris despoiled much of the regenerating forest. Thus, a survey of over 16 000 ha of cut-over jarrah forest near Collie found the average number of sound jarrah with d.o.b. 25 cm to be 6.0 ha^{-} and useless jarrah to be 52.3 ha^{-} (*Annual Report* 1921).

In 1929 the last of the Timber Concessions (ch. 10) expired, and the stands of jarrah within them came under Forests Department management for the first time (Stewart n.d.). In the 1920s and 1930s most of the high quality forest was given a 'regeneration cleaning' (Figs 21-25), in which worthless jarrah and marri trees were removed. Restocking with sound stems rather than thinning was given first priority (Lane-Poole n.d.). Rehabilitation of cut-over stands gained impetus from cheap labour available during the Depression of the 1930s, and was completed by 1938 (Stewart n.d.).

Figure 21
Stand improvement in progress. Note ring-barked cull trees.

Figure 22
Stand improvement creating openings in preparation for regeneration and leaving healthy growing st [illegible] in groups for later logging.

Figure 23
Final burn (after stand improvement) for regeneration.

Figure 24
Jarrah sapling stand three years after regeneration cleaning (1925) c. 20 years after heavy logging.

Figure 25
Eighteen-year-old second growth jarrah. Dwellingup Division (1932). Tallest pole is 20 m in height. Note fi. killed veteran tree at right and result of regeneration cleaning of the stand.

The sequence of silvicultural operations in the forest was as follows (Forests Department 1927):

Operation	Purpose
(1) Low intensity fire before logging	To reduce fuel and lessen risk of wildfire during and after logging.
(2) Tree marking (trees to be logged), their direction of fall marked and growing stock (seed trees) to be retained	To control logging, avoid waste, retain growing stock, and avoid damage to immature trees.
(3) Logging	Commercial.
(4) Regeneration Cleaning	
. Removal of useless trees and undergrowth	To encourage development of jarrah regrowth (well formed stool coppice).
. Retention of seed trees	To restock blank areas from natural seed supply.
. Half ring-barking of seed trees	To stimulate seed production.
(5) Final burn	To burn lop and top and provide ashbeds for seeding and accelerating early growth of jarrah.
(6) Removal (by complete ring-barking) of seed trees once established.	To reduce competition.
(7) Protection of regeneration from fire	To prevent malformation of young stems.

According to Stoate (1923), all useless trees of d.o.b. < 30 cm had to be coppiced and all useless trees of larger d.o.b. not meeting the standards (very high) of the day were to be ring-barked. 'Useless trees' were not defined by Forests Department (1927).

No tree containing a quantity of sound timber was to be ring-barked because of its probable value in the future. Such trees were to be left for logging 20-30 years later. No vigorously growing immature tree was to be cut because these would mature more quickly than the seedlings which would replace them if they were destroyed. When in doubt, the Foresters' Manual of 1927 instructed foresters to err on the light side: 'It is always possible to go back and cut trees which should have been destroyed, but the converse is not possible'.

The work done in openings consisted of felling all malformed (mainly fire-damaged) or seriously damaged saplings and poles which could not develop into satisfactory logs. It was considered better to have the ground occupied by those trees supporting a potentially useful crop. Any opening was to be at least 20 m wide; openings too much larger were not favoured because they exposed young crowns to damaging agencies which were thought to encourage forking of stems. Useless poles were felled 30 cm above ground, and those of d.o.b. < 30 cm were felled as close to the ground as possible ('mullinized') so as to induce strong, straight coppice.

All trees of d.o.b. > 38 cm and of no future value were ring-barked. Ring-barking was to be partial (half of the girth not rung) where regeneration from seed was necessary. An unresolved, though in retrospect unimportant, problem was whether ring-barking should be done when buds are forming, when flowers are open, when seed is about to fall, or not until seed is on the ground (Stoate 1923).

Treatments early in the floral cycle influence blossom and seed production. By 1927, it came to be realized that it was often unnecessary to retain seed trees because of the abundant advance growth (*Annual Report* 1927). Seed trees proved to be a dilemma: if they were left they tended to suppress the regrowth; if they were later removed, the logging often damaged the regrowth. Thus the treemarker had to decide whether the seed tree could be removed without damaging regrowth. Large marri were 'sap rung' (c. 10 cm band of both xylem and phloem tissues was cut out) and small marri were ring-barked (a band of phloem was removed). All felled trees were then arranged so that their branches lay on the ground, in order to help form ashbeds. All lop and top was cleared before burning for a distance of 1 m from retained trees.

As detailed in Chapter 9, marri occurs throughout the jarrah forest. Because commercial cutting was confined to jarrah, the remaining proportion of marri to jarrah in the seed trees increased, until the introduction of regeneration cleaning in the treated stands. This did not lead to marri forming a greater proportion of the regrowth of the original forest (*Annual Report* 1928). Because both species have similar rate of growth in height, the removal of codominant marri constituted a useful crown thinning (*Annual Report* 1928).

Differences in professional opinion occasionally arose. Harris (personal communication*) felt that felling of all damaged stock resulted merely in massive stool coppice, a gain of nothing. He regarded the best treatment as removal of the competitive unmerchantable trees in order to stimulate regeneration. The disadvantages of regeneration cleaning include ring-barking of uncommercial timber becoming marketable later and the subsequent increase in dead stagheaded trees causing a fire hazard. After 1935 ring-barking to induce seeding ceased because of wastage of the then non-commercial poles which would later become marketable. The standard of acceptable sapling was reduced and the felling of trees to 15 cm d.o.b. stopped (Harris 1956). On balance, regeneration cleaning proved useful, as many prime jarrah stands resulted.

Some stand improvement work was carried out concurrently (Figs 26-28). This involved the removal of so-called culls (large over-mature trees) suppressing young growth (a thinning from above or removal of overhead competition) and the thinning of groups of poles and piles. There were no detailed prescriptions. For the history of early thinning treatments, see Campbell (1966).

Regeneration cleaning and stand improvement ceased due to shortages of labour during the 1939-45 war. They were not revived after 1945 because the cost of labour had risen greatly while the Forests Department budget remained static. During the 1950s and 1960s emphasis was on removing the least thrifty stems. In the 1970s when the cause of dieback disease was appreciated, the emphasis changed to a more intensive cut in order to reduce the area cut-over (Forests Department 1972). A response to containing the spread of dieback fungus was the complete cutting of badly infected

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stands. The operations previously listed are still carried out, apart from regeneration cleaning and ringbarking (items (4) and (6), page 83).

The logging of mature and overmature trees was continued, and transmission poles and bridging piles were also cut when required. All trees of d.o.b. > 60 cm were removed from stands of mean mature codominant height ≥ 20 m, unless regeneration was inadequate for restocking.

Figure 26
Sixty-year-old jarrah pole stand (1930s) before thinning.

Figure 27
Sixty-year-old jarrah pole stand (Mundaring Division, 1930s) immediately after thinning. Note unwanted stems stacked against cull tree.

Figure 28
Thinning of sixty-year-old jarrah pole stand (Jarrahdale Division) from above.

Since 1967 stand improvement rather than regeneration has been emphasized (Fig. 29). This involved thinning stands of immature jarrah trees resulting from the treatment of the 1930s, removal or killing of useless or cull trees, and the killing of the densest component of the understorey, *Banksia grandis*. These practices were facilitated by the application of hormone-type arboricides (2, 4, 5-T and tordon) to prevent coppice development from stumps. For detailed prescriptions for each procedure, see Forests Department (1964, 1972).

Improvement work came to be confined to stands in so-called Intensive Management Units (Kimber[+]). These were areas chosen because they had a low incidence of dieback disease and a high proportion of A class jarrah forest (see ch. 9). The small amount of money available could then be spent on the most worthwhile stands. The object was to maintain the highest possible yields and a healthy forest (Forests Department 1972). The following procedure was followed:

(1) All stands were to be assessed for adequacy of regeneration 25 years before final felling.

(2) After burning of lop and top, fire was to be excluded until saplings had reached a size where they would not be damaged by prescribed low intensity fire.

(3) Regenerating stands were to be thinned initially to about 1100 (stage (5)) ha^{-1} when ten years old. However, this would be uneconomic, so instead thinning was to be deferred until the height of the 250 tallest stems ha^{-1} reached c. 18 m.

+. Forest Department file H.O. 79/72.

Figure 29
Increase in leaf density of jarrah crowns after thinning of a 40-year-old pole stand and poisoning of stumps: left, 9 months after thinning; right, 35 months after thinning.

(4) Subsequent thinnings were to be merchantable, with the timing dependent on availability of markets and full stocking of the site.

(5) The existing crop was to be brought into a more even-aged condition by the removal of all merchantable jarrah with d.o.b. ≥ 72 cm, by the removal of small trees with poor crowns or malformed stems, and by the poisoning of competing cull trees.

(6) Dense thickets of *B. grandis* were to be poisoned and jarrah regenerated in its place.

Kimber developed the I.M.U. concept in response to the 'small sum of money spent on jarrah silviculture'+. He reasoned that because about half of all trees in the forest became malformed by fire in the first 30 years of life, the younger age classes should be concentrated in relatively smaller areas where fire protection could be better managed. In effect Kimber recognized the practical shortcomings of the Australian group selection scheme and advocated other logging systems resulting in concentration of age classes.

Application of the I.M.U. concept stalled in the early 1970s because of uncertainty about the extent and location of bauxite mining within high quality jarrah forest and the prevailing pessimism about the effect of dieback fungus on the forest. The most recent guidelines for cutting and regenerating jarrah stands are given by the Forests Department (1981). Because of many factors there is now no uniform prescription: logging varies according to major land use, stand health, structure, and site quality.

+. Forests Department file H.O. 14/69.

The ultimate aim is to maintain or improve the health and productivity of the forest, by selecting and protecting future crop trees and by strengthening the capacity of the forest to tolerate the fungus *Phytophthora cinnamomi*. The most recent prescription for silvicultural treatment of jarrah (Bradshaw 1986) is designed to maintain the most rapid diameter increment consistent with maximum wood production.

The question of forest utilization - the most appropriate methods of harvesting, converting and profitably disposing of forest produce (Kessell 1921a) - falls outside the scope of this Bulletin.

Stand dynamics

Campbell (1956) states that under virgin jarrah forest there is enough advance growth present to ensure the establishment of a new forest when the virgin one is felled. A major shortcoming of this view is that the significance of the early stages of the development of jarrah was not recognized. Consequently, there are areas of jarrah forest which do not regenerate after logging because of insufficient numbers of ground coppice (Stage (4)). Even though germination occurs yearly some of the seedlings fail to survive or develop into incipient growth coppice. Remnants of virgin forest that we have inspected differ considerably in the stages of regeneration present. There is also much variation within the one remnant, with patches of small poles amongst considerable ground coppice (Fig. 30; see also Harris 1956; van Noort 1960).

Beginning with seedling establishment, the development of the stand is influenced by the site and species, age and density of the trees. Inherited vigour, favourable position in the stand, and freedom from inimicalities must all contribute differentially to the survival and growth of seedlings, and rapid development of the lignotuber. Some saplings and poles begin to emerge as the dominant or codominant members of

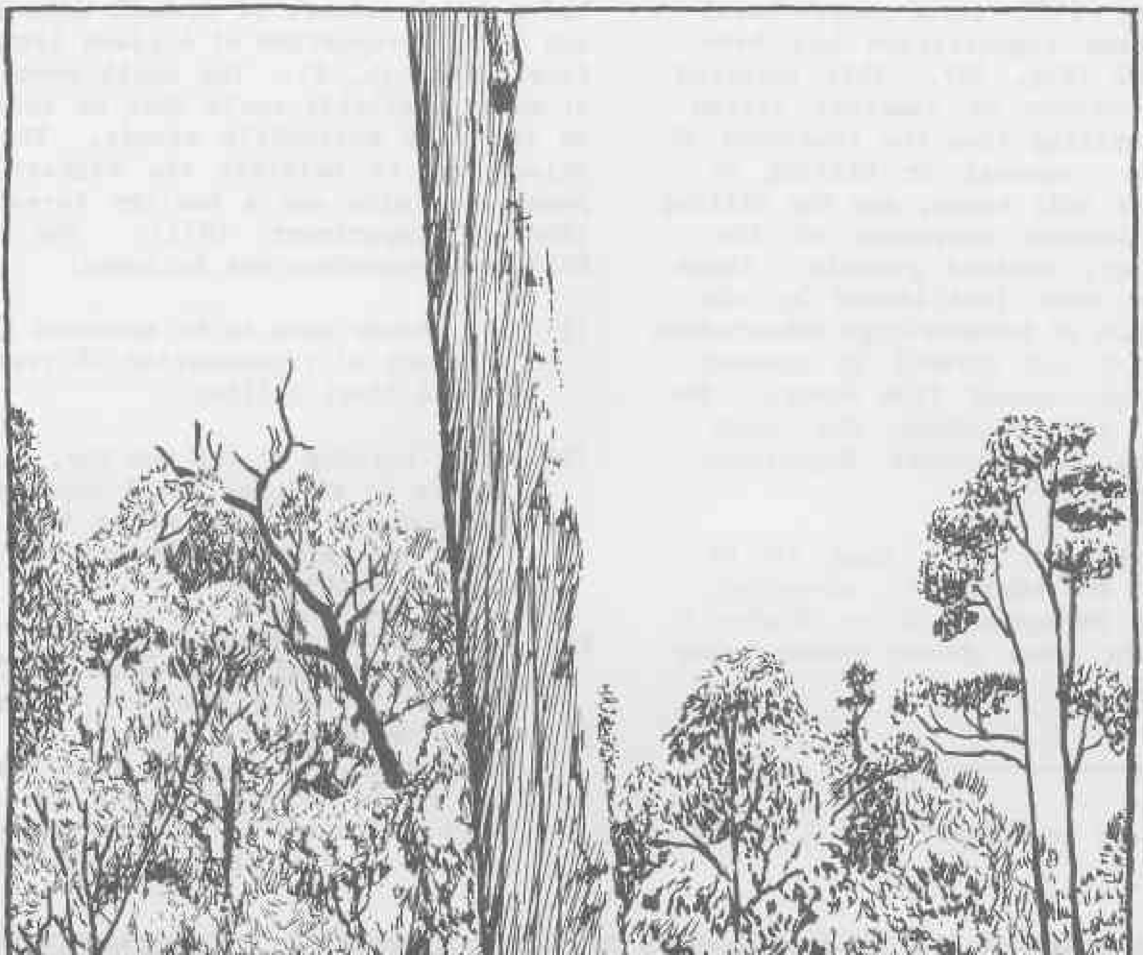

Figure 30
Example of advance sapling and pole growth around fire-killed veteran tree in virgin jarrah forest (Location A4596).

the developing stand, with the rest being forced into subordinate positions.

Concomitant increase in stand density makes the environment less favourable for development of individual trees. Natural thinning in crowded clumps of saplings, poles and piles is in part due to inherited differences in growth and external influences, particularly fire. Over time the number of stems decreases, the difference in d.o.b. between dominant and dominated becomes more pronounced, most of the stand b.a.o.b. is contributed by the overstorey and crown cover and crown area increase (Table 42). Forest management seeks to supplement and accelerate this natural thinning process.

Table 42

Changes in various stand properties with development, based on comparison of three types of jarrah stand, Dwellingup Division (after Hatch 1964).

Characteristic	Virgin: Whole stand	Virgin: Overstorey (*c*)	Pole: Whole stand	Pole: Overstorey	Young Pole: Whole stand	Young Pole: Overstorey
Age (yr)	c. 1000		41		28	
No. stems (*a*) ha^{-1}	198	-	870	-	1 097	-
b.a.o.b. (m^2 ha^{-1})	38	29	36	25	32	21
v.u.b. (*b*) (m^3 ha^{-1})	269	-	155	-	108	-
Crown area (%)	73	55	68	56	-	40
Crown cover (%)	62	53	59	54	-	38
Plot size (ha)	0.71		0.81		0.61	

(*a*) All stems with d.o.b. >10 cm. Marri is included.

(*b*) No allowance for defect.

(*c*) Dominants, codominants and sub-dominants.

Early intervention in typical coppice stands (Chandler 1939; Bednall 1942) was fruitless, as height and diameter growth were little affected by thinning of coppice clumps to one or two coppice stems per stool. This is because the thinning still left the stand in an overstocked condition. The question of thinning jarrah coppice is thus more one of removing the malformed codominants to favour those of good form and vigour. Control of unwanted coppice did not become possible until 1959 when arboricides were first used. Without such control, coppice rapidly restores stand b.a.o.b. to an overstocked condition.

A delayed crown thinning in regrowth jarrah (53 years old, codominant height 20 m) doubled (relative to an adjacent unthinned stand) the merchantable volume increment 28 years later (experiment of Bednall and Kinsella in Mundlimup block, summarized by Podger 1959). The results of several other experiments have been collated (Abbott and Loneragan 1983c). In agreement with worldwide evidence (O'Connor 1935; Craib 1947; Moller 1954; Opie *et al.* 1978) they show that thinning should be carried out as early as possible to put as much growth as possible on the valuable present or potential crop trees. Diameter growth is improved and the length of the rotation is shortened.

For example, consider a stand of poles of d.o.b. 30 cm growing in d.o.b. at 0.2 cm yr^{-1}. It would take 150 years for d.o.b. of 60 cm to be attained. With thinning so that d.o.b. growth rates were increased to 0.4 or 0.6 cm yr^{-1}, this period reduces to 75 or 50 years respectively.

Since writing our review of thinning experiments in the jarrah forest (Abbott and Loneragan 1983c) we have analysed the data of the Mundlimup experiment in detail. Inspection of various early reports (Podger 1959; Forests Department file H.O. 133/58) showed conflicting figures. These have been resolved and an accurate summary is presented in Table 43. The stand was first logged in 1872, and

Table 43

History of the Mundlimup jarrah thinning plots in 1875 regeneration
Units: crown cover (%); b.a.u.b. (m^2 ha^{-1}), v.u.b. (m^3 ha^{-1}), d.o.b. (cm).

Year	Age (yrs)	Plot Treatment	Unthinned	Thinned: Before Cut	Thinned: After Cutting	Thinned: Removed	Increments yr^{-1} m.a.i. Unthinned	m.a.i. Thinned	c.a.i. Unthinned	c.a.i. Thinned
1870s		Virgin forest crown cover		51	15.5	35.5				
		No. stems ≥14.5 cm d.o.b.		148	111	37				
		b.a.u.b.		36	3	33				
		v.u.b.		300	20	280				
1875	0	Regeneration				1926–1928				
1928	53	Codominant height	21 m	Before 1st Thin	After Thinning	Removed				
		Regrowth forest crown cover		64	41	23				
		No. stems >14.5 cm d.o.b.	445	318	160 + coppice	158				
		b.a.u.b.		24	13.1	10.9		0.45		
		v.u.b.		100	60	40		1.9		
1956	81	Codominant height	28 m	Before 2nd Thin	After Thinning	Removed 1957				
		No. stems <14.5 cm d.o.b.		198	148	50				
		No. stems >10 cm d.o.b.	533	296						
		b.a.u.b.	33.3	26.6	20.4	6.2	0.41	0.46		0.48
		v.u.b.	235	203	158	45	2.9	3.0		5.1
		v.u.b. for d.o.b. 43.5 cm	80	158						
		v.u.b. for d.o.b. 58 cm	30	72	Coppice Retained	Coppice Removed				
		v.u.b. for d.o.b. 50 cm	43	98			0.53	1.2		
		d.u.b. 50 crop trees	46.9	51.9	51.9	51.9	0.58	0.64		
		d.u.b. 100 " "	40.3	45.1			0.50	0.56		
1972	97	Codominant height	31 m	After 2nd Thin						
		No. stems >10 cm d.o.b.	511	333						
		b.a.u.b.	36.8	26			0.36	0.44	0.22	0.35
		v.u.b.	265	198			2.7	2.9	1.9	2.5
		v.u.b. for d.o.b. 50 cm	66	133			0.68	1.4	1.4	2.2
		d.u.b. 50 crop trees	50.3	58.2			0.52	0.60	0.21	0.39
		d.u.b. 100 " "	43.3	47.8			0.45	0.49	0.18	0.29
1981	106	No. stems >10 cm d.o.b.	554	325						
		b.a.u.b.	38.7	28			0.37	0.43	0.21	0.22
		v.u.b.	280	215			2.6	2.8	1.7	1.9
		v.u.b. for d.o.b. <50 cm	90	158			0.85	1.5	2.7	2.8
		d.u.b. 50 crop trees	51.1	60.7	60.8	60.6	0.49	0.57	0.09	0.28
		d.u.b. 100 " "	43.9	51.6			0.41	0.49	0.07	0.20
		d.u.b. 150 " "	39.2	46.4			0.37	0.44	[illegible]	0.17
		d.u.b. 200 " "	34.9				0.33		[illegible]	

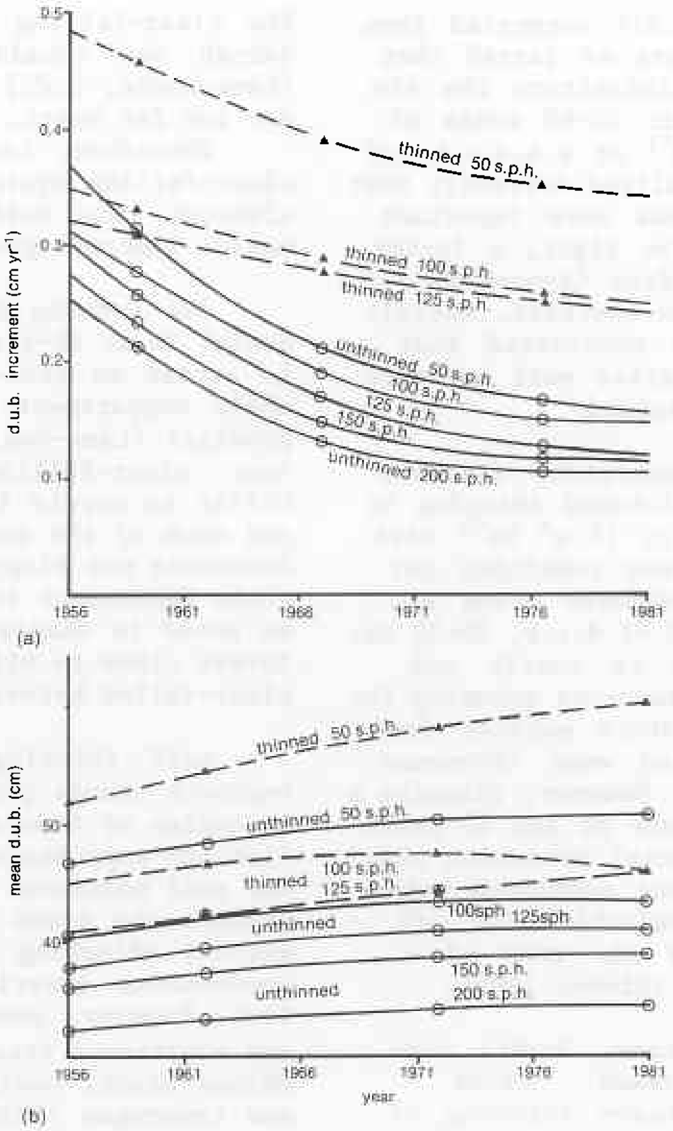

Figure 31
Comparison of (a) d.u.b. increment, (b) mean d.u.b. of thinned and unthinned plots in Mundlimup block for 50, 100, 125, 150, 200 largest stems per ha. The thinned plot lacks 150 and 200 stems per ha. Based on measurements in 1956, 1962, 1972, 1981.

regenerated after wildfire in 1875. In 1928 when the stand was given a regeneration cleaning a small section was left untouched. Plots were installed then. In 1957 the thinned plot was subdivided and coppice was removed from one half and retained on the other half of the plot. The character of the stand before 1928 has been inferred from the diameter of the stumps and the use of crown ratios (Podger 1959). By 1928, the number of jarrah stems in the thinned plot had more than doubled and the b.a.o.b. was two thirds of that in the virgin stand. The 1928 thinning reduced stand b.a.o.b. by half, but by 1956 it had attained its previous level of 1928.

Detailed analysis of d.u.b. growth on these plots is possible only since 1956, when the Inventory and Planning Section of the Forests Department took over plot mensuration and bark thickness of each tree was first measured. When the 50 and 100 largest trees per hectare are considered, the growth rate of the trees in the thinned plot is superior to that in the unthinned stand (Fig. 31).

Lane-Poole (n.d.) suggested from the crown shy nature of jarrah that under intensive silviculture the aim should be to attain 50-60 trees of d.o.b. 60-70 cm ha^{-1} or a b.a.o.b. of 18 m^2 ha^{-1}. He realized correctly that root competition was more important than competition for light, a factor espoused by Richardson (*Annual Report* 1912). However, in contrast, Kessell and Stoate (1937) considered that competition for limited soil moisture had been over-emphasized.

The 1972 prescription (Forests Department 1972) dictated thinning to stand b.a.o.b. of c. 15 m^2 ha^{-1} with about 270 crop trees remaining per hectare. These regrowth stems are 50-70 years old and of d.o.b. 20-30 cm. Thinning to waste is costly and wasteful of wood resources assuming the availability of future markets for currently unutilized wood (Stoneman unpublished data). However, thinning a jarrah stand to waste at age 40 years is a sounder financial operation than leaving a pole stand unthinned until enough trees of saleable size are available to cover the cost of a thinning operation (Kimber 1965).

In earlier times, doubts were frequently expressed about clear-felling or heavy thinning of jarrah stands. Trees were regarded as developing more side branches, and increasing diameter increment at the expense of wood quality (Stoate and Wallace 1938). Evidence for this comes from jarrah in open-grown plots established at East Kirup in 1941 and at Inglehope in 1965, but only for trees on the edge of these plots.

Young jarrah regrowth was stated to grow straighter under a light shelterwood or in comparatively small openings in the forest than in extensive openings from which practically every member of the original stand had been removed (*Annual Report* 1937). However, this view fails to recognize the importance of regrowth density in that good form can be attained with wider spacing between regrowth stems in small gaps than is possible in larger gaps (Jacobs 1955). The clear-felling system applied to jarrah was considered undesirable (Lane-Poole, n.d.) because seed years are too far apart.

Therefore, Lane-Poole endorsed a clear-felling system with seed trees, although this method might destroy useful immature growing stock.

The cutting down of potentially useful 20 to 50-year-old trees in order to attain an even-aged stand over a whole compartment was considered too prodigal (Lane-Poole n.d.). Nevertheless, clear-felling was practised at Collie to supply firewood for mining, and much of the catchment of Mundaring Reservoir was ring-barked by the Public Works Department in 1903. Furthermore, as noted in Chapter 10, parts of the forest close to mills and railways were clear-felled before 1919.

Self thinning of overstocked regrowth stands probably occurs during centuries of time as a result of both fire and suppression due to competition for soil moisture. Low intensity fire hastens the death of dominated trees without affecting the crowns of the codominants (Harris 1956). Without fire, however, none of the dominated and suppressed trees in a pole stand in Holmes block, Dwellingup died (Abbott and Loneragan 1983c). Suppression of the weaker individuals from competition results in the separation of individual trees into dominants, codominants, sub-dominants, dominated and suppressed (Opie *et al*. 1978). The proportion of dominant and codominant stems decreased from 34 per cent to 21 per cent over 16 years in the long-unburnt Holmes pole stand. In a 38-year-old regrowth stand in Holyoake block, 90 codominant trees marked in 1952 had, by 1981, sorted out into six dominants, 20 sub-dominants and one suppressed. Four had died and 59 (66 per cent) remained codominant.

Stagnation in growth of dense, uniform stands of regrowth may occur three or four times per century (Wallace and Podger 1960). The first occurs in dense sapling stands some 10-15 years after regeneration, and the next when the main crowns form at the pole stage. At these times considerable abrasion of crowns occurs, and thinning before both stages are reached would be useful. However, the precise details about when to thin jarrah stands are not known. The application of O'Connor's correlated curve trend method (Marsh 1957) would be difficult given the irregularity of jarrah stands.

The process operating in jarrah forest may be inferred from describing stand structure, but the method is not totally reliable (Abbott 1984b). Two models may be applied. In the first, disturbances are regarded as small and infrequent relative to the degree of competition experienced among trees in the stand. The presence of relatively few smaller diameter classes could thus indicate strong competition from the existing overstorey. Alternatively, competition may be less important than continual and ubiquitous disturbance. In this case, the presence of relatively few small diameter classes implies that there has been little recent disturbance. Stand structure in both virgin and cut-over jarrah stands is diverse (ch. 9; Abbott 1984b).

In virgin forest, advance growth persists indefinitely in a dormant condition (van Noort 1960). Growth of ground coppice is very rare, even though the numbers of dormant ground coppice and earlier stages practically doubled over 20 years (van Noort 1960). Advance growth is concentrated under gaps in the canopy, with the highest concentration on old ashbeds.

When virgin jarrah forest is logged, recruitment comes not from seed but from existing ground coppice, saplings, poles and stump coppice. Seedlings, lignotuberous seedlings or seedling coppice do not immediately form saplings. Instead, shoots grow from the lignotuber resulting in a hemispherical multi stemmed bushy shrub < 1 m in height (Harris 1956), until released later for regrowth development.

Ground coppice only develops into the sapling stage when the lignotuber attains a diameter of c. 10 cm (Campbell 1956) or long axis of c. 15 cm (Abbott and Loneragan 1984b). In the absence of any adversity, a seedling in typical fully-stocked stands takes 15-20 years to attain this lignotuber size (van Noort 1960; Abbott and Loneragan 1984b). If the logging is very light, ground coppice does not respond although many seedling coppice may develop (Abbott and Loneragan 1984b). Halving of the stand b.a.o.b. results in about one-third of ground coppice developing into saplings (Abbott and Loneragan 1984b). It then takes 5-6 years for dynamic ground coppice to reach 5 m in height (Campbell 1956).

The deep, infertile soil of the jarrah forest (ch. 4) may be responsible for the early slow development of jarrah regeneration. There is a need to establish whether the lignotuber size of 15 cm corresponds to the time when the roots gain access via fissures to underground supplies of water.

Because of the great age of trees in virgin forest, a long period of decline is probably the rule (Harris 1956). This provides an opening of the canopy and a long regeneration period during which the new crop of advance growth establishes under the parent stand (Table 44). That is, the decline and not necessarily the death of a veteran tree reduces competition sufficiently to allow development of the dynamic shoot. In the small openings caused by the deaths of individual trees, Harris (1956) noted abundant regrowth consisting of from 3-20 codominant stems. Such groups were observed to be scattered throughout virgin forest; this is expected from the patchy nature of regeneration (see Table 44).

An experiment in Amphion block (Kimber unpublished data) to determine whether fire or removal of shoots stimulates advance growth into producing a dynamic shoot found no effect. However, no lignotubers were measured, so it is difficult to be sure that all of the advance growth was actually incipient ground coppice. The length of the longest shoot grown between October 1965 and May 1967 ranged from 62.2 cm (all stems cut off) to 80.0 cm (control).

Harris and Wallace (1959) speculated that areas of dense regrowth stands along the older logging railways had developed, not in spite of, but because of the regular light burning caused by locomotives lacking spark arresters in earlier days. Bradshaw (personal communication*) disagrees and suggests that lack of competition may have been the critical factor.

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Table 44

Regeneration in virgin and cut-over jarrah forest (data of Stoate and Helms 1938).

% milacre plots without regeneration	N(*a*)	Stages of Regeneration (*b*) (numbers ha^{-1}) 2+3	4a	4b	10a	10b	Total jarrah	Marri (*c*)
Cut-over forest								
69.3	730	198	52	859	188	106	1403	388
63.0	896	872	37	640	67	72	1688	531
64.8	1586	835	69	881	170	143	2098	654
62.5	624	205	89	1163	244	119	1820	2212
88.0	274	62	10	800	10	10	892	514
45.2	230	516	215	956	684	259	2630	558
68.0	200	617	86	531	25	12	1271	37
77.0	180	138	15	247	207	30	637	1180
38.7	80	1047	0	2746	0	0	2793	0
Virgin forest								
64.0	500	632	25	677	-	-	1334	99
62.0	500	825	15	484	-	-	1324	69
34.4	500	4637	10	3694	-	-	8341	543
35.0	500	1254	30	3081	-	-	4365	104
36.2	500	978	15	2607	-	-	3600	188
60.0	500	677	25	1457	-	-	2159	59
82.0	500	365	0	336	-	-	701	2

(*a*) No. milacre quadrats.

(*b*) Stages of regeneration: 2+3 = lignotuberous seedling + seedling coppice
4 = ground coppice; a, with leader; b, no leader
10 = stool coppice; a and b as above

(*c*) Marri was not differentiated into stages

Note that seedlings (stage 1) were excluded.

What is reasonable regeneration?

Early foresters were concerned most about stocking of the early stages of regeneration in the jarrah forest. This was quantified by using milacre quadrats in both cut-over and virgin stands (see Table 44). The percentage of milacre quadrats without regeneration varied from 30 to 88 per cent in cut-over stands and from 35 to 82 per cent in virgin stands. The number of jarrah regeneration (stages (2)-(4)) ranged from c. 1000 to 8000 ha^{-1}.

Stoate[+] regarded a milacre quadrat as stocked if one or more seedlings (Stage (1)) were present. Four degrees of stocking were recognized:

- bare (0 seedlings/milacre quadrat) i.e. 0 ha^{-1}
- inadequate (< 3/milacre quadrat) i.e. < 7400 ha^{-1}
- adequate (3-6/milacre quadrat) i.e. 7400-14 800 ha^{-1}
- overstocked (≧ 7/milacre quadrat) i.e. ≧ 17 000 ha^{-1}

Stoate and Helms (1938) stated that 2470 ha^{-1} of stages (1)-(4) *evenly distributed* is satisfactory stocking. Bednall (1938) also assumed 2500 seedlings and seedling coppice (i.e. stages (1)-(3)) would be sufficient if spaced regularly; as this does not occur, he assumed spacings of 0.61 m, equivalent to c. 12 000 ha^{-1}.

The regeneration cleaning program of the 1930s allowed regeneration blanks (space for regeneration) to be as narrow as 20 m from stem to stem at the narrowest point. This left a minimum hole in canopy between the crowns of the two nearest trees of 3-5 m (Lane-Poole n.d.).

An inventory of some 200 000 ha of cut-over jarrah forest in c. 20 years after the original cut showed (*Annual Report* 1955) that all forest (of mean mature codominant height ≧ 28 m) regenerates satisfactorily on the basis of 3.7 m x 3.7 m. This, however, includes the seedling coppice. In lower quality stands, regeneration is generally satisfactory at 5.5 m x 5.5 m spacing.

The causes of poor regeneration and differences between site-vegetation types in the amount of regeneration are not well known. Contributory factors probably include site differences in competition from the overstorey (for nutrients and water at depth) and fire which kills seedlings, seed trees, and advance growth when lop and top is burned (Stoate and Helms 1938).

Determination of adequate stocking should, however, take into account all sizes of jarrah from advance growth to the largest trees. A stand was considered to be stocked if it carried one of the following (Kimber 1970):

	(1) d.o.b.'s 36-73 cm	at 148 stems ha^{-1}
or	(2) d.o.b.'s 13-35 cm	at 295 stems ha^{-1}
or	(3) saplings (3 m tall - d.o.b. 12 cm)	at 295 stems ha^{-1}
or	(4) large ground coppice with at least 6 shoots, with the longest exceeding 60 cm	at 1034 stems ha^{-1}
or	(5) small ground coppice (longest shoot > 30 cm)	at 1477 stems ha^{-1}
or	(6) combinations of the above to give the equivalent number ha^{-1}.	

The above is somewhat awkward to use because the elements of the classification do not match those

+. Forests Department file H.O. 190/32.

advocated in this Bulletin (ch. 7). Trees of d.o.b. > 73 cm are considered mature and ready for logging, and have therefore been omitted from the above assessment of stocking. Kimber (1970) thought that a level of 65 per cent stocking is the lowest acceptable. Below 65 per cent, the stand would be considered under-stocked. Treatment to establish regeneration (as described earlier) would then be necessary.

Ways of raising productivity in jarrah forest

The main factor contributing to low productivity of jarrah stands is understocking of good, healthy growing stock (Kimber[+]). Paradoxically, most high quality stands are overstocked with useless jarrah and to a lesser extent with a less desirable species (marri).

Until the 1960s most knowledge about stand development and productivity was observational. Little silvicultural research had been attempted, probably for reasons specified by Stoate (1953). Manipulative experiments on thinning, fertilization, crown scorching and control of seeding (*Annual Report* 1970) demonstrated the vast potential for increasing forest productivity on a broad scale. At present only \$0.43 ha^{-1} is spent on jarrah silviculture in contrast to \$4.88 ha^{-1} for karri and \$505 ha^{-1} for pines (Western Australian Parliament 1982). This partly reflects continuing doubt about the long term security of the northern jarrah forest in the face of dieback and bauxite mining.

The most valuable present and potential crop trees need to have their growing space and their crowns improved. Current thinking in the Department of CALM is that selected high quality regrowth stands in areas designated for timber production should be thinned to a b.a.o.b. as little as 10 m^2 ha^{-1} until they reach sawlog size (Bradshaw 1986). Although this results in very little loss in stand basal area growth, this is not crucial because of the faster diameter growth of the crop trees. There is a need to conduct research on the use of N fertilizer at these low stand basal areas. The combination of fertilizer and such heavy initial thinning should result in relatively rapid growth rates. Furthermore, if fertilizing were repeated at each thinning, then rapid growth should continue while the stands are fully stocked. Such a system is already partially applied to some *Pinus pinaster* plantations on the coastal plain near Perth.

There is a need to ensure that some superior trees are left in the forest as the parents for subsequent crops. Repeated thinning of stands would achieve this by leaving behind the best trees. This contrasts with the possible long term deterioration in stand quality following the removal of desirable trees in selection logging.

The production of timber that is free of tension wood and has the most desirable grain (straight or curly) also requires attention.

+. Forests department file H.O. 14/69.

CHAPTER 12

Adverse Influences and Causes of Death

In this Chapter we review natural factors that harm or kill jarrah, from seed to over-mature tree. These damaging agents include fire, drought, frost, wind, insects and fungi. This Chapter therefore indirectly examines those factors governing the healthy growth of jarrah. We do not discuss unnatural factors incompatible with conservation of the forest, namely land uses such as mining, agriculture, rights of way, and settlement in towns. An early assessment of external damages (Lane-Poole n.d.) was that

> 'Man, his stock and his fire stick, are the only serious dangers that jarrah forests have to face... Its extraordinary capacity of surviving has enabled this species to persist when a less hardy tree would have long ago been wiped out...'

There have been few specific studies of population dynamics of jarrah of the kind where a population of tagged individuals is monitored over a period of time. However, much of the growth data collected by the Inventory and Planning Branch of the Forests Department are based on tagged trees in well-defined plots. We use these later to quantify mortality of jarrah in relation to d.o.b. and site quality.

As is the case with most tree species, the survival curve of jarrah is positively skewed rectangular, with high juvenile mortality and low mortality thereafter. Most mortality of seedlings occurs before the first summer (Abbott and Loneragan 1984b). After that jarrah copes successfully with many harmful factors. Indeed, before arboricides became available, Harris (1956) noted that attempts to kill jarrah were usually abortive. The physiological age attained by jarrah is estimated to be 800-1000 years (Jacobs 1955).

Fire

Fire is a natural part of the jarrah forest environment. Almost certainly during the past 100 000 years or so there have been marked changes in the fire regime experienced by the jarrah forest. These regimes should have differed in the season, intensity, and frequency of fire.

On current knowledge, Aboriginals were absent from south-western Australia until c. 40 000 years ago (Pearce and Barbetti 1981). Before that the only source of fire was lightning. Forests Department records show that lightning strikes are a regular feature of each summer in the jarrah forest (Table 45). During a period of 33 years, the number of fires caused by lightning was 445 ranging from 0 to 85 per year. No obvious periodicity is evident, with most fires occurring in 1940-1, 1943-4, 1950-1, 1953-4, 1958-9, 1960-1, and 1961-2. Fires started by lightning do not occur randomly. A tally of such fires recorded in a 21-year period from 1939-40 to 1960-61 in each Forest Division shows the following (*Annual Report* 1961): Mundaring Division, 29 (most fires 1953-4, 1960-1); Gleneagle (Jarrahdale) Division, 41)1953-4, 1958-9, 1960-1); Dwellingup Division, 107 (1940-1, 1943-4, 1950-1, 1953-4, 1958-9, 1960-1); and Harvey Division, 32 (1960-1). The main lightning belt in the northern jarrah forest passes south-west from Jarrahdale and north of Dwellingup through Wuraming (Stoate 1953). Once Aboriginals colonized Western Australia, their regular use of fire (Hallam 1975) mainly in summer (Abbott and Loneragan 1983b) and possibly every year and at least every 3-5 years (Harris and Wallace 1959) must have had profound effects on the flora and fauna present 40 000 years ago. Such a regular fire regime would not have allowed excessive accumulation of fuel. Moreover, the crowns of the virgin (unlogged) jarrah forest were

Table 45
Number of fires caused by lightning in State Forest, from 1937-8 to 1969-70.

Year	No. lightning fires	Total no. fires recorded
1937- 8	1	381
1938- 9	6	408
1939-40	3	386
1940- 1	26	440
1941- 2	10	200
1942- 3	1	149
1943- 4	22	517
1944- 5	3	363
1945- 6	1	356
1946- 7	3	252
1947- 8	4	278
1948- 9	4	527
1949-50	6	569
1950- 1	19 (17 from 1 storm)	217
1951- 2	6	324
1952- 3	3	289
1953- 4	34 (28 from 1 storm)	324
1954- 5	8	278
1955- 6	7	313
1956- 7	13	359
1957- 8	14	530
1958- 9	42	434
1959-60	3	232
1960- 1	85 (19 from 2 storms)	398
1961- 2	62	463
1962- 3	9	231
1963- 4	16	281
1964- 5	5	214
1965- 6	6	251
1966- 7	6	365
1967- 8	10	248
1968- 9	0	252
1969-70	7	294

Source: Forests Department *Annual Reports* 1938-1970.

high enough above ground to escape damage from fires started by Aboriginals or lightning (Harris and Wallace 1959).

With permanent settlement by Europeans in 1829, the Aboriginals were forced to leave the south-west. Therefore, over a period of 30-50 years there was a gradual change in fire regime to one of fewer fires lit by humans. When lightning strikes occurred or fires escaped from farms, they would have attained a higher intensity after advancing into the fuels that had accumulated in State Forest. During the period of great expansion in agricultural settlement and logging of the forest (1880-1920) such fires became more frequent, more extensive, and more damaging to the forest canopy (Harris and Wallace 1959). This made the jarrah forest 'the ugliest and most deformed stand in Australia' (Lane-Poole n.d.).

One of the first priorities of the Forests Department was to bring fire under control (Hutchins 1916), which in effect meant excluding fire from the forest except under special circumstances (ch. 11). From about 1927 high quality forest was subdivided into compartments and the regenerating cut-over stands were protected from fire by 100-m-wide firebreaks which were burnt every three years (Forests Department 1927). Forests around sawmills and towns were burnt annually if possible in order to reduce the chance of fire destroying property. Next, lookout towers were constructed, fire suppression techniques were developed, and weather conditions conducive to fire were forecast (Wallace 1936).

In the early days, before effective fire protection, the eastern boundary of the jarrah forest was recognized as the most critical because the fiercest fires always came from that direction (Forests Department 1927). In 1938 three arbitrary zones of fire control were instituted (*Annual Report* 1938).

The A zone covered all reforested areas and was given complete protection from fire. In the B zone (virgin forest and cut-over forest not yet regenerated) fires were suppressed as soon as possible. The C zone covered that farthest removed from protected forest and was not subject to organized forest fire suppression. In 1939 emphasis in the Forests Department changed from regeneration cleaning (ch. 11) to fire control, following severe damage resulting from fires during the 1930s (Stewart n.d.). By 1950 there were so many ring-barked trees in the forest and fuel loads had increased to such levels that containment of most fires following lightning strikes or other causes became impossible. The use of low intensity fires for regular fuel reduction then became routine (Campbell 1971; Underwood and Christensen 1981). This fire regime is believed to approximate that used by Aboriginals (Abbott and Loneragan 1983b). Wollaston's (1841) remark that 'For 50 miles through the forest a tree is hardly to be found, which had not the mark of fire upon it' is still true today. In recent times most wild fires have been caused by farmers' burning off, locomotives and travellers (Royal Commission 1951; Wallace 1966). At present most wildfires are lit by the public either deliberately or by accident (G. Peet personal communication*).

Jarrah is remarkably resistant and tolerant to fire, as evidenced by the thick fibrous bark of older stems, by how quickly most of the young stages re-coppice from the lignotuber and by how quickly epicormic shoots develop when the crown has been destroyed by fire (Kimber 1971; McArthur 1968). Early popular opinion was that fire does little harm to the jarrah forest, and actually does good (Royal Commission 1903; Stoate and Helms 1938).

In contrast, professional opinion emphasized the detrimental consequences of fire: damage to the bole, including fire scars, gum pockets and hollow butts; death of trees caused by lethal temperatures being reached in the cambium; temporary defoliation and reduction in cambial activity of the stem causing deterioration of the crown and temporary decrease of diameter increment; intensified attack of insects and fungi; lowered soil fertility because of combustion of leaf litter and humus; and malformation of regrowth (Kessell 1921b; Stoate and Bednall 1940; Harris and Wallace 1959).

Malformation and bole defects were the most obvious damage, causing loss of saleable timber. Kinks in the stem from 2-5 m above ground represent the destruction of the leading shoot and therefore loss of 3-4 years' height growth. Each kink results in a 'gum pocket' or 'bad heart'. Gum or more correctly kino is an aqueous solution of polyphenols retained in pockets in the xylem (Nelson and Hillis 1978). Epicormic branches (so called 'greedy branches') formed after higher intensity fire also result in gum pockets along the length of the trunk. The occurrence of crooked trees, double crowns and lack of regrowth were also blamed on fire (Lane-Poole n.d.). Damaged crowns of the overstorey trees were also thought to have caused the density of ground flora and understorey

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*. G. Peet - Department of CALM, Kelmscott.

trees to increase (Harris and Wallace 1959). Following regeneration cleaning (ch. 11), there was to be adequate fire control to prevent malformation of regrowth. Details of the technique of burning lop and top are provided by Forests Department (1927) and Harris (1936). Harris and Wallace (1959) state that

> 'Chronological studies have indicated that there was virtually no damage to the tree bole over several centuries and most of this type of defect is seen within the last hundred years of growth'.

No fire scars were observed (Stoate and Bednall n.d.) on the interior surface of recently cut stumps, these being found only on or near the periphery of such stumps. Thus, severe fire damage was not experienced by jarrah trees before European settlement. The kinds of damage to trees expected in jarrah forest under various ranges of fire intensity are summarized and illustrated by Underwood and Christensen (1981). The major criticism of earlier discussions of fire in the jarrah forest is that fire is poorly characterized or documented. This is because precise characterization of fire behaviour was not possible until Byram developed an index in 1959 (McArthur and Cheney 1966). This was first applied to the jarrah forest by Peet.

(a) Effect of fire on forest composition
Despite jarrah being the main overstorey tree species of the forest (see ch. 9), seedlings of marri survive better than those of jarrah (Abbott 1984a). The reason that marri does not replace jarrah in the overstorey is that it is more susceptible to fire than jarrah (Kimber 1971; Table 46). The dominance of jarrah is therefore attained after the seedling stage.

(b) Effect of fire on growth rate
All early opinion was that fire retarded the growth of jarrah (*Annual Report* 1910; Lane-Poole n.d., 1921). This is correct in that height growth of small regrowth is impeded by fire. However, fire does not decrease diameter growth of jarrah poles, piles and trees (see ch. 7). The suggestion of Kessell (1921b), that the finer roots are scorched by fire, requires further study in relation to fuel, seasonal conditions and fire intensity.

(c) Effect of fire on seedfall and regeneration
Moderate intensity fire that scorches the crowns of jarrah trees decreases the production of seed capsules, with 88 per cent of unscorched trees and only 37 per cent of scorched trees producing a

Table 46

Comparative mortality of jarrah and marri after the 1961 Dwellingup wildfire (data of Peet and Williamson, 1968). Based on 220 randomly located 0.4 ha plots.

Type of crown damage	Species	% of total volume ha^{-1} (d.o.b. >30 cm) killed by fire
Defoliated	Jarrah	11.7
	Marri	23.1
Fully scorched	Jarrah	7.6
	Marri	12.4

crop of seed capsules (Kimber 1978). Benefits of lower intensity fire include (Gardner 1923) seedfall, preparation of the seedbed, improvement in light intensity and destruction of parasites on the ground. However, it was recognized that any seed already present on the ground was destroyed by fire. The fact that seedlings are more easily seen on burnt ground was thought (Stoate 1923) to be the reason behind the assumption that burning was beneficial. Stoate speculated that seedlings in unburnt forest may be protected from high temperatures during summer by leaf litter.

Jarrah seedlings are susceptible to fire until the lignotuber is adequately developed (Harris 1956; Abbott and Loneragan 1984b), about two to three years of age. Experimental studies with both low and high intensity fires showed that no plants with well-developed lignotubers were killed, agreeing with the statement that fire 'will not greatly affect advance growth or seedlings over two to three years of age' (Campbell 1956). Such plants simply redevelop the shoots from the lignotubers after fire. However, under dry soil conditions as in autumn fires, some lignotubers would be killed.

The effect of long term exclusion of fire on regeneration has been studied in two compartments in Amphion Block, Dwellingup (Kimber unpublished data). A quadrat (consisting of four adjacent milacre quadrats) was defined as either unstocked (jarrah absent) or stocked (jarrah present). Three separate size classes of regeneration were recognized on the basis of the length of the tallest shoot (0-15 cm, 15-61 cm, > 61 cm). The two compartments differed ostensibly only in their fire histories, with one having been unburnt for 30 years since 1932, the other experiencing several low intensity fires since 1955. There was no significant difference in stocking of the 0-15 cm size class between compartments (Table 47). For the 15-61 cm class, there were significantly more stocked quadrats in the unburnt compartment. The converse applied for the largest size class. It is thus difficult to draw any firm conclusions from these data.

A second study (Kimber unpublished data) was more extensive. In each

Table 47

Number of quadrats (4 m^2) with or without jarrah plants of size specified. Amphion 6, unburnt since 1932; Amphion 7, several prescribed low intensity fires.

Locality	Height class *(a)*	Stocked	Not stocked	N
Amphion 6	0-15 cm	105 (50%)	103	208
Amphion 7	0-15 cm	31 (51%)	30	61
Amphion 6	15-61 cm	125 (61%)	79	204
Amphion 7	15-61 cm	27 (44%)	34	61
Amphion 6	> 61 cm	70 (34%)	138	208
Amphion 7	> 61 cm	62 (57%)	47	109

(a) Length of tallest shoot.

area a transect was established. The first quadrat (4 m^2) was selected at random and thereafter all quadrats were at 20 m intervals. Seedlings younger than one year were excluded from study. The findings (Table 48) do not unequivocally show that fire limits regeneration. The weakness of both these experiments is that undescribed differences between localities in, for example, seed production may have confounded the effect of fire history.

Table 48

Regeneration in jarrah forest in relation to fire history.

Locality	Fire History	Height class (a) (N ha^{-1}) 0-15	15-61	> 61
Plavins 4	Normal prescribed burn regime	1064	1499	
Amphion 7	" " " "	988	677	1244
Amphion 8	No fire for 30 years	1277	1138	407
Banksiadale	(annually burnt firebreaks, up to 10 years earlier)	1812	247	64

(a) Length of tallest shoot (cm).

The most convincing data come from an experiment inaugurated in November 1955 (J.B. Campbell, unpublished data). Fifty milacre quadrats were marked out in an area of Plavins block that experienced a wildfire in 1950. In all but one quadrat ten lignotuberous seedlings varying in age from 2.5 to 5 years were tagged. Twenty-five quadrats were set aside as controls. Then, each November, five different quadrats were subjected to a low intensity fire. The number of tagged plants alive was counted each November until November 1960. The experiment was destroyed by a wildfire in January 1961.

Mortality was always higher in the burnt treatments than the control (Table 49). Details are as follows: per cent mortality = 3.2 (control 1957), 31.8 (burnt Nov. 1956), $P>0.05$ by χ^2 test; 14.7 (control 1958), 73.2 (burnt Nov. 1957), $P<0.001$; 12.2 (control 1959), 61.5 (burnt Nov. 1958), $P<0.05$; and 25.3 (control 1960), 73.5 (burnt Nov. 1959), $P<0.05$.

(d) Effect of fire on tree form

Lane-Poole (n.d.) considered that many 3-m tall saplings of jarrah had often been burnt, as evidenced by kinks at close distances along the stem. Between 3 and 6 m the kinks were a little farther apart because of the greater height growth. Fire had killed the leading shoot, but the new one made was never a prolongation of the old, giving the stem a dog-leg shape.

Stoate and Helms (1938) drew attention to the obvious reduction in merchantable log volume, from 23 to 65 per cent. In the plots studied by them in virgin forest in Chalk block, the percentage of merchantable trees that were damaged by fire ranged from 10 to

Table 49

Mortality of lignotuberous seedlings in relation to low intensity fire. Prefire counts are italicized.

Treatment	No. alive (% mortality) in November						% mortality
	1955	1956	1957	1958	1959	1960	
Control (No fire)	247	218 (11.7%)	211 (3.2%)	180 (14.7%)	158 (12.2%)	118 (25.3%)	52.2%
Burned Nov. 1956	*50*	*44* (12.0%)	30 (31.8%)	30 (0)	25 (16.7%)	17 (32.0%)	66.0%
Burned Nov. 1957	*50*	*44* (12.0%)	*41* (6.8%)	11 (73.2%)	10 (9.1%)	8 (20.0%)	84.0%
Burned Nov. 1958	*40*	*33* (17.5%)	*29* (12.1%)	*26* (10.3%)	10 (61.5%)	6 (40.0%)	85.0%
Burned Nov. 1958	*47*	*42* (10.6%)	*38* (9.5%)	*37* (2.1%)	*34* (8.1%)	9 (73.5%)	80.9%

82 per cent. None of these writers defined the intensity of the fires causing this damage.

Jarrah is sensitive to fire from the time the dynamic sapling emerges until it reaches a height of c. 5-6 m (Campbell 1956). At this height the bark of the stem is thick enough to allow the plant to withstand a low intensity fire. According to Harris (1956), this corresponds to a period of c. 8-10 years after release, when the lower level of the crown is c. 4 m above ground level.

Mortality of sapling crowns (2.4 m average height, range 1.1-5.3 m) varies directly with fire intensity (Peet and McCormick 1971). For example, a fire intensity of 67 kW m^{-1} killed nearly 30 per cent of sapling crowns. The crowns of most saplings < 3 m and all saplings < 1.2 m in height were killed by such a mild fire. Peet and McCormick (1971) recommended the following fire intensities:

Mature stands	< 167 kW m^{-1}
pole stands	< 100 "
5-6 m tall saplings	< 67 "
4-5 m " "	< 40 "
< 4 m " "	no fire

In practice the Forests Department condones intensities of up to 300 kW m^{-1} in mature stands and pole stands, mainly because they are overstocked: such fires help to thin dense stands of dominated poles and stagnant saplings (Harris 1956; Harris and Wallace 1959). The values of fire intensity just quoted may be compared with that obtained during wildfire (> 10 000 kW m^{-1}).

The effect of both low and higher intensity fires on the crown, bole, wood density, fibre length and kino veins of jarrah poles was studied by Nichols (1974). Low intensity fires caused no external damage and were not detrimental to wood quality. In contrast, higher intensities caused scorching of most crowns, damage to the bole, and formation of kino veins.

The intensity of fire increases under certain weather conditions and a heavy accumulation of leaf litter. Where heat penetrates the bark it kills underlying cambial cells, resulting in a fire scar, known locally as a 'dry side' when it extends along the bole. As the bark dries out the sapwood becomes exposed to weathering and attack by insects and fungi. With further drying out this leads to the development of cracks into the heartwood, borer holes, and rot in the sapwood. Callus (wound tissue, growth developed from the fringe cells and over the scar) and kino veins (where the epicormic shoots were attacked) are other more visible effects appearing on fire damaged limbs and boles.

Unpublished studies by O. Loneragan in Plavins block after a wildfire in February 1950 showed that when the tops of small poles were killed back from 11 m to 5 m, the bole was deformed and the growth wasted. Where height was reduced from 16 m to 15 m, the shape of the main bole was not altered.

More recent studies of the effect of fire on wood (McCaw 1983b) were based on the felling of 13 fire-scarred poles of d.o.b. 23-26 cm. Sapwood behind the dead area of cambium was affected by fungal decay and termite attack, but decay was confined to the wood present at the time of injury. Over a period of 30 years most wounds had occluded completely, although our studies in stands affected by the 1961 wildfire at Dwellingup showed that external evidence was still detectable after occlusion (see below). Kino veins, a major source of degradation to the timber of jarrah, are associated with fire scars, being localized to the zone of dead cambium (McCaw 1983b). In contrast, Podger and Peet (cited by McArthur 1967) found little evidence that formation of kino veins was related to fire.

Wildfire caused 17 per cent of tagged poles in a plot in compartment 10 of Holmes block to experience damage to the bole. Of 90 codominant poles tagged in Holyoake block, 16 per cent were dry-sided. Only one tree had fully occluded the dry side 20 years later. In another stand in Holyoake block, 24 per cent of 51 crop trees tagged before the 1961 wildfire experienced fire damage.

A comprehensive study of stand recovery two to four years after the 1961 Dwellingup wildfire was made by Peet and Williamson (unpublished data; see also Peet 1965). They stratified the forest into four types and sampled each with 0.4 ha plots. Defoliated stands (100 plots) suffered complete defoliation, and consisted of bare black stems and black ground. These stands covered c. 26 000 ha. In fully scorched stands (220 plots) all leaves were scorched but some trees were defoliated. These stands covered c. 77 000 ha. In stands experiencing less damage (50 plots), only the lower parts of the crowns were scorched. These stands covered 43 000 ha. In addition 45 plots were installed in 32 000 ha of control burnt forest to the east of the wildfire.

The volume of timber killed varied according to whether it was merchantable or not, and was also related to the severity of the fire (Table 50). Most merchantable trees that were defoliated or fully scorched replaced their crowns. Defoliated non-merchantable trees, although remaining alive, tended to lose their crowns permanently. Trees of smaller d.o.b., the young growing stock, fared worse: most in the defoliated stands did not replace their crowns (Table 50). This is not so important for the so-called surplus trees, which lie beneath the forest canopy and are so positioned as to be superfluous to the stand on a 6 m x 6 m

Table 50

Effect of the 1961 Dwellingup wildfire on volume and number of stems ha^{-1} (data of Peet and Williamson, unpublished)

d.o.b. (cm)	Feature	Type of fire damage: Defoliated	Fully scorched	Lesser damage	Control burn
≥ 30	Merchantable volume (*a*)	% of total v.u.b. m^3 ha^{-1}			
	Crown replaced (*b*)	70	88	100	100
	No crown. Bole epicormics only	22	9	0	0
	Tree killed	8	3	0	0
	(Total v.u.b.	64.5	61.6	41.4	44.3)
	Non-merchantable volume	% of total v.u.b. m^3 ha^{-1}			
	Crown replaced (*b*)	31	57	87	99
	No crown-bole epicormics only	41	18	0	0
	Tree killed	28	24	13	1
	(Total v.u.b.	15.8	16.0	21.3	20.0)
< 30	Potential crop trees	% of total no. stems ha^{-1}			
	Crown replaced	43	74	97	92
	Crown dead (*c*)	57	26	3	8
	(Total N ha^{-1}	253	185	236	220)
	Surplus trees	% of total no. stems ha^{-1}			
	Crown replaced	13	30	58	51
	Crown dead (*c*)	87	70	42	49
	(Total N ha^{-1}	474	405	599	450)

(*a*) Includes trees which were burnt down or had suffered severe bole damage but still retained a useable log.
(*b*) These trees can also have epicormic growth on the bole.
(*c*) Tree not necessarily dead.

spacing. Fire damage to the growing stock was least in the control burnt stands. Thus, these data suggest that the lowering of fire intensity to an acceptable level would benefit the stand by killing the worthless and surplus trees. The amount of crown recovery is related to the degree of crown damage and natural vigour. These differences probably result partly from differences in bark thickness before the fire.

McArthur and Cheney (1966) produced a very useful graph relating the proportion of the final crop of jarrah that has experienced physical damage to fire intensity. The graph shows that a low intensity fire of 300 kW m^{-1} should cause nearly 20 per cent damage to a pole stand whereas a moderate intensity fire of 1200 kW m^{-1} should result in nearly 60 per cent damage. McArthur and Cheney (1966) suggested at 50 per cent physical damage there would be enough trees remaining for the final crop, though most would carry severe fire scars and at least 20 per cent of timber would be degraded.

Fire damaged trees are generally of smaller diameter and have thinner bark than trees remaining undamaged (Table 51). In practical terms this means that sub-dominant and dominated trees in the forest are more likely to develop fire scars than codominants and dominants.

The degree of crown scorch obtained from a prescribed low intensity fire in November 1971 north of Dwellingup was studied 3-4 months later (McCormick 1972). Most of the crown scorch (to a height of c. 3 m) took place in the smallest d.o.b. class (Table 52). In the larger d.o.b classes most individuals were unscorched.

Finally, an experiment relating bark thickness and d.o.b. to the surface area of the bole killed by fire was conducted by Peet and McCormick (unpublished data). Thirty plots, each with five dominant or codominant jarrah poles, were marked out near Dwellingup. Five plots were grouped into a block, and four treatments were applied randomly to each block: 'hot' fire in spring, mild fire in spring, 'hot'

Table 51

Mortality of, and damage to, jarrah caused by the 1961 Dwellingup wildfire in relation to d.o.b., bark thickness (b.t.), or both.

Stand	Dead	Alive: Fire damaged	Alive: Undamaged
Holmes 10 (litter plot)			
d.o.b. (cm) (*a*)	15.6	24.6	26.9
b.t. (cm) (*a*)	2.3	2.7	2.9
N	45 (37%)	20 (17%)	56 (46%)
Holmes 10 (fire plot)			
d.o.b. (cm) (*b*)	15.7	18.5	21.6
N	15 (20%)	19 (23%)	45 (57%)
Holyoake (plot 28)			
d.o.b. (cm) (*c*)	14.9	38.2	23.2
N	12 (27%)	12 (27%)	21 (46%)

(*a*) measured 1959
(*b*) measured 1948
(*c*) measured 1961 before the fire

Table 52

Crown scorch of jarrah after low intensity fire in relation to d.o.b. and individual importance in the stand.

Importance Class	d.o.b. (cm)	Degree of crown scorch (% of N in class d.o.b.): Unscorched	Half Scorch	Full Scorch	Defoliated	N stems ha^{-1}
Crop trees						
	0.8- 2.4	47.0	15.3	36.9	0.7	133.8
	2.4- 4.9	87.0	5.3	7.7	0	70.4
	4.9- 9.7	95.1	1.8	3.2	0	70.1
	9.7-19.4	94.4	2.2	3.4	0	22.0
	19.4	96.8	0	3.2	0	7.7
Suppressed trees						
	0.8- 2.4	40.8	12.1	46.4	0.7	201.7
	2.4- 4.9	86.5	6.4	7.1	0	65.9
	4.9- 9.7	92.6	2.9	4.4	0	33.6
	9.7-19.4	95.2	4.8	0	0	5.2
	19.4	100.0	0	0	0	4.0

fire in autumn, mild fire in autumn, and no fire. A 'hot' fire was achieved by heaping slash to c. 1 m around the base of each tree. These heaps burnt out after 14 minutes. The area of fire scar was measured after the dead bark was removed.

Three of the poles given the 'hot' fire were killed (33 per cent mortality). Linear regressions (Table 53) were calculated between d.o.b., bark thickness, and surface area killed. The last was also expressed as a percentage of surface of a log 2.4 m long. Extent of the fire scar is related to d.o.b. and bark thickness before the fire. Larger trees were less susceptible to bole damage than smaller ones. Trees with thicker bark developed smaller fire scars than trees with thin bark, probably because of better insulation of the cambium. Big trees generally had thicker bark than small trees.

The temperature of the cambium was monitored on both sides of seven of the trees during this experiment (Table 54). One tree experiencing temperatures of at least 68°C on both sides was killed. Damage occurred to five others for which the cambial temperature on one side of the bole reached 58°C. One tree for which temperatures reached 50°C and 52°C did not develop a fire scar.

Table 53

Linear regressions between d.o.b. (cm), bark thickness (b.t.) (cm) and surface area of the bole killed by fire (m^2, A). %A is the percentage of surface of a log 2.4 m length killed by the fire (data of Peet and McCormick, unpublished).

Equation	N	r^2	$\bar{y}$	$\bar{x}$	P
b.t. = 1.019 + 0.023 d.o.b.	30	0.25	1.7	28.0	<0.01
A = 0.821 - 0.011 d.o.b.	27	0.03	-	-	>0.05
A = 1.739 - 0.724 b.t.	27	0.29	0.5	1.7	<0.01
%A = 108.40 - 2.68 d.o.b.	30	0.42	33.4	28.0	<0.01
%A = 124.71 - 54.78 b.t.	30	0.37	33.4	1.7	<0.01

Table 54

Effect of fire on cambial temperatures and percentage of surface bole area killed (unpublished data of Vines).

Tree No.	Cambium temperature (°C) side 1	side 2	% of surface area of a log 2.4 m long killed by fire
21/2	95	68	100.0
5/4	55	68	31.2
21/3	67	53	27.4
21/5	50	75	38.5
22/4	53	58	37.5
23/1	60	62	38.4
23/4	50	52	0

Table 55

Mortality of jarrah in plot 11, Holmes Block after the 1961 Dwellingup wildfire in relation to d.o.b. and bark thickness (b.t.).

	No. jarrah Dead	Alive
d.o.b. (cm)	20.3 (14.6-35.2 range)	27.1 (16.6-35.0)
b.t. (cm)	2.1	2.5
N	35	46

(e) Effect of fire on mortality

A survey of over 16 000 ha of cut-over forest near Collie (*Annual Report* 1921) found an average of 3.2 dead trees per hectare, the implication being that these had been killed by fire.

Mortality after the 1961 Dwellingup wildfire was surprisingly variable. We determined this by examining survival of jarrah tagged before the fire. Of 90 codominant poles in Holyoake block, only three (3.3 per cent) were killed. Of 81 poles (d.o.b. 15-35 cm) in Holmes block, 35 (43 per cent) were killed. In other stands in Holmes block, 37 per cent of 121 individuals were killed, 19 per cent of 79 individuals were killed, and 3 per cent of 76 individuals were killed. Of 51 individuals marked in another stand in Holyoake block, 31 per cent were killed.

Factors important in determining whether a tree survives wildfire are d.o.b., bark thickness, and the amount of fuel that lies close to the base. Trees killed have smaller d.o.b. and thinner bark than those surviving (Tables 51, 55). Tree mortality results when the temperature of the cambium is raised to 60°C (McArthur 1968). As explained in Abbott and Loneragan (1983a), this can be achieved only in a low intensity fire when logging debris completely surrounds the base of the tree. As the intensity of the fire increases, the amount of surrounding debris needed becomes less but is complicated by diameter and thickness of the bark at the base of the tree and dryness of the fuel.

(f) Bark as an important fuel source in the forest

The d.o.b. of jarrah after certain fire intensities decreases because the bark is burnt (Peet and McCormick 1965; see also ch. 6). About 40-50 per cent of bark on the bole is dead. The Dwellingup wildfire removed 60 per cent of the bark, i.e. all dead bark. Burning bark is thought to be a major cause of severe crown fires (Peet and McCormick 1965). The moisture content of bark is, as expected, higher in spring and early summer than in late summer and early autumn. These authors state that three-year-old litter will not support a defoliating fire in jarrah forest unless additional fuel is introduced. The dead bark on the bole contributes such fuel.

(g) When is jarrah most resistant to fire?
According to Peet (1964), jarrah should be most resistant to fire damage in spring and least resistant in autumn. This is because of the difference in moisture relations and food reserves at these times (see also ch. 7).

The timing of leaf replacement also favours burning in spring rather than in autumn. Autumn scorching may inhibit wood production in the current year; this is because leaf replacement is delayed until the following summer. Peet recommended that burning should be completed by early November each year. However, subsequent research (Kimber 1978) has shown that scorching of crowns in spring actually increases wood production, mainly because production of flower buds (and hence flowers and seeds) is prevented.

Drought

Drought is probably one of the main causes of mortality of seedlings. A study of seedling establishment (Abbott 1984a) showed that the first deaths occurred in late August when soil moisture content began to decrease. Most mortality occurs before the first summer (Abbott and Loneragan 1984b).

Nunn* counted 41 jarrah seedlings and lignotuberous seedlings (up to three years old) in a 4.05 m^2 plot in Zamia block unburnt for four years. Four years later only three (7 per cent) remained. Seedlings (189) germinating in Samson block after a wildfire in March 1941 were marked by W. Lockhart+ in May 1941. Survival was as follows: 98 (April 1943), 61 (August 1944), 35 (July 1945), 28 (August 1946), 24 (September 1947) and 10 (December 1958; Van Noort unpublished data). Kimber (unpublished data) tagged 587 seedlings in November 1964. By May 1965 47 per cent had died. Six years later only 40 (6.8 per cent) were still alive (see Table 6).

Such poor survival is typical of eucalypts (Jacobs 1955) and is not surprising given the low oven-dry weight of one-year-old seedlings (0.16 g), the small lignotuber (0.17 cm long axis) and the shallow root system (maximum length 8.5 cm, Abbott 1984a).

Extensive data on the mortality of later stages of development are available. We based this analysis on the growth plots used by Abbott and Loneragan (1983a), converting number of trees dying in each plot in the interval between measurements to percentage dead yr^{-1}. In 26 stands in the high rainfall zone, mortality was 0.02 per cent yr^{-1} (i.e. 2 trees dead per 10 000 trees per year). In 21 stands in the lower rainfall zone, mortality was about two orders of magnitude greater, at 2.42 per cent yr^{-1} (i.e. 242 trees dead per 10 000 trees per year). It is important to emphasize that not all these deaths are attributable to drought as other factors such as dieback fungus and fire are doubtless involved. Nevertheless we suspect drought is most important (see ch. 4).

It is also useful to examine mortality in terms of the number of trees in each d.o.b. class because there are generally more trees in the smaller d.o.b. classes. Mortality varies to some extent with d.o.b. (Table 56). In low quality forest

*. Forests Department file H.O. 1318/50.

+. Forests Department file H.O. 879/41.

mortality was greatest for d.o.b. classes 10-40 and 70-80 cm, whereas in high quality forest greatest mortality was for d.o.b. 50-60 and 80+ cm.

Other factors affecting seedling mortality

Fertilizer usually lessens mortality of seedling jarrah, probably because it increases vigour. When a jarrah plot was established in the Inglehope arboretum in June 1965, one hundred one-year-old seedlings were planted and fertilized (Hart 1977). Survival was high, with 92 alive in May 1966, July 1967 and July 1968. By 1981, 39 per cent had survived for 18 years. However, too much fertilizer may be toxic (see Table 13).

The importance of insect attack and mulching on seedling mortality has been studied by experiment (Kimber unpublished data). Three plots (each c. 15 m^2) were marked out in Plavins block after a control burn in April 1964.

Seedlings which then germinated naturally were marked out with wires in September 1964. Treatments were: control; seedlings sprayed fortnightly with a solution of 0.5 per cent 'Dieldrin'; and seedlings similarly sprayed, and mulched with a polythene sheet which covered the whole plot and a small surround.

Seedlings survived best in the control plot (Table 57). The combination of mulching and insecticide

Table 56

Relative annual mortality of jarrah trees in each d.o.b. class. Number of jarrah trees in each d.o.b. class is shown in parentheses.

Site quality	d.o.b. class 10-20	20-30	30-40	40-50	50-60	60-70	70-80	>80
High quality forest								
% mortality	0.2 (392)	0.2 (273)	0.1 (166)	0.1 (143)	0.5 (91)	0.4 (53)	0.2 (34)	0.7 (26)
Low quality forest								
% mortality	3.6 (158)	3.6 (118)	2.5 (142)	1.3 (95)	0.7 (63)	0.6 (35)	2.7 (13)	0 (7)

From hardwood growth plots analysed by Abbott and Loneragan (1983a). The raw data sheets are held by the Inventory Branch, Department of Conservation and Land Management.

Table 57

Mortality of jarrah seedlings in relation to insecticide and mulch.

Treatment given to germinants	No. alive Sep. 1964	Dec. 1964	March 1965	May 1966	% survival
Control	82	75	59	51	62
Insecticide	79	57	33	30	38
Mulch + insecticide	82	53	38	18	22

was most detrimental. It is possible that the sheeting, instead of acting as a mulch, prevented condensate and rain from entering the soil around the seedlings.

More recent experiments (Abbott 1984a) show that seedling survival to the middle of the first summer is c. 50 per cent and is not improved by trenching or shading. Type and depth of litter are also not significant, though the data hinted that survival was more difficult in *Banksia grandis* or *Allocasuarina fraseriana* litter. Browsing of seedlings by kangaroos and wallabies reduced survival from 49 per cent to 17 per cent.

Frost and wind

Both factors are undoubtedly important but there have been no rigorous studies. This may be because severe frosts and cyclonic winds are extreme events and so their occurrence is hard to predict.

The average number of frosts per year in the northern jarrah forest is not high, being 11 at Dwellingup and 16 at Collie. In 1937 A.C. Shedley* noted considerable frost damage between Jarrahdale and Collie. Every sapling was not affected; in some cases jarrah 8 m tall had been frost bitten whereas in others the leaves on only one side of the crown were killed. Crowns generally were killed back 1-2 m. Bark of the side limbs, particularly where these leave the main stem, was observed to have split. Jarrah was observed to be more susceptible to frost than marri.

W.R. Wallace+ also noted that jarrah is subject to frost every year, with the damage usually being confined to the extreme tip and rarely affecting the dormant bud in the leaf axils at the tip of the plant. Two cold snaps were recorded during 1937. Jarrah was killed back 1-2 m from the tip, and saplings 9 m in height developed 0.5 m of brown tops. Other smaller stunted jarrah 1.5 m in height were completely killed back to the lignotuber.

Aspect, particularly the eastern slope, density of canopy, relative vigour of the growing tip, and a screen temperature < -1°C are probably the critical factors (Wallace unpublished data). Although a rapid thaw causes damage, a slow freeze over a longer period (as from 10-12 June 1937) does more damage than a sudden cold snap (as happened twice in August 1935). The frost of 10-12 June 1935 was worse than those of 28 June-1 July or 23-25 July of the same year because autumn shoot growth was still healthy. In contrast, a frost in spring kills only the young spring shoots.

Damage from a frost in April was recorded in compartment 10 of Kennedy block (P.H. Barrett unpublished data). Some 20 ha were severely damaged, with leading shoots being killed back to 0.5 m and much coppice regrowth < 3 m tall killed. Another 10 ha was less affected.

A severe frost on 26-27 May 1964 caused extensive damage to jarrah in low lying areas east of Mundaring*. Even the crowns of large trees were observed to have been affected. A record was kept of 50 damaged and 57 undamaged stems over two years (*Annual Report* 1966). Of the 50 damaged plants, 21 developed major forks at or near the lower extent of damage. Only three of the undamaged stems formed forks in the same period. Frost is therefore one of the causes of forking in jarrah. The same frost in 1964 affected all low lying areas in Gleneagle Division with death of crowns

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being common (Quain 1964). In some areas in the eastern part, frost damage extended up to the mature crowns. It is possible that malformed sapling stands along some sections of the main rivers have resulted from past fires or a combination of frost and fire. Clear-felling may also increase the susceptibility to frost and therefore the incidence of forking.

Wind damage is caused mainly in extreme conditions, for example in a tornado or cyclone. A tornado swept through some 27 km of State Forest in Collie Division on 6 April 1960 (Stewart n.d.). It cut a swathe 200-600 m wide, trees were uprooted, or crowns twisted-off and hardly a tree crown remained. An earlier instance was recorded near Wuraming in 1929. In 1980 we observed a 0.2 ha patch of jarrah forest in Dale block in which many trees had their crowns broken off, possibly by cyclone Alby in April 1978.

Insects

We do not know how much the northern jarrah forest is affected by insect species inimical to jarrah (Abbott 1985). There are probably hundreds of (unnamed) species of leaf-chewing and sap-sucking insects present in the forest, but their impact on the condition of the crown and diameter growth has not been studied. Similarly, although many species of borer are present, it is important to distinguish between those attacking live trees and those decomposing dead ones.

Five insect species of some commercial significance are present (Jenkins and Curry 1971). These are the moth *Perthida glyphopa* (jarrah leaf miner), the termite *Coptotermes acinaciformes* and the beetles *Atractocerus kreuslerae* (Pinhole borer), *Phoracantha semipunctata* (Bardi) and *Tryphocaria acanthocera* (Bullseye borer).

Jarrah leaf miner was recorded by Mazanec (1974) west of Collie in Lennard and Gervasse blocks just in the northern jarrah forest. The latest distribution map (Inventory and Planning, October 1983) recorded infestation in the same blocks but also between George and Saddleback blocks (Dwellingup Division East) and between Yourdamung and Trees blocks (Collie Division NE). In October 1980 infestation was also mapped in Bednall, Morgan, Stockyard and Stene blocks (Harvey Division East) though these may refer to Flooded Gum (*Eucalyptus rudis*) and not jarrah. The larvae of this moth tunnel through the leaf tissue of jarrah from June to October (Wallace 1970), thereby resulting in reduction of diameter growth (Mazanec 1974).

The ecology of Pinhole borer has not been studied for 60 years. The female beetle lays her eggs on bare injured timber such as old blaze marks, fire scars, or where limbs have fallen off (Clark 1925). The larvae then bore into the tree for about two years before emerging through small holes. Borers (species not specified) have been recorded entering bark split by frost (Barrett unpublished data).

The Bardi beetle has been recorded as attacking live eucalyptus overseas but it is not known whether it attacks live jarrah. Wood damage is caused mainly by the last larval stage boring deep into the heartwood. The Bullseye borer may cause formation of kino veins in jarrah (McCaw 1983b).

The termite *Coptotermes acinaciformes* is the most abundant and destructive species in the southern part of Western Australia (Calaby and Gay 1956), though jarrah has 'considerable resistance' (Ratcliffe *et al*. 1952). Termites require pre-existing fungal decay in order to gain access to the wood of jarrah (Perry personal communication*). Heartwood of jarrah is distasteful to

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termites (Rudman and Gay 1967). Nevertheless the condition of 'mud gut' (mud in the heart, mainly in the lower bole of affected trees) is caused by termites. Fast grown trees appear to contain a greater proportion of durable wood than slow grown trees of similar size (Rudman and Gay 1967). However, preliminary observations made by several members of the Forests Department suggest that the reverse may be true. It is thought that fast growing trees have not fully developed the extractives to give the heartwood durability (J. Sclater personal communication*). In this context, note that Boas (1947) placed jarrah in durability class 2, not class 1.

There has been no research comparable to that of Greaves *et al.* (1965) in which the relative importance of fire, insects and fungi as causes of timber losses was determined.

Fungi

There are probably many hundreds of species of fungi in the jarrah forest (see Aplin 1951; Hilton 1982), but the ecology of only a few has been studied (Forests Department 1971). Carne (1925) does not mention fungal diseases of jarrah, though marri and karri were each referred to once.

In the forest the most obvious fungi are those causing decay; not surprisingly these were given most of the early attention (Tamblyn 1936, 1937a,b, 1939; Rothberg 1937, 1938). These wood-rotting fungi are important in recycling carbon in the jarrah forest. Early research concentrated on taxonomy, distribution, relative importance of the decay produced, and microscopic effects of the fungus on the wood. It has proven difficult to satisfy Koch's postulates and confirm that fungi collected on trees are the primary cause of decay.

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Tree decay starts with a wound, in which xylem is exposed by a break in the bark (Shigo 1979). Injured tissue is compartmentalized with gum, tyloses, and other resistant chemical products. A common result of fire or logging damage of jarrah is 'included sapwood', referring to the inclusion of an area of dead sapwood at some depth in true heartwood. The dead sapwood may or may not be decayed. This condition is caused by a wound which exposes the fresh sapwood, allowing it to become infected by wood-destroying fungi. Eventually the injured area is overgrown.

It is important to distinguish between decays commencing in the living tree, as against those attacking only fallen log. Rots are classified by colour, shape, and position in the tree. Discoloured wood results from alteration of cell contents and does not involve loss of strength, whereas digestion of cell walls leads to decay and loss of strength (Shigo 1979). Colour changes often reflect the relative digestion of lignin and cellulose.

Economically, most important of the decaying fungi to living jarrah is the brown trunk rot caused by *Piptoporus portentosus* (syn. *Polyporus eucalyptorum*) and dry rot caused by *Polyporus pelliculosus* (syn. *P. pelles*). *Fistulina hepatica*, a beefsteak fungus, is the most common fungus on living jarrah boles. It is associated with pencilled wood but not with obvious decay. Pencilled wood is a very common abnormality, occurring in the bole, limbs and roots of all sizes. The pencilling begins in the outermost ring of truewood and occasionally extends into the sapwood. Although penciling is found in all d.o.b.'s, the sporophores have been collected only on mature or over-mature trees.

The bracket fungus *Piptoporus portentosus* occurs throughout the jarrah forest, commonly as a trunk and top rot of jarrah. The rot column normally works down the trunk from the point of entry of infection, normally a dead or broken limb. The sporophore defines the lower limit of the rot column. Laboratory studies of factors affecting the growth of this fungus have been made (Morrison 1971). *Polyporus pelliculosus* and *F. hepatica* are common on old wounds of living jarrah.

In jarrah, ageing increases the volume of heartwood and renders the inner truewood or heartwood susceptible to decay (Rudman 1963). Decay is apparently limited in the younger tree by the presence of toxic chemicals. These become less toxic as the tree ages (Rudman 1963).

The control of heartrots in jarrah is directly limited by the difficulty or impossiblity of economically manipulating the environmental factors affecting the entrance and progress of wood-destroying fungi in the living tree (Tamblyn 1937 a, b). Young stands are, as expected, relatively free of decay because of the lack of fire damage, logging scars, and the small proportion of overmature trees left. However, stump coppice may be affected by decay present in the stump at the time of felling. Decay should be less extensive in regrowth stands because cutting occurs well before the physical rotation (Tamblyn 1937 a, b).

One of the principal causes of a cubical heart rot on dead jarrah wood in the forest is *Polyporus tumulosus*. Although not of economic importance, its biology has been recently studied (Wills 1983).

The other major class of fungi of significance is the root-rot fungi (mainly *Phytophthora* species). Most attention has been given to the soil-borne fungus *Phytophthora cinnamomi* which causes jarrah dieback (Kimber 1981). *Armillaria luteobubalina* is associated mainly with small roots of jarrah (Shearer *et al*. 1983). It acts as a primary pathogen in some areas but not in others. In winter it can rapidly invade the cambium of the stem of jarrah and kill the tree by girdling. Although Aplin (1951) did not record it on jarrah, *A. luteobubalina* is probably indigenous to the northern jarrah forest.

Phytophthora cinnamomi is not indigenous to Western Australia (Shea 1979) but now occurs in c. 220 000 ha of State forest (McKinnell 1981). Patches of dead and dying jarrah were first recorded near Karragullen in 1921, and over the next few decades many patches of unthrifty jarrah associated with sudden death of *Banksia grandis* were noted elsewhere (Podger 1968, 1972; Batini and Hopkins 1972). In 1948 a concerted effort was first made to define the extent and determine the cause of these patches. Many factors, including waterlogging, salt, nutrition, fire history, logging history, insects and fungal infection were investigated but none proved conclusive. The fungus *P. cinnamomi* was first isolated in 1964 (Podger *et al*. 1965), and was found to be easily spread by movement of soil during logging or road construction.

The stages of dieback (Forests Department 1971a; Batini and Hopkins 1972) are: chlorosis and thinning of crown; partial death of crown; death of entire crown; production of epicormic shoots; and death. The death of the aerial parts is merely an indication of a damaged root system (Shea 1975). The actual cause of mortality, through nutrient deficiency (Shea 1979) or interference with uptake of water (Shea *et al*. 1982), is uncertain. Early attention focussed on the fine roots, but recently the fungus has been recorded from the bark and wood of large horizontal roots, the lower stem and vertical roots (Tippett *et al*. 1983).

Evidently many factors have to coincide before death of the tree results. New root growth occurs when soil temperature and moisture are favourable for the growth of *P. cinnamomi* (Dell and Wallace 1983). Summer rain is important in providing conditions suitable for infection. Whether death occurs seems to depend on the growth rate of the fungus and how quickly the tree responds to infection. Formation of kino veins is ineffective against the fungus. Annual mortality is generally less than 2 per cent (Podger 1972; Shea and Dillon 1980) though 5 per cent has been recorded (Podger 1972). Jarrah trees infected with the fungus achieve lower d.o.b. growth (0.03 cm yr^{-1}) than healthy trees (0.20 cm yr^{-1}) (Podger 1972). Nevertheless in dieback affected patches some healthy and vigorous trees often remain (White 1974).

The fungus does not affect the strength or durability of jarrah timber (Batini and Hopkins 1972; MacKay and Campbell 1973). However, wood in standing dead trees degrades rapidly because of cracks in the wood from drying stresses. For this reason timber is promptly salvaged (Stewart n.d.).

The view that *P. cinnamomi* is the cause of jarrah dieback (Podger 1972) has been disputed by Davison (unpublished data) on the grounds that Koch's postulates have not been satisfied.

During the early 1970s the general attitude about the effect of the fungus on the jarrah forest was pessimistic. The forest was thought to be doomed (Hopkins[+]) and therefore there was no point in trying to improve its productivity. Recent better understanding of the biology and ecology of the fungus indicates that management practices may diminish its impact on the forest (McKinnell 1981), and that not all sites are equally susceptible (Shearer personal communication*).

Other fungi that are economically important in the jarrah forest are those causing cankers, which are sharply limited necroses of cortical tissue. Three species of indigenous fungi, *Cytospora eucalypticola*, *Discosporium eucalypti* and *Endothia havanensis*, and the introduced fungus *Botryosphaeria ribis* are associated with twig, branch and upper trunk cankers of jarrah (Davison and Tay 1983; Sutton and Davison 1983). Dead twigs and branches are common on jarrah. Cankers, if they completely girdle a limb, will cause its death. Fungi were isolated from 97 per cent of cankers, and about one quarter of the cankers examined were associated with obvious insect damage (oviposition sites or beetle galleries).

Other inimicalities

The mistletoe *Amyema miquelii* (Lehm. ex Miq.) Benth. is widespread on eucalypts in south-western Australia (Barlow 1966). We have examined specimens in the W.A. Herbarium, and have found that *Eucalyptus gomphocephala*, *E. wandoo*, *E. patens*, *E. calophylla*, *E. rudis*, *E. todtiana*, *E. gracilis* and *E. salmonophloia* have been recorded as hosts. However, there are no records for jarrah, and we have never observed mistletoe on jarrah.

Another form of minor injury to jarrah that is no longer practised resulted from the Aboriginal practice of cutting notches along the bole. This enabled trees to be climbed for possums (Ogle 1839; Wollaston 1841).

+. Forests Department file H.O. 14/69.

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