

A review of silvicultural research in the karri (*Eucalyptus diversicolor*) forest

R. BREIDAHL¹ AND P.J. HEWETT²

¹ Formerly Department of Conservation and Land Management, Manjimup, 6258. Present address: Bunnings Tree Farms, South West Highway, Manjimup 6258 Western Australia.

² Formerly Department of Conservation and Land Management, Manjimup 6258. Present address: Department of Conservation and Land Management, Albany 6330 Western Australia.

SUMMARY

This review is a synthesis of published and unpublished research on silviculture of karri (*Eucalyptus diversicolor*) up to the end of 1988, aimed at providing background information to researchers and operational staff.

The wet sclerophyll karri forest occurs only in the south-west of Western Australia, and extends over more than 167 000 ha. It is highly valued in terms of conservation, recreation, visual amenity, water conservation and timber production.

The karri floral cycle is complex and generally four to five years are required from the initiation of the inflorescences to the dissemination of seed. Trees may have a number of crops at different stages of development on them at any one time. Seed production is influenced by soil moisture, pollination vectors, stand density, insects, temperature, nutrition, genetics and fire. The floral cycle has been studied in detail and its importance is discussed in relation to seed collection and regeneration.

Research into regeneration of karri dominated work until the early 1980s. Natural regeneration may occur owing to a variety of events. These include extensive, high intensity fires which kill large areas of overstorey, small localized fires, death of single trees, or windstorms which blow over swathes of mature forest. Seedbed is vital to successful germination and establishment of karri seedlings. Regeneration burning is a successful method of preparing seedbed, stimulating seedfall and disposing of logging residue. Successful germination and establishment is also influenced by insect depredation, allelopathy, soil type, time of sowing, fungi and presence of retained trees.

Karri forest can be regenerated artificially by using seed trees, by planting seedlings or by direct seeding. The various merits of each of these methods is discussed. Phosphorus has been shown to be important in stimulating early growth of karri seedlings. The type of fertilizer and rate of application has been refined to produce optimum growth which is cost effective. Initial espacement of seedlings influences diameter growth and clean bole length. Various spacings are being tested to fully define the optimum initial espacement to meet management objectives.

Production of readily collected, high quality karri seed was identified as an important task in 1972 and a number of seed orchards and seed production areas have since been established. Vegetative propagation of karri using different techniques has been tried but is not considered a viable option at present.

Soil disturbance is recognized as an important factor influencing successful regeneration and growth. Control measures are in place but it is suggested that work continue in this area.

Thinning of regrowth has dominated karri silvicultural research since 1984 and a number of experiments have been established. Thinning has increased growth of retained trees in both young (12-year-old) and older stands (50-year-old). Work in this area should continue.

Research in karri silviculture has given land managers a good basis on which to plan and implement timber harvest and regeneration operations. While many areas of silviculture have been studied, it is suggested that future research should take a more integrated approach. The aim of the research should be to further refine silvicultural systems so that all values of the forest are provided for in a sustained way.

INTRODUCTION

History of Karri Silvicultural Research

Research into the silviculture of karri (*Eucalyptus diversicolor* F. Muell.) has a long history owing to the value of the timber and its very fast growth rates compared with most other eucalypts. The research

done on karri silviculture by the Western Australian Forests Department, now incorporated into the Department of Conservation and Land Management (CALM), has covered many aspects of growing and tending this unique tree. The aim of this project was to provide a summary of research completed on karri silviculture for forest managers and research workers. It does not provide intricate detail in all areas, but gives a guide to what work has been done and the pertinent information that has been gained from it. This paper provides information of where further details can be found and identifies gaps in our knowledge, thus indicating areas for further research.

The reviewed literature and experiments summarize past work within ten broad categories which follow the life of a karri tree from seed, through seedling, to mature tree. Where relevant, the results of eastern States or overseas work have been included, particularly when this involves a species similar to karri, e.g. mountain ash (*Eucalyptus regnans*).

This paper covers research into silviculture for timber production only. It does not cover research into conservation of flora and fauna or hydrology. This is not to say that research into these areas is not important or has not been done, it is simply not within the scope of this document.

Formal research on karri silviculture was commenced in the 1930s by the Forests Department of Western Australia. Much of the research focused on short term projects, aimed at solving operational problems; so early work was not always well documented. In recent years the Department of CALM has published several papers on aspects of karri silviculture. The evolution of methods and procedure over this period makes the history of karri silviculture uneven at times.

Most of the early research on karri silviculture dealt with the problems of achieving successful regeneration, either after clear felling in the 1920s and 1930s and since 1967, or after selection cutting between 1940 and 1967. An example is the very detailed research described by Loneragan (1961, 1971, 1979), especially that dealing with the floral cycle of karri and the estimation of seed supply. The ability to estimate likely seed production from the abundance of flowering buds and other floral structures means that forest managers can predict whether areas to be harvested are likely to have enough seed for natural regeneration or whether areas will need to be artificially regenerated. This allows the efficient collection of seed from the forest and for nursery operations to be planned in advance to produce the required number of seedlings for each year's regeneration program.

Over the last two decades, research has concentrated on studying different methods of regenerating the karri forest, e.g. Loneragan (1971), White and Underwood (1974), White (1974a), Annels (1980) and Schuster (1980a,b). These studies have resulted in the use of seed trees as the favoured

regeneration method whenever seed is available in sufficient quantity, and the use of planted seedlings when it is not. Artificial sowing has not been favoured because of its high use of seed and the cost of seed collection, but effective techniques have been developed.

In comparison with studies into the regeneration of karri, comparatively little research has been undertaken on tending the regenerated forests. Over the last few years a number of thinning experiments have been established in karri regrowth stands. These experiments have provided useful data for prescriptions for operational thinning which will be refined as more data is collected.

The Karri Forest

Description

Karri is the tallest tree growing in Western Australia (WA) and, with mountain ash (*E. regnans*) and alpine ash (*E. delegatensis*), forms one of the world's three tallest hardwood forests. Karri commonly reaches 50-70 m in height; and heights of up to nearly 90 m have been recorded. The bole is usually long and straight and may be up to two-thirds of total tree height (Hall *et al.* 1975). Diameters are generally relatively small for such a tall tree, commonly 2-3 m, although diameters of over 5 m have been recorded.

The bark of the karri tree is shed annually in irregular patches leaving a smooth surface. The colour of the trunk is very variable and changes with the season; however, it is commonly creamy with brown or blue-grey patches. The leaves are strongly discoloured being dark green on the upper surface and pale green on the lower surface, hence the specific name, *diversicolor*.

Karri occurs naturally only in the extreme south-west of WA, although evidence suggests that in the past it was more widespread in times of greater rainfall (Churchill 1968). The current distribution covers about 300 000 ha, mainly within a belt about 200 km long and 20-50 km wide between Cape Leeuwin and Albany (Fig. 1). This belt is bordered by the south coast and on the northern side by the 1100 mm isohyet.

Two main outlier populations occur, one of which is over coastal limestone between Karridale and Forest Grove, 20-30 km north of Augusta (Hall *et al.* 1975), while the other is on soil derived from weathered granite outcrops on the lower slopes of the Porongurup Range 40 km north of Albany. Smaller outlier populations occur at Yallingup (the most northerly), Margaret River, Black Point and Mt. Manypeaks, 50 km east of Albany (the most easterly occurrence).

The climate over the karri range is mild temperate, with small daily variations of temperature and humidity both in summer and winter. The mean maxima and minima at Pemberton are 26°C and 12°C for the hottest month, and 16°C and 7°C for the coldest

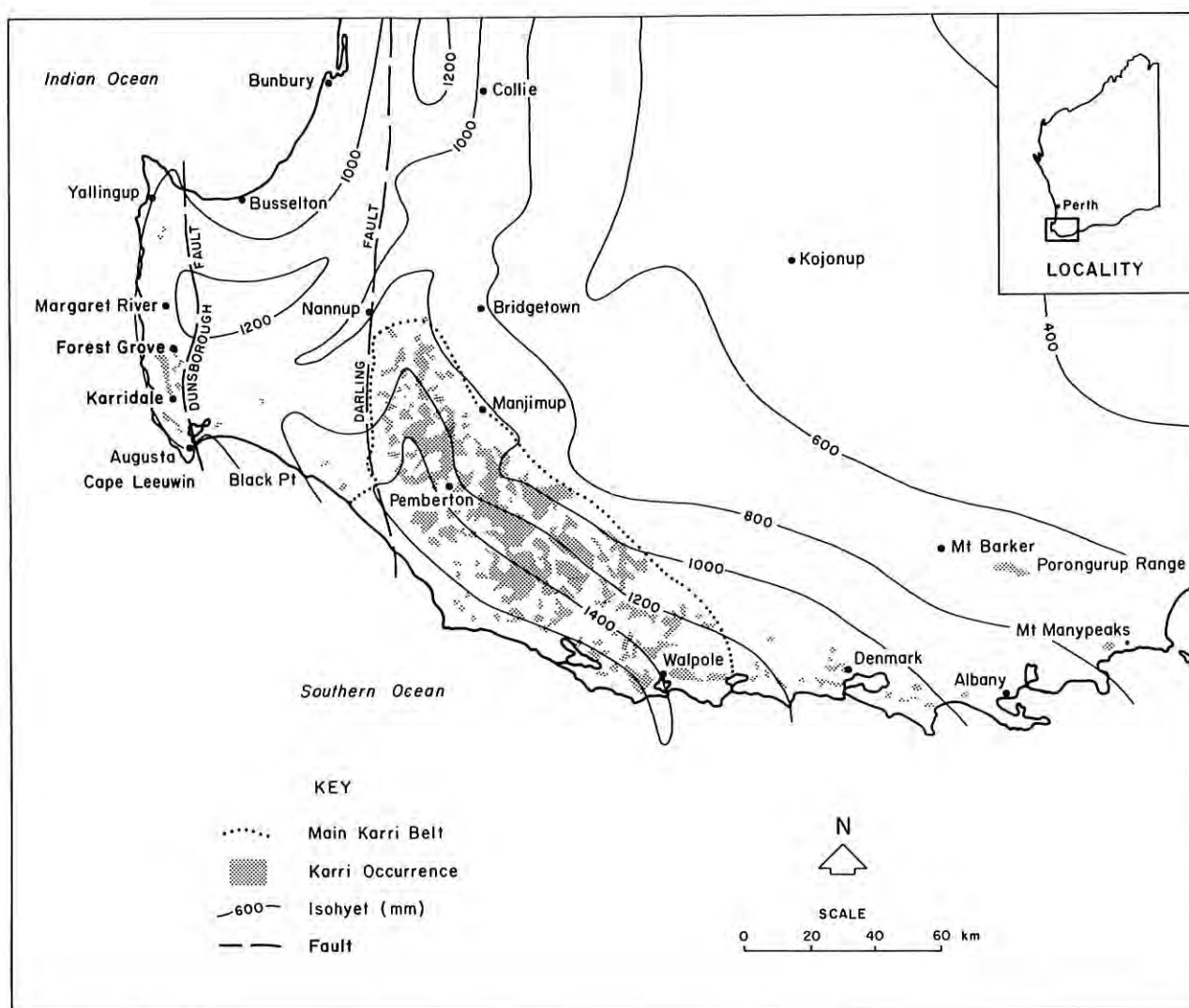


Figure 1. Karri occurrence in south-west Western Australia.

month. Frosts are rare. Mean annual rainfall over the main karri belt ranges from 1100 mm to 1500 mm, although in some of the outlier populations, for instance the Porongurup Range, it may be as low as 900 mm. Most of the rain falls during the winter months from May to August.

The topographic occurrence of karri varies from the north-west to the south-east, and is virtually dependent on the presence of the younger reddish-brown to yellowish-brown podzolic loams (Bradshaw and Lush 1981).

Bradshaw and Lush recognize three major distributional foci corresponding to the north-west, central and south-east parts of the main occurrence. In the north-western or Donnelly type, karri is typically found in deeply incised valleys with increasing proportions of marri (*E. calophylla*) upslope. Further up the slope karri disappears and is replaced by jarrah (*E. marginata*), so that on the lateritic ridges pure stands of jarrah occur. As the lateritic duricrust

becomes more dissected further south and south-east, numerous smaller tributaries to the major rivers develop shallower gullies and karri extends from the gully onto mid and upper slopes. The Warren-Dombakup area illustrates this situation and it is in such areas that the largest, contiguous occurrences of karri can be found.

Still further dissection occurs to the south and south-east, where in the past these areas have been inundated by the ocean. Bradshaw and Lush (1981) note that the subsequent depositional podzolic soils now support extensive flats of swampy heath and scrub. Karri occurs where remnants of the older land surface protrude, i.e. on the low hills standing above the flats. It is also found in river courses where erosion, following inundation, has dissected the podzols and exposed younger soils. Jarrah occurs wherever the original lateritic duricrust remains, as well as on the fringes of the flats.

The soils of the karri region are acidic with textures varying from fine sands to sandy loams. Such soils are

of very low nutritive value by agricultural standards and are deficient in such trace elements as zinc, copper and cobalt (Hall *et al.* 1975).

The main commercial occurrence of karri covers about 150 000 ha, where it occurs mainly as a pure stand or in association with marri. It also occurs to a considerably less extent with jarrah, WA blackbutt (*E. patens*), red tingle (*E. jacksonii*) and yellow tingle (*E. guilfoylei*). The best development of karri occurs on deep loam soils along the valleys of the Donnelly, Warren, Shannon, Frankland and Deep Rivers.

Schuster (1979c) subdivided pure karri stands into three ecotypes. In the north-west of the range the understorey of pure karri stands tends to display two seral stages, the first dominated by legumes, mainly netic (*Bossiaea laidlawiana*), the second dominated by netic and hazel (*Trymalium spathulatum*). In the central area of the species range around Pemberton, a two-seral stage is also displayed, where the first is again dominated by legumes, in this instance *Acacia* species, and the second is a mixture of hazel and karri oak (*Allocasuarina decussata*), and soapbush (*Chorilaena quercifolia*). In the southern karri forests, however, only one seral stage is seen, and this is dominated by the leguminous species, karri wattle (*Acacia pentadenia*).

Karri Site Classification

A comprehensive site classification of the karri forest was not undertaken until 1986/87. This study was done in response to the recognized need for an easily used system for designating a site to a particular productivity class at year zero of the rotation. This is an alternative to using site index curves (based on age standardized top height) which is not a reliable method of predicting productivity of very young even-aged karri stands. Sampling was carried out on 219 permanent inventory plots stratified across various ages and geographic locations of even-aged regrowth karri. The classification used a number of different site variables such as climate, edaphic factors and presence or absence of perennial plants to stratify the karri into five community groups and 13 relatively homogeneous community types.

Soils were grouped into five distinct groups, all of which occur throughout the geographic distribution of the study area. Climatic attributes were grouped into three homoclines with distributions strongly related to geography.

The description of each community group and type which follows is taken from Inions *et al.* (1990).

This site classification has only recently been developed and its correlation with site productivity is yet to be confirmed. It is already being used for stratification of research projects and, if proved to be sound in terms of productivity, will be a useful tool in planning and implementing silvicultural treatments of karri stands.

Community Group 1 - This group is comprised of three types. They tend to occur in areas where the

climate is quite cold, rainfall is relatively low and tends to be less seasonally distributed with more rain days in the driest quarter than other groups. Mean annual radiation is also high. Soils are low in phosphorus and are more acidic than community groups 3, 4 and 5, but more alkaline than community group 2.

- (i) **Ednie-Brown Community Type:** These are the forest-heathland ecotones where soils are quite sandy. They occur in both the northern and southern sections of the karri distribution.
- (ii) **Lane-Poole Community Type:** This type has a limited geographic distribution, occurring only on the eastern edge of the southern half of the study area.
- (iii) **Kessell Community Type:** This type occurs in the southern half of the study area on gravelly yellow or brown duplex soils.

Community Group 2 - This group occurs on the cold, wet areas of the southern half of the study area. Temperatures are colder than for other groups during winter. Soils are significantly more acidic than those of other community groups.

- (iv) **Stoate Community Type:** This type has a central and southern distribution. Sites are moist with brown gravelly duplex soils that are significantly more alkaline than the Harris and Wallace types.
- (v) **Harris Community Type:** Harris communities are restricted to cold wet areas of the extreme south of the study area at the forest-heathland ecotone. Soils are significantly more acidic and low in phosphorus.
- (vi) **Wallace Community Type:** These sites are moist but well drained, with soils of low phosphorus and acidity intermediate between Harris and Stoate.

Community Group 3 - This group occurs on the drier fringes of the northern half of the study area. Precipitation in the driest quarter is low and radiation is high in both summer and winter. Soils are significantly lower in phosphorus than community groups 1 and 2.

- (vii) **Stewart Community Type:** These sites are characterized by species occurring on gravelly soils on the north-eastern edge of the karri. Soils are low in phosphorus and subject to summer drought.
- (viii) **Beggs Community Type:** This type occurs in the north of the area on well drained gravelly soils high in the profile.
- (ix) **McNamara Community Type:** These sites occur on a wide range of soils but are restricted to where summer rainfall is low.

Community Group 4 - This group occurs in the high rainfall areas in the northern half of the study area. Temperatures are high and rainfall is higher than other groups, but is strongly seasonal with precipitation in the wettest quarter significantly higher than for community groups 1, 2 and 3.

- (x) **Shea Community Type:** This is the only type in group 4. Soils are gravelly and are high in phosphorus.

Community Group 5 - This group occurs in the high rainfall areas of the northern half of the study area. Temperatures are warmer than for groups 1 and 2, annual precipitation is higher than for groups 1 and 3 and is very seasonal. Soils are less acidic and higher in phosphorus than those of groups 1 and 2.

- (xi) **Havel Community Type:** These sites are characterized by species occurring on moist sandy sites in riparian environments. Phosphorus is low, but cation exchange capacity is high.
- (xii) **White Community Type:** These sites are moist but freely drained, and occur low in the profile.
- (xiii) **Annels Community Type:** This type is characterized by species occurring in moist but freely drained sites low in the profile. Conditions are similar to those in White Community types except that values for phosphorus are particularly high.

Importance

Karri is the second most important commercial timber species in WA and since the 1890s has been exported in large quantities for use as sleepers, building timber, flooring and guides of sliding beams in mines. Its great strength, high stiffness, comparative freedom from defect and availability in large sizes make it highly suitable for heavy construction (Hall *et al.* 1975, p 50).

The timber is also made into plywood, where strength and resistance to abrasions are important. Inferior and small karri logs which would previously have been unusable have been chipped for use in the pulp and paper industry, mostly to produce high quality writing paper, since 1975.

Karri forest is also important for its nature conservation value. It occurs naturally only in the south-west of WA and as such is unique. It has high value for recreation, visual amenity and water production. The focus in this paper is on its value in terms of timber production, but its conservation value is recognized and current regeneration strategies seek to ensure all values are sustained.

THE KARRI FLORAL CYCLE AND SEED PRODUCTION

The karri floral cycle is complex, with variations among trees and seasons, within crops on one tree and among stands within a forest (Loneragan 1979). Flowering may be advanced or delayed by genetic or environmental factors or by a combination of the two, and up to five stages of development can be found on one tree at any one time. Usually one or two crops in every four to seven set good seed, while only vestiges of the others remain. Two crops on one tree usually

form in consecutive years and secondary bud crops initiated one year after the main crop merge with it by the time of seed dissemination.

The Karri Floral Cycle (adapted from Loneragan 1979)

Karri generally takes four to five years from the initiation of the inflorescence in the terminal axil to the dissemination of seed from the resulting mature capsules. The inflorescence initials form early in summer. They swell and lengthen by 1-2 cm and bear seven floral bud initials which can be distinguished when the bracts are cast at the end of March. Bud development is slow during winter but resumes in spring. By autumn of the second year the full length of about 2 cm is reached.

During the third summer the buds become plump and clavate (club-shaped). Before flowering the clavate buds turn yellow-green to pale brown and their opercula become dome-shaped and reddish-brown.

Approximately one week before flowering, a white abscission line appears at the junction of the operculum and hypanthium (cup). Shortly afterwards the operculum falls off exposing the stamens, which take four or five days to open out and expose the anthers. By this time the stigma is sticky and ready for fertilization. After about one week the anthers turn brown and the stamens become depressed, wither, and usually fall off. The inside of the hypanthium dries up within one month of shedding the operculum.

A tree may flower for six months, with the peak lasting two to three months. Other crops formed before or after the main crop may or may not flower, as dominant crops (resulting from a very heavy development of bud initials) can suppress the development of others. The time and season of flowering is difficult to forecast, especially for small crops between abundant crops, and seed is not necessarily present in quantity on every tree every year, even though inflorescence initials are formed in most summers.

After flowering, the immature hypanthia continue to develop through one full winter before the seed crop is ripe. Seed maturity is associated with three- to four-year-old leaves and may be assessed by the full shape of the capsules and by the relative position of capsules and leaves. Hypanthia and immature capsules are mingled with the leaves, but mature capsules become exposed close to the base of the foliage.

Seed is disseminated when the capsules open, either on the tree or after the capsules have fallen to the ground. Drying of the capsules and dissemination of seed is related to the fall and flush of the leaves, respectively. Timing of the dispersal is also influenced by the position of the capsules in relation to the main and vigorous side branches, or the weaker side branchlets. On fruiting side branchlets, which die after leaf fall, the capsules turn brown and cast their seed immediately. In contrast, the capsules attached directly

to main branches and low order side branches (which continue to grow), retain their seed for a further twelve months. At this stage the crop is four to five years old. Overall, karri seed supply tends to be cyclic with good crops roughly every five years.

For the twenty-year period from the early 1950s to the early 1970s, the pattern was for a light seed crop early in the decade (1961-62, 1971-72) followed by a heavy crop later in the decade (1956-57, 1967-68). Seed was available for two or three summers around each crop, but between crops there were similar periods in which there was little or no seed (White and Underwood 1974).

The Importance of Knowing the Floral and Seed Production Cycles of Karri

An understanding of the floral cycle and the seed production cycle of karri is essential to ensure success in seed collection and regeneration. 'Approximately half of the 1500 ha of mixed karri-marri forest cut annually is artificially regenerated owing to the cyclic nature of seed availability,' (CALM 1991). Effective seed collection is therefore essential. Loneragan (1979) emphasizes the need for the infrequent abundant crops to be fully exploited as seed collection is much cheaper in abundant seed years. In addition, seed collected from trees with good crops, in an area where seeding in general is poor, is likely to be largely self-pollinated. These crops are therefore avoided. Seed collected during good seed crops can be stored for many years without a major decline in seed viability.

Until the introduction of planting, all stands were regenerated by the seed tree method (with the exception of some direct seeding in the 1920s). Knowledge of the floral cycle allowed regeneration burns to be delayed until adequate seed was available on the seed trees. This still applies, and only with this knowledge can the potential seed harvest be reliably estimated. Then it is possible to decide whether collection of the coming seed crop for subsequent artificial regeneration is economically feasible (abundant crops only), whether natural regeneration using seed trees is possible (moderate and heavy crops) or whether artificial regeneration is needed (poor or light crops) (Loneragan 1979). The average time taken for maturity of capsules from flowering is 11 to 12 months (Christensen, unpublished). This information is a valuable aid in planning the timing of regeneration burns to coincide with seed maturity where natural regeneration is being used, and in the planning of seed collection.

Research on the floral and seed production cycles in karri has been comprehensive and no further work is planned.

Factors Affecting Seed Production of Karri in the Virgin Forest

Soil Moisture

The cyclic nature of karri seed production has been noted above. Loneragan (1979) suggested that the moisture status of the soil influenced the seed and the resulting seed supply. Both graphically and mathematically, he found a distinct relationship between cumulative deviation from annual rainfall and the cumulative seed crop. Loneragan used cumulative rather than annual parameters to take account of the preceding year's rainfall influence and the dispersal of seed crops over several years.

Peaks and troughs in the cumulative rainfall index are followed a few years later by corresponding peaks and troughs in the seed crop index. Positive cumulative deviation from annual rainfall is significantly correlated with cumulative seed crop one year later ($r = 0.50$). This one-year interval corresponds to the time lapse between flowering and seed maturity. Positive cumulative deviations from annual rainfall are also significantly correlated ($r = 0.49$) with the cumulative seed crop four years later.

This is the time interval between the appearance of inflorescence buds and seed maturity. Loneragan (1979) concluded that 'regular seed cycles can be expected only when soil moisture storage is adequate as indicated by positive cumulative deviation from average annual rainfall' p. 28. When soil moisture is depleted, seed crops become poorer and more unpredictable. Major droughts of 1940, 1953, 1959 and 1969 appeared to cause major disruptions in the seed cycles, the effects of which were apparent for several years. Conversely, initiation of heavy bud, flower and capsule crops is usually associated with spring-summer rainfall 40 per cent above average.

Within the broad pattern of climatic periodicity and flowering and seeding behaviour of karri, individual trees vary in the duration of development of their annual shoots and initiation of floral buds. Other individual differences (apparently genetically based) occur in the frequency and seasonality of flowering. The need to replenish food reserves exhausted by heavy flowering and fruiting is probably common to all trees. During the 1930s there were three separate seed crops with seed available for eight of the ten years. This phenomenon occurred while cumulative deviation of rainfall was positive for that entire decade, which probably enabled individual trees to quickly replenish their depleted food reserves.

There are two main practical implications of Loneragan's findings. Firstly, the cumulative deviation from average rainfall can be used as an index of likely heavy bud formation. Secondly, in view of uncertain weather conditions during long term observations, it can never be assumed that a heavy seed crop will be

followed by another within the decade. As a result, each heavy seed crop should be fully used. All seed not immediately needed should be stored to ensure that regeneration requirements for the following decade can be met.

Natural and Artificial Pollination

A number of studies have noted poor seed set in karri (Loneragan 1961, 1979; Christensen 1971a; and White 1974b). A higher yield of seed per capsule would reduce the cost of seed collection and subsequent regeneration operations. A major study was commenced in 1965 (Loneragan 1979) to investigate the effect of the following on seed production:

- (1) the introduction of honey bees to improve pollination;
- (2) partially ring-barking trees to improve fruit-setting; and
- (3) applying artificial pollination to increase the ratio of seeds to capsules.

Methods (1) and (3) were tested on two individual trees, Diamond and Gloucester fire look-out trees. Partially ring-barking trees and the introduction of bees were tested on a whole stand. Ring-barking did not affect the seed yield per capsule. The introduction of bees significantly improved the seed yield per capsule near the apiary site. The average yield of seeds per capsule was 50 per cent higher for the 8 trees near the apiary site than for the 28 trees 400-800 m distant. With increasing distance from the apiary, the yield declined still further. The yields from three sets of samples in a medium quality, karri-marri stand 2-3 km from the apiary, averaged less than half that of the 8 trees near the apiary site. These results suggest that the bees were most active near the apiary and their activity declined with increasing distance from the apiary.

On Diamond and Gloucester trees, branches were caged and bees introduced into these cages. Fruits on these branches yielded 1.98 seeds per capsule nine months after flowering. This was nearly twice that from flowers on branches which had been caged but had not had bees introduced, and approximately 25 per cent higher than from flowers in the surrounding open crown. It was also superior in yield per capsule compared with caged, artificially self-pollinated flowers (Table 1). The most outstanding yield resulted from manual cross-pollination on Gloucester tree in April-May (4.03 seeds per capsule) which is above any reported natural yield.

Pollination in eucalypts is normally achieved by insects or birds rather than wind (Pryor 1951). Insect activity is often restricted in cold, wet winter months (Keighery 1982), so bird pollination is likely to play a more important role in the karri seed cycle than insect pollination. Loneragan (1979) also found that honey bees (and presumably other insects) are inactive during the cold, wet months.

Keighery (1982) lists karri as a eucalypt that has been observed being visited by nectar-feeding birds. Purple-crowned Lorikeets are likely to play a dominant role in pollination as they are still active during the winter period and have a very large range of movement, therefore having the capacity to cross-pollinate karri over a greater distance than is likely through insect pollination (Christensen 1971a).

Stand Density

Above a certain stand density (corresponding to about 20 per cent canopy cover) seed production is quite consistent, although seed production within individual stands may vary greatly (Loneragan 1979). Two partially cut stands of 20 and 30 per cent canopy cover produced the same amount of seed as two well stocked stands of 60 to 90 per cent canopy cover. In contrast, one partially cut stand and a virgin stand produced one and a half times the amount of seed produced by a dense 90-year-old regrowth stand. The poor seed production in dense regrowth stands is almost certainly owing to competition for light and water.

Insect Damage

Inadequate pollination of flowers is only one factor contributing to poor seed production in karri. There is a continual abortion of developing floral parts (buds, flowers and capsules), much of which is attributable to insect damage. In 1960 a weevil similar to the tuart bud weevil (*Haplonyx tibialis*), nipped off about 600 000 buds from one karri crown with an area of 370 m² (Loneragan 1961). Also, in the lean seed year of 1960, further karri seed losses caused by another insect were noted by C.F.H. Jenkins, Government Entomologist (Loneragan 1961). Karri seed capsules with 25 per cent showing borer (*Bruchidae*) holes yielded 37 000 seeds/kg of seed and chaff compared with 160 000 seeds/kg in the prime year of 1956. Soil insects were attracted to the seed and to the tarpaulins where the fruit was drying. In autumn 1960, six *Collembolla* (springtails), six *Curculionid* (weevils) and six *Acarina* (mites) were collected per thousand karri seed, together with 128 bruchid beetle larvae. Ants (*Pheidole* sp.) were also recorded collecting both fallen seed and emerged larvae from the drying fruit. Much seed is also lost to insects on the ground (Christensen and Schuster 1979).

The capacity of parent trees to support these large losses yet still blossom well and produce seed has not been studied. Nor have techniques been developed to reduce or eliminate insect-caused losses. They are not considered to be a major problem.

Temperature

Temperature influences the rate at which floral development proceeds, and is likely to be a dominant factor in determining the time of flowering of a genotype (Loneragan 1961). This could have a

TABLE 1

Mean seeds per capsule in pollination experiments.

SOURCE	BEE POLLINATION			ARTIFICIAL POLLINATION	
	CAGES WITHOUT BEES	CAGES WITH BEES	OPEN CROWNS	SELF	CROSS
Capsules 9-12 months old					
Diamond tree	1.08	1.98	1.60	1.32	-
Gloucester Tree	1.23	-	1.94	-	4.03
Capsules 8 months old					
Diamond Tree	0.85	1.15	1.11	0.67	0.96

Source: Loneragan (1979)

significant effect on seed production. The main blossom in the karri forest usually occurs in April and May (Loneragan 1961) when the weather is still relatively warm and honey bees are active. Lower than normal temperatures during the summer-autumn period may slow development so that the main blossom does not occur until June and July when the temperature is lower and the bees inactive. This is likely to have a significant effect on seed production, considering Loneragan's findings that bees increase seed yield.

Low temperatures at other crucial stages in the floral cycle (e.g. ripening of the capsules) could also affect seed production, although this has not been studied.

Nutritional Requirements

Karri seed production tends to be cyclic, implying that food reserves of individual trees are probably exhausted at each seeding (Loneragan 1961). The tree then needs to accumulate new stores of starch over a number of years before seeding again. The rate at which this takes place appears to be determined by soil moisture status. During the 1930s, when soil moisture levels were high for the whole decade, there were three heavy seed crops, each lasting a few years. This indicates that if conditions are right, replenishment may take a year at the most. In contrast, there were only moderate seed crops in the 14 years from 1953 to 1966 when soil moisture levels were low.

Application of fertilizer at a time of reasonable soil moisture may decrease the time needed to build up food reserves after seeding, and so increase seed production in the long term.

Genetics

'Flowering and seed production vary in individual trees owing to the complex interaction of heredity and environment' (Loneragan 1979, p. 28). This would become an important factor in the possible introduction of clonal seed orchards of karri where clones could be made of high quality parent trees with high seed production rates.

Fire

An experiment carried out by Schuster in 1977/78 (unpublished) investigated the effect of a mild intensity spring fire on the karri floral cycle. A large amount of seed and mature capsules fell in the five weeks immediately following fire. A survey twelve months after this fire indicated that all floral elements were below their expected values, while in the unburnt plot the floral parts were present in expected numbers.

Schuster drew two conclusions from the experiment:

- (1) immediately following a fire of this type there is a large reduction in the mature seed and capsule crop and smaller reductions in the other stages of the floral cycle; and
- (2) there is a tendency for the initiation of floral parts in the next two years to be at a slightly lower level. This takes no account of the trees severely scorched in the fire, where time to recovery may be even longer.

The Harvesting and Storage of Karri Seed

Harvesting

The high expense and effort involved in collecting karri seed, and hence the need to make maximum possible use of good seed crops, has been strongly emphasized by Loneragan (1961 and 1979). Owing to the great height of mature karri trees, capsules can only be collected when the trees or branches are felled. As a result seed collecting is concentrated in stands which are being logged. Prompt collection of capsules is essential as seed will shed within one or two days of a tree being felled, given the right conditions.

Seed collection is most efficient when the stands and their individual trees are assessed beforehand. For stands the primary concern is with the overall vigour and form of trees, the quantity of capsules and the number of seeds per capsule. For individual trees the accent is on dominance and form, though it is realized that these are only phenotypic expressions of survival and therefore genetic potential.

(Loneragan 1979, p.21)

Trees should have a minimum of seven capsules per twig, but preferably more than nine to reduce collection costs.

The collection rate for an inexperienced harvester is about 10 000 capsules per person per day (Loneragan 1979). In 1967, ten tonnes of capsules at two million capsules per tonne were collected. This corresponds to 27 kg of pure seed and twenty million seed. It was an exceptionally good seed year. At the time, the overall cost of collection and extraction of this seed was about \$5 000 (< \$200/kg). Current costs are very high (between \$3 000 and \$4 000/kg clean seed). Using an inflation rate of 10 per cent, the 1967 value compounds to around \$1 480/kg in 1988.

Storage

Loneragan (1979) emphasizes that karri seed (whether intended for long or short-term storage) should be placed in a closed container and fumigated with carbon disulphide at the rate of 5 mL L⁻¹ for 24 hours to minimize insect damage. Karri seed stored this way loses viability very slowly, at a rate of only 1 per cent per annum over eight years of storage (Loneragan 1979). After ten years of storage, cold stored seed had a viability of 90 per cent while seed stored at room temperature had a viability of 86 per cent (Loneragan¹ unpublished data).

High temperatures, high moisture content and frequent changes in storage conditions reduce viability (Loneragan 1979). Seed intended for long term storage should therefore be dried to 10 per cent moisture content and then stored at low humidity in a sealed container at 2-4°C. Even seed stored locally for shorter terms should be kept in sealed bags with silica gel, which acts as a drying agent and moisture indicator, and stored in sealed bins at a cool, constant temperature. The bins should be insect and vermin proof.

Sampling Techniques for Estimating Seed Supply

It is vital to have a reliable estimate of expected seed supply in a stand selected for cutting and regeneration, especially where seed trees are to be used. There are two methods of estimating seed supply. The first (sampling trays) is not a routine method as it is very detailed and used mainly for predicting future supplies, not for estimating seed supplies for regenerating a coupe.

Sampling Trays

Loneragan studied the floral cycle in stands of different ages and structures, estimated seed production (using the methods of Ashton 1956 and Cunningham 1960) and related this to requirements for natural regeneration.

An estimate of predicted seed supply is only useful once an estimate of the number of seeds needed for adequate regeneration is available. Using known tree survival percentages (obtained from personal communications and his prior work), and an acceptable density of established seedlings of 1250-2500/ha, Loneragan calculated that 300 000 seeds/ha were needed in spring and 200 000/ha in autumn. Seed numbers for other desirable stockings may be calculated allowing 150 seeds (120 to 180) for each seedling (Loneragan 1979).

Floral components shed into trays under the karri trees in the forest were collected each month from 1956 to 1967. They were then separated and counted. The number of seed capsules per unit area may be calculated from the floral balance. The number of capsules remaining on the trees at any one time after flowering is equal to the number of bud-caps cast during flowering minus the number of fallen flowers and immature capsules cast after flowering (Ashton 1956; Loneragan 1979). Total seed supply is then simply the number of capsules per unit area multiplied by the number of seeds per capsule. An example of this technique is as follows (Loneragan 1979, p. 13).

Tray sampling in 44 widely dispersed cut-over stands between April 1960 and March 1961 provided the following floral balance :

	numbers/ha
Opercula	2 965 000
Less hypanthia shed during flowering	-915 000
Equals immature capsules retained on trees at completion of flowering	2 050 000

Sampling in a virgin stand at the same time, but extended to observe maturing of the seed crop, provided the following figures :

	numbers/ha
Opercula	5 500 000
Less hypanthia and immature capsules shed during flowering and maturing	-5 000 000
Equals capsules approaching maturity	500 000

However, even this markedly reduced crop of near-mature capsules is much larger than the ripe crop, indicating that the loss of floral components continues right up until the seed is shed.

Branch Sampling and Seed Testing

The use of sampling trays is least efficient in forest cut to seed trees (Loneragan 1979). However, it is in this situation that accurate and reliable prediction is most necessary so that slash disposal burning for seedbed preparation can be timed to coincide with seed maturity.

Using branch sampling and seed testing, the number of capsules can be estimated by multiplying the number of crown units, which is estimated visually, by the number of floral components per unit, which is obtained by sampling.

¹ O. W. Loneragan, retired, formerly Department of Conservation and Land Management, Como.

The number of capsules in a crown can be assessed using a suitable telescope with a grid. The degree of crown cover can be measured using a densiometer or assessed by vertical projection of crown cover along a line transect. Branch samples can be either shot down from standing trees or collected from felled trees prior to or during the logging operation. An adequate sample is five to ten branches per crown. The samples can be used to assess the average number of capsules per twig and the average number of seeds per capsule. From these basic data, taking thirty samples per population, the yield of seeds per tree or per unit area of forest can be estimated.

The floral components of different crown regions have different flowering seasons and, therefore, must be separated in the above samples and counted separately. The samples for each crown region must be thoroughly mixed and sub-sampled to determine the size, viability and vigour of the seeds from different crops.

The known relationship between crown area and number of twigs during seed production (in karri there is an average of 21 twigs per m² of crown area) is a useful short-cut in the sampling procedure (Loneragan 1979). Therefore, the amount of seed for a given stand can be found as:

$$\text{Seeds per capsule} \times \text{capsules per twig} \times \text{twigs per unit crown area (21)} \times \text{crown area.}$$

Seed crops should be monitored during development and ripening of capsules, as losses will reduce earlier estimates. During the first summer the number of twigs bearing mature to near mature seed is halved to about 10 twigs per m² and this decreases to 1 twig per m² during the second summer (Loneragan 1979).

REGENERATION BURNING

Karri has been observed to regenerate where disturbance or fire has resulted in the baring of mineral soil without compaction of the soil (Kimber and Schuster 1979). Fire is generally the more efficient means of achieving regeneration. Natural regeneration occurs in mature and senescent virgin stands in which gaps have formed in the upper canopy and seed can reach the mineral soil through reduction in competition from shrubs and small trees by fire or soil disturbance.

The Aims of Regeneration Burning

The three aims of regeneration (slash) burning are (Jones 1978):

- (1) to prepare a seedbed suitable for the regeneration of karri following logging;
- (2) to stimulate seedfall from seed trees; and
- (3) to dispose of logging residue so that fire hazard within the regenerating forest is minimized and access for future operations is improved.

Karri Seedbeds and their Preparation

Loneragan (1961) found that the properties of the surface layers of the seedbed have quite remarkable effects on germination and plant growth. Seedbeds suitable for the establishment and development of karri seedlings are ashbeds and exposed mineral soil (Jones 1978). The best way to prepare these seedbeds is by burning.

Loneragan (1961) divided seedbeds into two broad categories: those that were receptive, and those that were unreceptive, to germination of seed. Receptive seedbeds included:

- (1) both ashbed and fringes of ashbed, formed from felled crowns and logging debris;
- (2) soil incinerated seedbeds, where a layer of ash lies on the incinerated soil;
- (3) soil char seedbeds, where the litter is burnt to expose the bare soil; and
- (4) unburnt disturbed topsoil.

Unreceptive seedbeds included:

- (1) surface char, where the burn was incomplete and patches of litter remain;
- (2) duff or litter surface, where no litter was burnt; and
- (3) subsoil or compacted surface soil.

Ashbeds have been studied extensively because they stimulate very fast early growth, the results of which are sustained and show up prominently in pole stands (Meachem 1961). Hatch (1960) found that regeneration burns have temperatures of the order of 850° C (at ground level and in the centre of the ashbed) which cause immediate and marked changes in the chemical properties of the soil. This is especially the case in the upper 2-3 cm of the soil; the effects decrease rapidly with depth. The most important of these changes are increases in pH, total soluble salts, available nutrients and the formation of calcium carbonate. However, soil organic matter is reduced by these high temperature burns.

The stimulating effect of ashbeds on the early development of karri is probably owing to a combination of factors. These include releasing a rich source of nutrients, increasing availability of nitrogen to young seedlings (despite total soil nitrogen decreasing), breaking up the soil surface to provide a suitable seedbed and sterilizing the soil in ashbeds which reduces competition from other plants and fungi.

Generally, the hotter the fire the greater the percentage of seedbed produced (Jones 1978). However, regeneration burns cannot be evaluated in terms of seedbed preparation alone. The fire intensity must be modified to ensure that the fire is both controllable and safe for lighting and suppression crews.

In clearfelled stands the optimum regeneration burn is that which is most intense within the prescribed condition, but which can also be safely controlled.

The Stimulation of Seedfall in Karri

In laboratory studies, Christensen (1971b) found that moisture was the key factor controlling the opening of seed capsules of karri. Capsules dried out under laboratory conditions shed no appreciable amount of seed until the moisture content dropped below the fibre saturation point (20-25 per cent). Christensen also studied the effect of various burning intensities on seedfall, these were:

- (1) control (unburnt);
- (2) very low intensity fire (less than 5 per cent crown scorch);
- (3) moderate intensity fire (35 per cent crown scorch); and
- (4) very high intensity fire (75 per cent crown scorch).

All stands had similar seed crops. Seedfall commenced about two days after the very high intensity fire, five to seven days after the moderate fire and seven to ten days after the very low intensity fire. The moderate and high intensity fires had similar patterns of seed shed, with seedfall being almost complete within a fortnight. The very low intensity fire induced seedfall much later and only a fraction was shed.

Christensen (1971b) also found that a fire of only low to moderate intensity (15 per cent crown scorch) induced almost total seedfall. He concluded, therefore, that seedfall was not dependent on high intensity fires and that there was no detrimental effect on seedfall in such a fire. The main benefits of a high intensity regeneration fire, therefore, appear to be not its effect on seedfall, but its effect on the seedbed and reduction of logging debris.

Disposal of Logging Residue

The removal of logging residue is a very important function of the regeneration fire. Between the ages of about 5 and 15 years karri is very susceptible to fires (Underwood 1978). The removal of logging slash by the regeneration burn greatly reduces the chance of a devastating wildfire occurring in young regeneration.

Apart from this, the removal of slash by fire reduces the amount of unavailable soil (soil covered by logging residue), and at the same time results in the formation of ashbed. It has the added benefit of commencing the destruction of large logs that could limit access when these areas of regeneration are being thinned.

Since the mid 1970s logging operations have generally moved from pure karri stands into stands with a large component of marri and some jarrah.

Initially it was thought that these stands would produce a larger proportion of logs unsuitable for sawmilling or woodchipping, and therefore increase the amount of logging debris produced. High standards of utilization have meant that the quantity of debris on the ground has been minimized and the threat of

damage to crop trees near logs during prescribed burning is small. Movement of machinery for thinning operations should not be a problem as machines specifically built for thinning operations and manoeuvrability can be used.

FACTORS AFFECTING GERMINATION

The collection of karri seed is a time-consuming and costly operation. The factors that affect germination of karri seeds play a vital role in determining the success or failure of regenerating the forest. Improved germination percentages would result in a less demanding requirement for seed tree regeneration and increase the viability of broadcast seeding as an artificial regeneration option.

There are many inter-related factors that affect germination of karri seeds, the factors described here are those that have been best documented and appear to be the most important.

Seedbed

Much of the early work on the germination of karri seed concentrated on the effect of different types of seedbed on germination. Loneragan (1961) found that, owing to the destruction of understorey plants and most of their seed in the soil during burning, ashbeds are sparsely occupied by understorey regeneration. However, where these beds are sown with karri seed, the germination rate is good. The germination of karri seed is greatest on ashbeds and poorest on snig tracks and landings (White 1974a; Annels 1980). The surface of snig tracks and landings is very hard, as a result the seed cannot fall into holes in soft earth and tends to get washed away. Snig tracks and landings can be rehabilitated by ripping or ploughing; this greatly increases the germination of karri seed (McCaw², personal communication).

Christensen and Schuster (1979) found that some ashbeds appear to inhibit germination. This is in contrast to findings of Meachem (1960), White (1974a) and Annels (1980). Christensen (personal communication) suggested that these apparent contradictions are because the edges of ashbeds are ideal for germination, but the centres are poor because of their resistance to initial wetting.

Once having germinated, the seedlings on the edge of ashbeds grow well as a result of the continued nutrient availability, while those on bare soil develop poorly or not at all. Seedlings in the middle of ashbed grow well if moisture status is also good. Compared with other karri soils, ashbeds are less structured, contain less organic matter and are more alkaline, with an accumulation of soluble salts in the surface layer (Hatch 1960). This partly explains why ashbeds have been observed to resist initial wetting by autumn rains

² L. McCaw, Department of Conservation and Land Management, Manjimup.

(Christensen and Schuster 1979). Ashbeds having less structure and containing less organic matter would also result in a poorer water holding capacity.

Insect Depredation

Loneragan (1961) observed ants consuming large quantities of karri seed.

Christensen and Schuster (1979) found that the effect on germination of insecticide (diieldren) dusted onto seeds, was significantly greater than that of fungicide, seedbed or shade treatments (Table 2). The effect of the insecticide was greater for autumn than for spring sowings, probably because the insecticide had been leached, blown away, or degraded during summer, prior to germination in autumn. Loneragan (personal communication) has observed insects to cause severe depredation of seeds and young germinants of karri.

Cunningham (1960) found that seed loss in mountain ash (*E. regnans*) forest is greatest on undisturbed ground vegetation and significantly less on mineral soil, probably because there are larger insect populations under this protective cover.

In alpine ash (*E. delegatensis*) forests in the Brindabella Range, ACT, O'Dowd and Gill (1984) found that in the absence of fire, postdispersal seed predators remove a large proportion of the small number of seeds. With fire, mass seedfall normally occurs (depending on the available seed crop), ant abundance on ashbed increases, but the ratio of ants to available seed decreases, so increased seedfall lowers the probability of a given seed being taken by ants. To minimize insect depredation and improve the effectiveness of seeding operations, seed should be sown in autumn and after a hot fire has removed ground vegetation.

Allelopathy

Several authors have found that eucalypt litter and topsoil appear to inhibit germination and seedling growth of some wet sclerophyll forest species (Kimber and Schuster 1979). Leachates from freshly fallen karri leaves inhibit karri germination to a level of 10 per cent of total available seed, when compared with a normal viability level approaching 95 per cent (Kimber and Schuster 1979). This factor is unlikely to be of concern under operational conditions, where a hot fire before seedfall or artificial seeding removes the litter layer. If other site preparation techniques were used, however, it would become an important consideration.

Soil Type

Soil type has little or no effect on the germination of karri seed. For both spring and autumn sowings, germination percentages did not significantly differ between red-loam and yellow podzolic soils (Table 3). Germination rates are the same for red earths (loams), gravelly red earths and deep and shallow podzols (Table 4) (Annels 1980). These results indicate that direct seeding methods are equally applicable to red-loam and yellow podzol soils on which karri occurs.

Time of Sowing

Autumn sowings of karri seed germinate better than spring sowings, probably (Table 3) because of reduced insect depredation and generally better conditions of temperature and moisture.

It is now operational practice to do all direct seeding in autumn after regeneration burns. However, there is no agreement as to which months produce the best results for direct seeding. Christensen and Schuster (unpublished) found that the period from late April to June accounted for 96 per cent of total germination, with highest germination occurring in April after the first rains (Table 5).

TABLE 2

Germination (percentage) of karri seed subject to various treatments on ashbed and non-ashbed sites in spring and autumn.

TREATMENT	SPRING			AUTUMN		
	ASHBED	NON-ASHBED	MEAN	ASHBED	NON-ASHBED	MEAN
Control	3.2	3.8	3.5	11.6	9.2	10.4
Shade	4.8	2.0	3.4	5.2	20.8	13.0
Insecticide	10.8	12.6	11.7	24.4	34.2	29.3
Fungicide	1.2	5.6	3.4	0.6	7.4	4.0
Mean	5.0	6.0	5.5	10.5	17.9	14.2

Source: Christensen and Schuster (1979)

TABLE 3

Germination (percentage) of karri seed sown on different soil types in spring and autumn.

SOIL TYPE	LOCATION	SEASON SOWN	
		SPRING	AUTUMN
Red loam	Gray Block 1	2.9	5.4
Gn 2.15 ^a	Gray Block 2	7.9	9.7
	Mean	5.4	7.6
Yellow podzolic	Sutton Block	8.8	10.2
Dy 3.62	Poole Block	1.9	3.9
	Mean	5.4	7.0

Source: Christensen and Schuster (1979)

^a After McArthur and Clifton (1975)

Annels (1980) compared sowing times by sowing the same quantity of seed for each time being tested. He found that for all soil types, seed sown in April resulted in significantly greater germination than seed sown in May or June (Table 4).

Although these results suggest that April is the optimum month for direct sowing of karri seed this may not always be the case. If autumn rains fail to occur (as was the case in 1981, 1982, 1983 and 1986) then the optimum sowing time will probably be late May. Soil moisture levels would be too low in April for favourable germination and increased insect predation is likely to occur. Moisture is probably the major factor limiting germination in autumn, but temperature is likely to be the major factor limiting germination in winter. This would explain the decline in germination rate from April to June (Table 4).

Fungal attack

From the limited amount of research done, it appears that fungi have little or no effect on the germination of karri seed. Christensen and Schuster (1979) found no improvement in germination when seed was dusted with fungicide (Zineb). It is possible, however, that

germination may be affected to some extent by fungal infection under the warm, moist conditions especially favourable to fungal development. Loneragan (1961) and Schuster (1979) suggest, rather, that the effect of fungal infection is greatest on newly germinated seedlings. It was hoped that pelleting seed with small amounts of fungicide and insecticide included in the clay would overcome fungal problems. However, the protective effect of the pellet had virtually ceased by the time the seed germinated, as the fungicide had been washed or leached away.

FACTORS AFFECTING EARLY SURVIVAL

The early survival of karri seedlings (whether germinated from seed *in situ* or planted as seedlings) is as critical as germination itself. The larger the number of seedlings that survive, the fewer seeds or seedlings are required to regenerate an area successfully, and the smaller the cost of infill planting to boost stocking.

Seedbed

As with germination, research on factors affecting early survival has tended to concentrate on the influence of seedbed. At the age of one year on one particular site, the proportion of seedfall surviving on ashbed, free topsoil and unreceptive seedbeds was 6.3, 2.7 and 0.6 per cent, respectively (Table 6) (Loneragan 1979). However, these differences were mainly owing to differences in germination rates, and Loneragan concluded that the effect of seedbed on early survival appeared to be minimal. Indeed, the survival rate (plant percentage - germination percentage $\times$ 100) calculated by Loneragan (Table 6) shows that survival is poorest on ashbeds.

Little seed germinated on the other seedbeds and it is likely that the seeds which did germinate were located on favourable micro-sites. This small amount of seed germinating on non-ashbed sites would have been only the most robust, and competition between seedlings would be less severe than on ashbed owing to fewer seedlings germinating.

TABLE 4

Effect of month of sowing and soil type on germination of karri seed.

SOIL TYPE	MONTH OF SOWING					
	APRIL		MAY		JUNE	
	STOCKED (%)	STEMS per ha	STOCKED (%)	STEMS per ha	STOCKED (%)	STEMS per ha
Shallow podzols	73.4	3 240	62.2	1 867	17.8	220
Deep podzols	73.3	3 020	62.2	1 208	17.8	275
Red earths	75.6	2 910	24.4	165	26.7	275
Gravelly red earths	86.7	2 689	44.5	1 262	35.5	658
Mean	77.3	2 965	48.3	1 126	24.5	357

Source: Annels (1980)

TABLE 5

Time of germination of spring-sown karri seed.

MONTH OF GERMINATION	RAINFALL (mm)	SOIL TEMP (°C)	TOTAL GERMINATION	GERMINATION (%)
Jan-April	47.0	25.5	-	-
Late April	122.8	18.1	751	47.0 ^a
Early May	19.0	17.4	259	16.2 ^b
Late May	63.7	15.1	315	19.7 ^b
June	172.3	14.6	209	13.1 ^b
July	146.5	13.2	34	2.1 ^c
August	88.1	13.5	16	1.0 ^c
September	49.0	13.0	3	0.2 ^c
October	12.9	21.1	11	0.7 ^c

Source: Christensen and Schuster (unpublished)

Data annotated with the same letter are not significantly different at $p = 0.05$ (Duncan's multiple range test)

TABLE 6

Karri germination and early survival in natural regeneration.

NORTHCLIFFE 1956 - 1957		SEEDBED			TOTAL
		FRESH ASHBED	CLEAN SURFACE	POOR SEEDBED	
Summer 1957 seeding and	Seedbed area sampled (m ²)	8.8	24.1	14.0	46.9
Winter 1957 germination	Number of seeds	139	471	205	815
	Germinants counted	44	34	5	83
	Germination(%) a*	31.7	7.2	2.4	10.2
Summer 1956 seeding and	Seedbed area sampled (m ²)	10.4	6.9	12.8	30.1
Winter 1957 establishment	Number of seeds	2665	2223	4214	9102
	1-year-old plants counted	169	60	27	256
	Plant success (%) b*	6.3	2.7	0.6	2.8
* Survival rate = (b/a) x 100%		19	38	25	27

Source : Loneragan (1979)

Soil Type

Christensen and Schuster (unpublished) followed the development of young seedlings during the first year after germination. They found that although germination had been the same for both the red loam and the duplex podzolic soil types, seedling survival was greater on the red loam type (Table 7). This difference was attributed to a greater proportion of gravel in the podzols. Increased percentages of gravel, particularly coarse gravel (>0.6 cm diameter) reduced seedling survival, probably because of the poorer water holding capabilities of soils containing significant amounts of coarse gravel. It is interesting to note that this appears to be in contrast with jarrah germination and survival, where gravelly soils produce the best results.

TABLE 7

Survival of karri seedlings at one year of age expressed as a percentage of the total number of germinants.

SITE NUMBER	1	2	3	4
Soil Type	Red Loam	Podzol	Podzol	Podzol
Survival %	41.1 ^a	34.3 ^{ab}	30.1 ^{ab}	19.0 ^b

Source : Christensen and Schuster (unpublished)

Data annotated with same letter are not significantly different at $p = 0.01$ (Duncan's Multiple Range Test)

Time of Planting

Any work which examines the best time to carry out a task is subject to seasonal variations between years. Results from such experiments can, at best, serve as a guide to timing of operations, but seasonality must always be considered.

An experiment begun in May 1975 to determine the best time for planting seedlings showed that survival of open-rooted, nursery raised seedlings planted in early May did not differ from that of seedlings planted in early June. Although height growth was much greater for the May plantings (Table 8a), this advantage was soon expected to disappear. Root pruned seedlings showed better survival.

Another experiment was established by Schuster in April 1977. The April plantings failed because there were no follow-up rains after an early break to the season. Plantings in late May, mid-June and late June showed good survival and growth (Table 8b). This research showed that three or four consecutive days of heavy rain are required at the start of the season so that the moisture status of the soil improves sufficiently after the summer drought to keep the seedlings alive. The best time to sow or plant will always vary with the season.

Presence of Retained Trees

The presence of retained trees is the major factor affecting the survival of karri seedlings during the first year after germination (Christensen and Schuster, unpublished). Survival decreases as the number and proximity of retained trees increases. This would be a major problem in a selection cut forest when only small gaps had been created by logging. In areas regenerated by seed trees it is operational practice to remove the seed trees within two years of regeneration to minimize seedling losses.

Incoll (1979) showed a definite curvilinear relationship between height, diameter at breast height over bark (d.b.h.o.b.), basal area and distance from an overwood tree. Regrowth of silvertop ash (*E. sieberi*)

TABLE 8b

Effect of time of planting on survival and height of open-rooted, nursery raised karri seedlings.

PLANTING DATE	HEIGHT (m) at PLANTING	HEIGHT (m) at MARCH 1978	SURVIVAL (%)
24 April 77	N/A	-	0
24 May 77	0.68	0.96	77
14 June 77	0.61	1.09	97
30 June 77	0.47	0.83	76

Source : Schuster (unpublished)

does not survive closer than 0.42 crown diameters to an overwood tree (just inside the vertical projection of the crown edge). Anything that does survive close to the overwood is severely suppressed.

In karri, the zone of influence of a retained tree is only twice the radius of the crown (Rotheram 1983). The total number of regrowth trees per hectare is severely reduced within this distance, and the number of crop trees (dominants and codominants) is reduced within 1.53 times the crown radius. Rotheram found that shading did not appear to be an important factor as there was little difference in growth between the northern and southern aspects.

This effect of retained trees on young seedlings could be caused by competition for moisture and nutrients, fungal infestation, allelopathy, reduced light intensities or a combination of all four factors. It is doubtful that the presence of retained trees significantly affects early survival of karri by competing for nutrients. Christensen (1974) found that decreasing nutrient levels were associated with enhanced survival. Drought, however, is a major factor affecting early survival of karri seedlings. On average, one seedling in four will die from the effects of drought during the first year after germination (Loneragan 1961). Competition for a limited water supply from retained trees is likely to lead to more seedlings perishing from drought.

TABLE 8a

Effect of time of planting on survival and height of open-rooted, nursery raised karri seedlings.

PLANTING DATE	No. of ORIGINAL SEEDLINGS	No. of SEEDLINGS SURVIVING at JUNE 1976	SURVIVAL (%)	HEIGHT (m)	No. SAMPLED for HEIGHT
9 May 75	100	73	73	0.61	33
26 May 75	100	67	67	0.43	33
5 June 75	78	54	69	0.35	26
5 June 75 ^a	84	45	54	0.40	22

Source : Schuster (unpublished)

^a All seedlings except these were root pruned prior to planting.

Growth rates of young seedlings, however, are likely to be affected by competition for nutrients from retained trees. The presence of retained trees may also create conditions suitable for pathogenic fungi. Ashton (1956) found that infection of seedlings of mountain ash (*E. regnans*) by soil-borne fungi increased under low light intensity. This could also occur in karri which is a similar forest type to mountain ash; however, little work has been done on this.

Survival of wet sclerophyll eucalypt seedlings (of which karri is one) increases with soil disturbance. Litter and topsoil adversely affect small seedlings. Cunningham (1960) found that survival of *E. regnans* seedlings during the first two years of life is three-to-five times greater on disturbed soil than on undisturbed soil.

Survival of karri seedlings decreases with increasing proximity to undisturbed scrub (Christensen and Schuster, unpublished). This may result from inhibiting chemicals present in undisturbed litter, or from competition for moisture.

Another possible explanation for reduced survival of karri seedlings near retained trees is that low light intensities may reduce photosynthesis and subsequent growth. The effect of light intensity on karri seedling growth and survival has not been studied in detail, although Rotherham (1983) concluded that shading did not significantly reduce growth of karri seedlings. Ashton (1956) found that *E. regnans* seedlings grown in about 30 per cent of full sunlight were not markedly different from those grown in 70 per cent of sunlight. At about 10 per cent of full sunlight, seedlings were etiolated.

In conclusion, competition for water is likely to be the most important factor.

NATURAL REGENERATION

Virgin Forest

In its virgin state the karri forest occurs in even-aged patches varying in extent from several to many hectares (White and Underwood 1974). In a natural situation fire or windstorm can provide the conditions suitable for the regeneration of even-aged stands. Their size depends on the severity of the fire or storm and the proportion of the original overstorey which it has killed. A similar process has been described by Mount (1964) for ash-type forests. However, karri does not appear to be as fire sensitive as many of the other very tall eucalypts such as mountain ash (*E. regnans*) and flooded gum (*E. grandis*). Forests comprising these species have large areas of fire-caused regrowth with none of the original trees surviving. In the karri forest (as in many other eucalypt forests) many trees of varying size and age in the original forest can survive and, with the regrowth, form a mosaic of even-aged and uneven-aged forest (White and Underwood 1974). As the stand ages the obviousness of different ages diminishes and it becomes difficult to determine whether a stand was originally even-aged or uneven-

aged. As an example of this, ring counts made on stumps in two clear felled virgin plots show a relatively wide divergence of ages. Age frequency distributions for these plots show peaks every 20 to 50 years, which apparently correspond with fires hot enough to kill part of the overstorey and allow for the development of regeneration. However, trees of the same age are not necessarily adjacent to each other, appearing to occur only where the fire has killed part of the overstorey, or where a gap was already present. The interpretation of even-aged or uneven-aged depends on the scale at which the stand is considered since all regeneration begins as an even-aged group.

Karri regenerates in the absence of fire only where ground disturbance results in the baring (but not compaction) of mineral soil (Kimber and Schuster 1979). Regeneration does not occur beneath a virgin stand (even when in a state of decline and where gaps have formed in the upper canopy) unless fire removes the litter layer and kills the understorey of shrubs and small trees. Regeneration is found in virgin stands that have been subjected to wildfires; but persistent regeneration, larger than small saplings, only survives in gaps created by deaths in the overstorey, and then only where the surrounding trees are not vigorous enough to dominate the space created.

Lane-Poole (1917) noted that natural regeneration can take place by seed falling into a hole where a large tree has fallen, but the number of seedlings that survive is only small. Thus, in its virgin state, before European settlement, the karri forest probably regenerated in four ways:

1. In large even-aged groups resulting from extensive high intensity fires started by lightning strike or by Aborigines. Talbot (1973) points out that the Aborigines rarely entered the karri forest (for both spiritual and practical reasons); however, they did travel along the coast and may have started fires that spread across the flats into the forest.
2. In small even-aged groups. This was probably the most common form of regeneration in the virgin karri forest. Most of the fires are unlikely to have been intense enough to cause the death of large areas of mature forest. Many of them, however, would have had 'hot spots', where small areas of the mature overstorey were killed.
3. As single trees resulting from the death of a tree in the overstorey caused by fire or occurring where a large tree had fallen. Regeneration would survive and persist if the surrounding trees lacked sufficient vigour to occupy the space which had been created.
4. Following winter storms or cyclones which occasionally blow down patches or swathes of mature forest. Regeneration may occur if such an area is subsequently burnt when seed is present in the surrounding forest. (Underwood³, personal communication).

³ R.J. Underwood, Formerly Department of Conservation and Land Management, Crawley, now retired.

The relative importance of these processes is uncertain, but examples of all can be readily observed in different parts of the forest.

Evidence of the wide variation in the size of even-aged patches can still be seen in the Deep River area in which the same stands were subjected to wildfire in 1937 and 1951.

The Selection Cut Approach

The clear felling system of regeneration using seed trees was successfully applied to the karri forest during the 1930s and many fine regrowth stands resulted (e.g. Big Brook and Treen Brook). At the end of the 1930s a selection system known as the Australian Group Selection System was introduced. This involved the removal of either single trees or large groups of trees. This system was introduced for the following reasons (White and Underwood 1974):

1. Good patches of sapling and pole growth occurred throughout the karri forest. At the time, there was no market for small sizes and this valuable resource was wasted with clear felling.
2. Disastrous fires in 1937 illustrated the need to open up fire control access and to salvage fire damaged material. This also helped management and inventory.
3. Clear felling of the forest often led to these areas being alienated for agriculture. Retention of a large proportion of growing stock helped prevent alienation.
4. The system was more flexible as intensity of cut could vary with the condition of the virgin stand. Overmature or fire damaged stands could virtually be clear felled.

Meachem (1960) noted that the group selection system required careful tree marking aimed at:

1. Removing the static volume (prime, overmature and defective stems).
2. Creating openings adequately served with seed trees for the regeneration of the new crop. Single tree removals are of limited value in this respect as competition from surrounding trees and inadequate light would restrict the development of regrowth. Removal of groups of two to four trees is ideal.
3. Removal of cull trees.

The fast growing dominants reserved after the selection cut were not only the most productive in terms of merchantable volume but were also the heaviest seeders, producing more than 80 per cent of the total seed supply (Meachem 1960). Apart from this, their seed was likely to be of higher genetic quality compared with less dominant trees. Up until the late 1950s, it was general practice to burn the annual

cutting section in advance of felling operations to reduce the fire risk, and to improve access and visibility which facilitated tree marking. This ceased when it was realized that this procedure reduced regeneration as fuel levels were too low to produce a fire hot enough to encourage seedfall or create good ashbeds, and that the development of karri flowers and fruit was adversely affected.

The harvesting was followed by a cleaning or top disposal operation which involved the removal of logging debris where it had been unavoidably heaped against growing stock. The regeneration burn was carried out in the first good seed year following this operation and ideally should have released adequate seed to fall on a cleanly burnt seedbed. The regeneration burning technique was assisted by a network of snig tracks which enabled the handling of the burn in units no larger than 8 ha. Areas carrying advance growth were ignited first, under mild burning conditions, while the rest was burnt under more extreme conditions to ensure a clean burn and the highest incidence of seedbed consistent with non-scorching of the canopy of the growing stock (Meachem 1960). Germination and early survival were generally good using this system. Meachem (1960) reported that at age one, stocking may be as high as 75 000 seedlings per ha, although it was usually substantially less, but still quite satisfactory.

It was soon realized that there were problems with the group selection system: the initial regeneration burn caused damage to the remaining growing stock; the regrowth tended to be suppressed by the retained stems, which themselves deteriorated owing to exposure from opening of the canopy; and managing the second felling cycle into established regeneration without causing excessive damage was difficult.

Rotheram (1983) quantified the suppressive effect of retained karri veterans on the growth of surrounding 50-year-old karri regeneration. No difference was found in the growth of the regeneration north and south of the veteran which discounted shading as being the factor responsible. Hence, competition from the veteran's roots for soil moisture and/or nutrients was the most likely alternative. Rotheram detected a strong suppression of regrowth up to 0.75 of the radius of the veteran's crown from its bole, with negligible volume of regrowth until 1.25R and normal volume beyond 2R (where R = radius of the veteran's crown). Incoll (1979) in a similar study on silvertop ash (*E. sieberi*) found that the zone of influence was 4-6R compared with 2R for karri. However, as karri crowns are twice the radius of *E. sieberi* crowns, the actual area in which the regeneration is suppressed is similar.

Because competition from the veteran's roots for soil moisture and/or nutrients seems the most likely explanation for the regrowth suppression, it follows that competition on the yellow podzolic soils, which have a very different nutritional and moisture status from that of red loams on which this study was done, is

likely to be greater. On the red loam Rotheram (1983) found that for each 1 per cent of veteran crown cover, regrowth volume was reduced by 2 per cent: i.e. 0 per cent veteran crown cover allows 100 per cent of normal regrowth volume, 10 per cent veteran crown cover allows 80 per cent of normal regrowth volume, and 20 per cent veteran crown cover allows 60 per cent of normal regrowth volume.

Beyond 20 per cent veteran crown cover, the zones of influence of veterans overlap and the combined influence has not yet been quantified. In some cases veterans are of good quality and loss of regrowth is partly compensated for by increment on the veterans. Usually, however, the veterans are of poor quality and valuable regrowth volume is lost (Rotheram 1983).

The clear felling system was reintroduced in 1967, when it was decided that the regeneration produced by the selection system was too difficult to manage satisfactorily.

The Clear Felling Approach

When clear felling was reintroduced into the karri forest, the seed tree method used in the 1920s and 1930s was chosen as the optimum method of regenerating the forest. In 1966/67 Loneragan set up a large scale experiment to examine all aspects of a system of clear felling with seed trees. The trial involved utilization; seed fall prediction; specification, timing and control of the regeneration burn; monitoring seed fall and germination; and subsequent removal of the seed trees.

An area of about 60 ha in Gray Block, 30 km west of Manjimup, was selected. Between March and October 1966 the area was clear felled with two-and-a-half to five seed trees per hectare being retained. The area received a high intensity regeneration burn coinciding with a heavy seed crop in January 1967. White (1974a) took over the experiment after the regeneration burn and the regeneration was appraised the following June. The seed trees were removed in October and November of the same year.

Seed Supply

The availability of seed and correct timing of the regeneration burn are vital to the success of the seed tree operation (White 1974a). The summer of 1966/67 coincided with the best seed crop in ten years, so seed availability was optimum, producing 1.48 million seeds per hectare. By December 1966, 85 per cent of seed capsules had matured, although seed availability was expected to be even greater the following spring.

The coupe was burnt in December to take advantage of optimum fuel conditions. The resulting high intensity fire left an ashbed free of residual scrub and all seed trees received crown scorch, indicating that most of the capsules would dry sufficiently to open and shed their seed.

Germination

Results of sampling for regeneration six months after the burn showed an abundant and well distributed stocking. White (1974a) found that the best germination occurred on ashbeds and the worst on snig tracks and landings. The very high stocking of germinants (85 000/ha) might suggest that there were too many seed trees per hectare. White (1974a) points out, however, that the seed crop was unusually good and that normally the number of germinants would be less. In addition, retention of a large number of seed trees of excellent size and quality encourages sawmillers to return and remove them, and seed tree density could be varied with anticipated seed crop.

Removal of Seed Trees

Removal of seed trees ten months after the regeneration burn did not excessively damage the young seedlings (White 1974a) because at this stage they were still flexible and able to tolerate the impact. Where large crowns fell into the young regeneration, enough seedlings survived to ensure no unstocked gaps. To reduce losses, the logging crews were instructed to use established landings and snig tracks and avoid sideways movement of logs. Damage was found to be considerably reduced with the use of logging arches which lift most of the log off the ground.

Stand Development

Three years after germination, rapid height growth (up to 1.5 m yr⁻¹) was recorded, particularly on ashbeds (White 1974a). Scrub was present, but was not dominating the young karri. Although overstocking of karri was evident in early regeneration surveys, marked dispersion of vigour ensured early dominance and continuous stand growth.

Despite the success of this experiment, irregular seeding meant that the karri regeneration program could not be achieved solely by using this method. The seed crop was particularly heavy and the experiment was carried out in an area widely recognized as being optimum for regeneration in the karri forest. To further quantify the practicality of the seed tree method, the experiment was extended over a number of years and a range of karri sites.

The potential of the seed tree method to manipulate the species mix of the new stand was later examined (White 1971). Three plots were established in a mixed karri-marri stand 30 km south east of Manjimup. On Plot 1, karri was favoured by retaining only a karri seed source. On Plot 2, marri was favoured by retaining only a marri seed source, while on Plot 3 both seed sources were retained to maintain the species mixture. Plot 1 was successful with karri dominating the regeneration. Plot 2 was borderline, owing to a lack of

marri seed, although there was a fair stocking of lignotuberous advance growth. Plot 3 was satisfactory with stockings of both karri and marri (Table 9).

On both Plots 1 and 3 there was acceptable stocking of marri as lignotuberous advance growth and coppice, despite the presence of abundant karri regeneration. This has generally been found to be the case, and in operational practice in mixed karri-marri stands, karri seed trees only are retained; lignotuberous advance growth provides adequate marri regeneration.

The clearfelling approach provides a highly effective and economical means of regenerating karri and karri-marri forest. It does, however, have two disadvantages.

1. All large trees are removed from the stand, eliminating habitat niches for some birds and mammals. This can be overcome by retention of uncut strips of forests along streams and rivers and in large reserves; and by regrowing the forest for sufficient length of time for hollows to develop.
2. The operation can be visually unattractive. However, the associated visual impacts of this silvicultural approach can be managed using a variety of landscape planning and design techniques. Landscape management systems can be applied at both the broad scale and specific site application levels (Revell 1991).

ARTIFICIAL REGENERATION

The most economical way to regenerate the karri forest after timber harvesting is to use retained dominant trees as a seed source. This method cannot be used exclusively for several reasons (Walker 1980).

1. Karri seed availability: assured crops may occur only one year in four, sometimes extending to one year in six.
2. The regeneration burning capacity: it is not feasible to delay regeneration burning following logging to wait for a good seed year before burning. This could result in 8000 to 10 000 ha of regeneration burning in one summer. The current capacity is 2500 ha yr⁻¹.
3. Sawlog/chipwood intakes: some coupes, regardless of the availability of seed, are not cut to seed trees in order to smooth out the gross annual imbalance of sawlogs and chipwood which occurs with seed tree operations.
4. Severe fire damage in the past may have left the seed trees unable to provide enough seed.

The alternative to natural regeneration using seed trees is to use 'artificial' methods, i.e. direct seeding or planting (Walker 1980). The scarcity and cost of karri seed permits direct seeding of only small areas each year. This area may be increased if techniques to reduce the amount of seed used in direct seeding can be developed, or if techniques are developed for a more economic supply of seed.

Direct Seeding

Seed can be sown directly by one of two methods. It may either be broadcast over an area or placed in discrete spots.

TABLE 9

Regeneration of karri and marri after cutting with different proportions of these species as seed trees.

SEED SOURCE		STOCKING (s.p.ha) at OCTOBER 1969 (percentage stocking by milacre)			
SPECIES	No. of SEED TREES/ha	KARRI (SEEDLINGS)	MARRI (ADVANCE GROWTH)	JARRAH (ADVANCE GROWTH)	TOTAL
Karri	3.5	44 900 (95%)	400 (12%)	-	45 200 (95%)
Marri	7.0	400 (12.5%)	1 200 (29%)	300 (11%)	1 900 (46%)
Karri-marri	3.0	16 000	1 900	30	17 900
	8.5	(90%)	(39%)	(2%)	(94%)

Source : White (1971)

Broadcast Sowing

Broadcast sowing of karri seed has variable success and depends mainly on site factors (Loneragan 1971). A number of experiments were established in the 1930s by D. R. Stewart and were reviewed by Loneragan in 1971. In Treen Brook, where a good seedbed was available, the broadcast sowing of 1.4 kg ha^{-1} (600 000 seeds/ha) resulted in the establishment of 2500 seedlings/ha. Broadcast sowing at rates less than 60 000 seeds/ha gave unacceptable establishment. At Quinninup, seed was sown on an ex-pasture and bracken site that had been burnt. Establishment was quite poor on most of the site; the only acceptable stockings occurring on the ashbeds around logs (16 500 seedlings/ha). Bracken and other weed species also caused problems. Seven years after sowing the average stocking on all seedbeds was only 1975 s.p.ha (stems per hectare).

The major cost involved in broadcast sowing is the cost of the seed itself. Many seeds will fall on unsuitable sites, and reasonable results are obtained only on the best sites under favourable conditions. The minimum number of seeds for average conditions to produce adequate regeneration is 200 000/ha (Loneragan 1971). A figure of this order was also used by White (1971) in relation to the seed tree method. Annels (1980) found that no more than 60 000 seeds/ha and probably as low as 20 000/ha could give satisfactory regeneration, but that the time of sowing was critical. The best results were achieved with April sowings. More than 60 000 seeds/ha increased stocking rates but did not improve distribution, as this was largely determined by the availability of seedbeds. Current operational practice is to use about 40 000 seeds/ha, but Annels⁴ (personal communication) is confident that this could be reduced in certain areas.

The seed used in Annels' (1980) work was pelleted using a seed pelleting technique developed by the Victorian Forests Commission in the early 1970s. This method involves coating the seed with a small amount of a water-soluble glue (Methofas) and kaolin clay, which has been mixed with small amounts of insecticide (DDT) and fungicide (TMTD). The seed is finally coated with further layers of kaolin clay until its final mass is approximately four times the original mass of the seed. Loneragan (1971) found that clay pelleted seeds result in three times as many germinants as unpelleted seed.

Current practice is to pellet seed with kaolin clay and methocel glue. The main advantage of pelleted seed is that it is more easily spread. Some fungicides have been found to inhibit germination, and insecticides lose their value once the seed has germinated. The time and cost involved in pelleting with fungicide and insecticide was not considered worth the minimal benefit.

An operational trial where 40 ha of clear felled karri forest was successfully regenerated (to 2430 seedlings/ha) by the aerial seeding of 45 000 seeds/ha was established in the late 1970s (Schuster 1980a). Aerial seeding requires more seed than manual broadcast sowing, but is considerably quicker and cheaper. With the establishment of karri seed production areas and seed orchards it may become a useful regeneration technique in the future.

Spot Sowing

The spot sowing technique has created interest because of its potential to use much less seed than broadcast sowing. Generally, only seedbeds suitable for germination are stocked following broadcast sowing (Annels 1980). The number of seeds per spot has no bearing on the success of the sowings, with 8 seeds per spot being as successful as 100 seeds per spot. This led Loneragan (1971) to try spot seeding onto suitable seedbeds to reduce the amount of seed required. He determined that spot seeding required an average of about 32 000 seeds/ha or 15 per cent of the amount he found was needed for broadcast sowing. He also observed that although seed is conserved, the extra time involved means that the total cost is not reduced and that successful results could only be obtained on better sites. Schuster (1980b) states that spot sowing is capable of using up to 40 per cent less seed than broadcast sowing.

Results with spot sowing of pelleted seed have continued to be disappointing and little success has been achieved using fewer than 27 000 seeds/ha. Schuster (1980b) attributes this mainly to seedling depredation following germination when the pellet is no longer protective. In addition, personal observations by Hewett suggest that a significant percentage of the seed may be washed away by heavy winter rains. These problems would, of course, also apply to broadcast sown seed.

A number of experiments to test a plastic cone-shaped shelter designed in Finland have been established. The shelter creates its own microclimate which enables quick germination, natural rooting and strong growth. It protects the seed and young seedlings from extremes of climate, insects and other predators. From early observations, it also appears to greatly reduce the amount of seed that is washed away, although the shelters themselves can be washed away by overland flow following very heavy rain.

The results of an experiment designed to determine stocking and early growth rates using this system indicate that 1700 shelters/ha (3 m x 2 m spacing) sown with 2-3 seeds per shelter provide a stocking of at least 1000 s.p.ha at one year. The number of seeds required per hectare for this operation (4000) is 10 per cent of the requirement for broadcast seeding and compares favourably with planting.

⁴ A. Annels, Department of Conservation and Land Management, Manjimup.

Three sites were chosen for this experiment and 500 shelters were sown at each site, each containing four karri seeds. Two of the sites (Sutton 18 and Lindsay 29) gave excellent results with 75 per cent and 74 per cent of shelters stocked respectively. The other site (Dombakup 8) gave very poor results with only 45 per cent of the cups stocked. The major problem at Dombakup was overland wash on a steep slope, and modifications to the design of the shelters are necessary if they are to be used successfully on such sites. Ashbeds were superior to non-ashbeds and snig tracks in terms of both stocking and early growth. Eighteen months after the experiment began, 86 per cent of ashbed sites were stocked, 57 per cent of non-ashbeds were stocked and only 31 per cent of snig track sites were stocked. Mean heights were 1.8 m on ashbed, 0.97 m on non-ashbed and 0.55 m on snig tracks. These results were achieved without adding fertilizer.

An operational trial has also yielded encouraging results. The average time to sow 1 ha at a spacing of 2 m x 2 m (2500 shelters) is about five hours. This compares favourably with planting seedlings. The time to sow is largely dependent on site preparation, i.e. if there is any scrub left after the regeneration burn, this needs to be cleared away first to create a favourable microsite by scratching the soil surface.

One of the major benefits of this system is that very little bending is involved, and therefore there is less strain on the planters' backs. One problem to emerge from the operational trial is that the pelleted karri seed became clogged in the shaft of the sowing device during wet weather. A new experiment has been established to determine whether pelleted seed is necessary.

Sheltercup sowing requires slightly more seed than planting nursery raised stock but it has the advantage of being less labour intensive, and therefore potentially less expensive. At present the cones are imported and are too expensive to be used on a large scale. In addition, the system has been designed for use on cultivated ground, and neither the sowing device nor the shelters are robust enough for use on all regeneration areas. They could, however, be used on some sites where steep slopes and very hard ground cover only a small area. Results have not been consistent enough to warrant using them on a large scale.

Hand Planting

Until 1988, up to two-thirds of the regeneration of karri was done by hand planting nursery-raised open-rooted seedlings in some years. In a typical planting season, about 2 million karri seedlings were raised for planting 1500 ha of karri forest. Containerized karri seedlings are now grown for all planting. Wildings (naturally regenerated seedlings) were sometimes used in earlier years if the number of nursery-raised stock was insufficient.

Wildings

Wildings constitute a readily available source of cheap planting stock (Christensen 1969). The most important factors in terms of survival and early growth are the size of the wildings and the time of planting. One-year-old large wildings (60-90 cm), pulled from the ground with their foliage and having their longest roots lightly trimmed, gave the best results. Percentage survival of these plants varied from 78.8 per cent on the worst site to 93.8 per cent on the best site (Christensen 1969). Survival was best following planting early in the season (May-June) (Christensen 1970). Christensen found little difference in the survival of plants lifted or pulled and those left untrimmed, trimmed or stumped (heavily root pruned). In contrast, Skinner (1972) found that lightly trimmed seedlings were more likely to survive than stumped ones, irrespective of size. Larger wildings tended to survive, as they were most able to overcome the scrub competition. However, smaller stock or nursery stock previously root pruned gave better results if planting was late in the season.

Skinner (1972) confirmed that the best time for planting wildings was mid-June to late July. Wildings planted in mid-April also showed very good survival, probably because their roots were still active and there was a reasonable amount of soil moisture. By May, however, the roots were less active and there was no corresponding increase in soil moisture until mid-June. Trimmed plants gave much better survival than stumped plants, and the ideal size was 30-60 cm, although plants up to 90 cm gave satisfactory results (Skinner 1972).

Planting wildings is a satisfactory way of regenerating the karri forest (Loneragan 1971). The height growth of root-balled wildings is consistently greater than for spade-lifted or pulled-up stock, probably owing to the retention of a greater number of small feeder roots. The major factor affecting the survival of wildings is desiccation at the time of lifting and during transportation (Loneragan 1971). This can be minimized by wrapping the plants in plastic sheeting. The shoots of the wildings tended to die back when transplanted; however, rapid growth of hardy plants in the early years after planting quickly occluded the dead tips. Wildings are expensive to gather and transport and are rarely used in practice.

Open-Rooted Nursery Stock

Planting stock raised in CALM's West Manjimup Nursery is more amenable to growth regulation than wildings. Through suitable fertilizer and irrigation treatments, the condition, size and time of planting can be adjusted to suit various planting requirements (Loneragan 1971). The number of seedlings raised each planting season is carefully calculated from the total area to be regenerated and estimated seed availabilities.

Open-rooted nursery stock is given special treatment including regular root pruning, weed control and controlled irrigation which ensures healthy, hardy plants, able to withstand the shock of lifting, transporting and transplanting into a harsh environment. Annual surveys of seedlings planted in the previous winter have indicated an average survival rate of 90 per cent.

One of the major problems encountered in karri open-rooted nursery beds is vigorous weed growth encouraged by high levels of fertilizer and regular watering. A number of experiments have been conducted in an attempt to solve this problem.

Schuster and Fremlin (1980) tested a total of seven pre- and post-emergent herbicides in the open-rooted karri nursery. The pre-emergent herbicides tested were nitrofen (TOK-E-25), diphenamid (Enide 50W), propazine (Gesamil) and chlorthal (Dacthal W75), all being applied at the time of sowing in January. The post-emergent herbicides used were nitrofen, glyphosate (Round-up), a mixture of terbuthylazine and terbutometon (Caragard) and monosodium methylarsonate (Daconate 8). These were applied 30 days after seeding when the karri seedlings were at the 6 leaf stage (approximately 5 cm tall). All of the herbicides were applied with a logarithmic sprayer, which supplies a continually decreasing amount of herbicide along a plot, enabling the testing of a wide range of application rates.

The two treatments to show the greatest promise for weed control were the pre-emergent applications of nitrofen and diphenamid, although diphenamid reduced the height growth of the karri seedlings. The other two pre-emergent herbicides gave unsatisfactory results, with propazine significantly reducing karri germination and survival, and chlorthal giving poor weed control, except at high rates of application. Apart from nitrofen the post-emergent herbicides significantly reduced karri stocking and only achieved adequate weed control at high rates of application. Schuster and Fremlin (1980) concluded that a pre-emergent application of nitrofen at an application rate of 3.5 kg ha⁻¹ (active ingredient) would be the most effective treatment. If a post-emergent herbicide were necessary, which is unlikely, a further application of nitrofen at 9.0 kg ha⁻¹ should prove effective. Shortly after this trial, however, nitrofen was withdrawn from sale.

Breidahl (1984) tested a further four pre-emergent herbicides using the logarithmic sprayer. These were simazine (Gesatop), alachlor (Lasso), oxyfluorfen (Goal) and metribuzin (Lexone). The herbicides were applied in December 1983 a few days after the karri seed was sown.

Simazine was very non-selective in its action, controlling both weeds and the karri at high application rates, but neither at low application rates. Alachlor gave poor control of broadleaf weeds, which adversely

affected karri seedling survival and growth.

Oxyfluorfen and metribuzin gave very satisfactory results in terms of both weed control and karri survival and growth. Optimum application rates were 0.45 and 0.35 kg ha⁻¹ (active ingredient), respectively.

A major weed problem in the karri nursery is caused by large infestations of crabgrass (*Digitaria sanguinalis*), which is not adequately controlled by pre-emergent herbicides. An experiment in January 1984 tested the effect of the post-emergent herbicide fluazifop-butyl (Fusilade) on crabgrass and karri seedling survival and growth. The results (unpublished data) show that young crabgrass (1-2 cm diameter) is killed by an application of 0.5 kg ha⁻¹ active ingredient with no effect on karri seedlings at the two-leaf stage. Large crabgrass in slightly older karri seedlings (> 5 cm tall) can be controlled by two sprayings at four-week intervals of 1.0 kg ha⁻¹ active ingredient.

When open-rooted seedlings are transplanted, the shoots often die back (Loneragan 1971). However, the plants quickly recover when fertilizer is applied. This recovery is even better in the absence of competing scrub. On unfavourable sites they do not recover quickly enough from the 'transplant shock' and cannot compete with scrub species. This is where containerized stock is invaluable.

Abnormal Root Development

Breidahl observed that some planted open rooted karri seedlings initially develop a different root system from those found in natural regeneration. Roots of both planted and natural regeneration have been excavated and keyed out using a karri root system key (Fig. 2).

Initial results (Table 10) indicate that in some instances root systems of open rooted planted karri lack the strong, vertical taproot, typical of natural regeneration. The root systems of the open-rooted seedlings have much larger lateral roots than those that have regenerated naturally, and where a taproot is present it invariably runs parallel to the soil surface with the lateral roots. This may make these trees more susceptible to windthrow.

This development of the root system of open-rooted seedlings may be caused by a combination of the following factors.

1. Fertilizer: which is applied only to hand planted regeneration.
2. Planting technique: Hocevar (1980) found that for certain tree species planting in a spade line resulted in a shallow root system with no apparent taproot, whereas planting in a hole resulted in a deeper root system with an obvious taproot. The hole made by a karri planting spear is small and narrow and this may affect root development. On hard sites the planting holes may not be deep enough for normal root development. Planting spears have now been replaced by 'Pottiputkis' which create a larger hole filled with a container-grown seedling with a compact root system.

3. Root undercutting: this nursery technique involves physically cutting the main taproot of seedlings in order to favour the development of a fibrous root system.
4. Soil type: karri taproots seem unable to penetrate a clay layer in the soil, tending instead to run parallel to it. In some areas this clay layer is very close to the surface and on these sites even the natural regeneration is unable to produce a strong taproot.

Containerized Nursery Stock

Containerized seedlings were not used in the past because of their greater cost compared with open-rooted seedlings. Loneragan (1971) found that the roots of peat-potted seedlings appear to be unchecked at the time of planting, enabling them to take possession of a site quickly. This is an important factor on unfavourable sites.

Compressed peat pots were found to produce healthier and sturdier seedlings in greater numbers, in shorter periods and more cheaply than any other type of container (Loneragan 1971). Containerized stock is now used exclusively: mechanized nursery operations have narrowed the price differential with open-rooted stock, survival in the field is more reliable, seed usage is reduced, it can be sown later in the season and there is less root distortion in planting. Alternatives to peat pots have been introduced with excellent results.

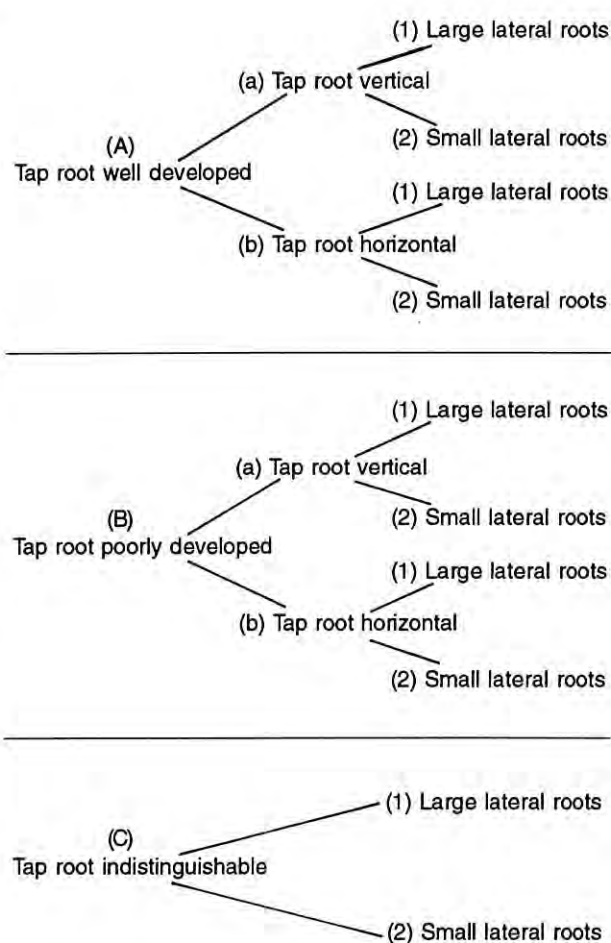


Figure 2. Karri root system key.

TABLE 10

Effect of soil type and regeneration method on karri root systems.

ROOT TYPE (from Fig. 2)	SOIL TYPE							
	LOAM		SAND		PODZOL		CLAY ^a	
	N	H/P	N	H/P	N	H/P	N	H/P
Aa 1 and 2	17	9	-	3	-	3	-	-
Ab 1 and 2	-	6	-	3	-	3	-	-
Bb 1 and 2	-	6	-	3	-	3	-	1
C 1 and 2	-	4	-	2	-	1	2	2
Total No. of seedlings	17	25	-	11	-	10	2	3

Source : Breidahl (unpublished)

N = Natural (seed tree) regeneration

H/P = Hand planted regeneration

^a = Close to surface

EFFECT OF FERTILIZER AND PLANT SPACING ON EARLY GROWTH

Increasing nutrient availability and growing space for young karri regeneration could significantly improve early growth and subsequent yield of regenerated stands. As a result, several experiments testing the effect of fertilizer, initial spacing, and their combined effect, on the growth of karri seedlings have been established.

Fertilizer

Although the stimulating effect of ashbed on the growth of karri seedlings has long been known, the nature of the response was not well understood until 1960. Hatch (1960) showed that karri ash contains significant amounts of phosphorus, calcium, magnesium and potassium. He also found that other marked chemical and physical changes are associated with ashbeds. These include increases in pH and total soluble salts and the formation of calcium carbonate. However, soil organic matter is reduced by high temperature burns.

The major effect of ash in stimulating karri seedling growth (grown from seed) in pots is attributed to an increase in the supply of phosphorus to the plant (Loneragan and Loneragan 1964). In the absence of ash, addition of phosphorus up to 22 t ha⁻¹ increased dry matter production of the shoot by 600 per cent. Application of ash alone increased height growth by 150 per cent, diameter growth by 200 per cent and dry matter production by 300 per cent. However, in the presence of phosphorus the response to ash disappeared, the interaction being significant at $P < 0.001$ (Table 11).

TABLE 11

Effect of phosphate fertilizers and ash on the growth of karri seedlings grown for four months in pots of karri topsoil.

ASH (t ha ⁻¹)	FORM OF PHOSPHATE	SUPERPHOSPHATE (kg ha ⁻¹)			
		0	500	1250	3125
		DRY WEIGHT OF SHOOTS (g x 10 ⁻¹ per plant)			
0	Na	4	67	69	76
	K	4	66	70	50
2.75	Na	8	69	66	74
	K	7	71	77	77
8.25	Na	12	72	72	81
	K	13	77	79	84
24.75	Na	18	73	82	77
	K	28	70	84	75

Source : Loneragan and Loneragan (1964)

Loneragan and Loneragan (1964) also found that ash treatment greatly increased nitrogen supply. In the presence of all known nutrients except nitrogen karri seedling growth was poor. In the absence of nitrogen the addition of ash doubled dry matter production of the shoot, but in the presence of nitrogen there was no response to ash (Table 12). Loneragan and Loneragan concluded that under all conditions phosphorus and nitrogen supply are the major limiting factors in the growth of karri seedlings on the soil examined. The primary effect of ash was to increase the supply of phosphorus, but the combined effect of nitrogen and phosphorus was also very marked.

TABLE 12

Effect of ammonium nitrate and ash on the growth of karri seedlings grown for four months in pots of karri topsoil.

	DRY WEIGHT OF SHOOTS (g x 10 ⁻¹ per plant)	
	- Ash	+ Ash
- Ammonium Nitrate	8	19
+ Ammonium Nitrate	86	86

Source : Loneragan and Loneragan (1964)

Under field conditions the two major factors influencing the early growth of karri are nutrient supply and competition from other plants (Loneragan 1971). Whether the increase in growth caused by fertilizer application was owing to an increase in nitrogen or phosphorus or both was not studied by Loneragan (1971). Potted seedlings showed a greater response to fertilizer in terms of height growth than to the removal of competition or to planting on an ashbed. At age 2.5 years the mean height of seedlings with fertilizer on a

recently burnt area was 3.1 m. Without fertilizer on the same site, the mean was 1.8 m. Fertilizer, therefore, increased growth by about 70 per cent. The response of wildings was similar, although variability within the treatments resulted in the responses not being significant. The effect of fertilizer at the time of planting was found to continue for at least five years.

Until 1970 no field experiment had been established to determine:

- (1) which nutrient is most important;
- (2) which phosphorus:nitrogen (P:N) ratio is most suitable; and
- (3) which quantities of nutrients should be applied to achieve rapid early growth of young karri seedlings at reasonable cost.

Christensen (1974) examined the effect of various P:N ratios and total quantities of fertilizer on growth of top-trimmed wildings. All treatments except those without phosphorus increased height growth significantly ($P < 0.01$), with the higher P:N ratios giving slightly better results. Superphosphate alone was among the best treatments. There was little or no increased growth with increasing rates of application (above 5 g of P and N per seedling), and little or no difference between a quick and slow acting nitrogenous fertilizer.

The more important conclusions of Christensen (1974) were:

- (1) important early growth increases in the first 12 months were obtained using fertilizer at time of planting;
- (2) phosphorus was more important than nitrogen in promoting this early growth. Phosphorus alone gave very good height growth, but nitrogen alone was no better than the control;
- (3) high rates of application (> 5 g/seedling of P and N) increased mortality and provided no significant benefit to early growth; and
- (4) significant cost savings could be achieved by using a P:N ratio of 3:1 with superphosphate as the phosphorus source, and Urea or Nitroform as the nitrogen source.

The research of Christensen (1974) and Loneragan (1971) was located on the red karri loams classified as Gn 2.15 by McArthur and Clifton (1975). With continued cutting, felling operations gradually moved into mixed karri-marri forests on gravelly yellow podzols. Schuster (1982) designed a new experiment to determine the type, rate, timing, placement and cost efficiency of fertilizer on these soils.

Type and Application Rate

Five fertilizers were tested. These were Superphosphate/Urea, Superphosphate/Agras, Magamp, Agras No. 1, and Vigran 9:9:9. Each of the fertilizers was applied at three different rates

corresponding to 5, 10 and 15 g of elemental P. The fertilizers were applied one month after planting and placed in a shallow hole 10 cm uphill from the seedling. All treatments produced significantly greater growth in all parameters (height, diameter and biomass) 14 months after planting, compared with the untreated control (Table 13a) (Duncan's Multiple Range test $P = 0.05$). Generally, both Vigran 9:9:9 and Agras No. 1 produced better growth than the other three fertilizers. In most cases there was little gain from increasing the application rate of fertilizer above the lowest rate applied (5 g P/plant) (Schuster 1982). Survival levels were acceptable (minimum 80 per cent) in all treatments except the Vigran 9:9:9 and Agras No. 1 at both 10 and 15 g P/plant treatments (Table 13b). Generally, survival levels decreased as application rates increased, a finding supported by Christensen (1974) who attributed the effect to nitrogen. The fertilizers with the highest N levels, Agras No. 1 (18 per cent) and Vigran 9:9:9 (9 per cent) produced the highest mortalities in this experiment.

Great care should be taken when applying N to karri seedlings under operational conditions (Schuster 1982).

Place of Application

The options tested were surface applications in a circle of 30 cm radius around the plant, a spot 10 cm uphill and a spot 10 cm downhill from the plant. Buried applications were placed 10 cm uphill, 20 cm uphill, 10 cm downhill or 20 cm downhill from the plant (Schuster 1982).

Although there were no significant differences in height growth increment, burying the fertilizer 10 cm uphill or 20 cm downhill from the plant produced slight increases in height growth and plant survival (Table 14a). The only treatment that produced significantly lower survival was the surface application 10 cm uphill from the plant.

Time of Application

The times of application tested were: at planting; two weeks after planting; four weeks after planting; eight weeks after planting; at planting and four weeks after planting; at planting and eight weeks after planting; and at planting, four weeks after planting and eight weeks after planting. Progressively larger height increments resulted from increasing the time between planting and fertilizing from 0 to 2 to 4 weeks (Schuster 1982). However, increasing this to eight weeks resulted in no improvement in growth compared with fertilizing at planting. The treatments at planting-plus-four-weeks after planting, at planting-plus-eight-weeks after planting and at planting-plus-four-weeks after planting plus-eight-weeks after planting did not result in significant increases in growth compared with the simple treatment four weeks after planting, which is operationally the most feasible (Table 14b).

TABLE 13a

Effect of fertilizer type and rate of application on growth of karri seedlings 14 months after planting.

HEIGHT GROWTH		DIAMETER GROWTH		ABOVE GROUND BIOMASS	
Treatment (type & rate)	Mean height increment (cm)	Treatment (type & rate)	Mean diam increment (cm)	Treatment (type & rate)	Oven-dried biomass (g)
N	49.5	N	0.61	N	110.1
C1	82.4	C1	0.79	B1	235.0
B1	88.4	B1	0.89	C3	269.4
C3	91.2	C3	0.94	C1	280.8
A3	99.0	D2	1.11	B3	282.6
B2	102.0	D1	1.13	A3	355.4
A1	102.5	B3	1.13	A2	357.1
D2	105.4	A2	1.14	B2	386.9
A2	108.7	A3	1.14	E1	397.1
C2	109.4	A1	1.15	D2	399.1
D1	113.7	C2	1.15	E3	401.3
E2	117.2	E2	1.21	C2	402.0
B3	117.6	E3	1.23	E2	418.3
D3	126.6	B2	1.25	A1	421.9
E3	126.6	E1	1.30	D1	529.1
E1	129.2	D3	1.36	D3	570.4

Source : Schuster (1982)

TABLE 13b

Effect of fertilizer type and rate of application on survival of karri seedlings 14 months after planting.

TREATMENT (type & rate)	SURVIVAL (%)	GRAMS N/tree
E3	72.2	27
D2	75.9	22
E2	75.9	18
D3	79.6	33
A3	87.0	15
D1	88.9	11
A2	88.9	10
B3	88.9	21
C1	88.9	3
C3	90.7	10
N	92.3	0
A1	92.6	5
B2	92.6	14
B1	92.6	7
E1	96.3	9
C2	98.1	7

Source : Schuster (1982)

Treatments for Tables 13a and 13b

N = control (nil application) 1 = 5 g elemental P/plant
 A = super / urea 2 = 10 g elemental P/plant
 B = super / agran 34 3 = 15 g elemental P/plant
 C = Magamp
 D = Agras No. 1
 E = Vigran 9:9:9

The success of the simple four weeks after planting application is likely to be a consequence of increased root activity resulting from warmer soil temperatures, and the recovery of the seedling from post-planting shock (Schuster 1982), making the plant more efficient at nutrient uptake. The reduced effect of the fertilizer application at planting may be owing to volatilization of N, and leaching of N and P away from the plant, before active nutrient uptake had begun. The poor result for the planting-plus-eight-weeks after planting application may have resulted from lack of nutrients at the beginning of the growing season. Woods (1976) observed a similar result with *P. radiata* seedlings.

Refertilizing One-year-old Karri

Schuster (1982) reported an experiment aimed at determining the potential for improving growth of one-year-old karri (fertilized at planting with 60 g of Superphosphate Urea mixture) with a further application of Agras No. 1 at 126 g/tree, Vigran 9:9:9 at 250 g/tree, and Magamp (slow release) at 56 g/tree (all of which are equivalent to 10 g of elemental P/tree.)

The fertilizer was buried in a hole 10-15 cm uphill from each tree. Only Vigran 9:9:9 significantly increased ($p = 0.1$) height growth over the control in the year after refertilizing (Table 15). All treatments showed greater than 95 per cent survival. No economic advantage was seen in refertilizing one-year-old karri with any of the options tested.

TABLE 14a

Effect of placement of Agras No. 1 fertilizer on height growth and survival of karri seedlings 13 months after planting.

	SURFACE APPLICATIONS			BURIED APPLICATIONS			
Distance from plant (cm)	30	10	10	10	20	10	20
Position *	C	U	D	U	U	D	D
Height growth increment (cm)	154.8	107.4	146.2	168.7	119.2	137.2	162.2
Survival percentage	85.2 ^a	63.0 ^b	84.0 ^a	85.2 ^a	88.9 ^a	87.7 ^a	91.4 ^a

Source: Schuster (1982)

Data annotated with the same letter are not significantly different at $p = 0.1$ (Duncan's Multiple Range Test)

No significant differences in height growth were noted

- * U = uphill from plant
D = downhill from plant
C = circle around plant

TABLE 14b

Effect of timing of Agras No. 1 fertilizer application on growth and survival of karri seedlings 14 months after planting.

	TIME OF APPLICATION						
	P*	P+2	P+4	P+8	P P+4	P P+8	P P+4 P+8
Height (cm)	109.1 ^c	126.8 ^{bc}	148.3 ^{ab}	105.6 ^c	166.7 ^a	117.4 ^{bc}	166.4 ^a
Survival Percentage	86.1 ^a	77.8 ^a	84.0 ^a	91.4 ^a	95.1 ^a	85.2 ^a	85.2 ^a

Source: Schuster (1982)

Where two or more application times were tested, the same total amount of fertilizer was used as in the single application

- * P = time of planting Data annotated with same letter are not significantly different at $p = 0.01$ (Duncan's Multiple Range Test)
P + 2 = 2 weeks after planting

TABLE 15

Effect of refertilization on height growth of one-year-old planted karri (assessed one year after refertilization).

FERTILIZER	CONTROL	MAGAMP	AGRAS No. 1	VIGRAN 9:9:9
Rate of application (g/tree)	0	56	124	250
Height increment (cm)	108.2 ^b	104.0 ^b	106.3 ^b	124.3 ^a

Source: Schuster (1982)

Data annotated with same letter are not significantly different at $p = 0.01$ (Duncan's Multiple Range Test)

Cost Effectiveness

Although growth increments are very important when choosing an appropriate fertilizer regime, cost is also important. Schuster (1982) noted that although Vigran 9:9:9 and Agras No. 1 were the best fertilizers for growth promotion, they were expensive. Some simple measures of growth rate per unit cost of materials were devised, to assess cost effectiveness (Schuster 1982). These are cm/cent (height), cm/cent (diameter) and g/cent (biomass). Each measure was obtained by dividing the growth increment for each factor (height, diameter, biomass) by the cost per plant for materials (Tables 16 a,b,c). Cost effectiveness decreased markedly as rates of application increased. In all cases the 5 g/plant treatment is the most cost effective. Superphosphate plus Urea is the most cost effective treatment, although its effect on plant growth is inferior to both Vigran 9:9:9 and Agras No. 1. Magamp and Vigran 9:9:9 are consistently the least cost effective of the fertilizers tested.

TABLE 16a

Cost effectiveness of height growth of karri seedlings for each fertilizer type and application rate tested.

TYPE OF FERTILIZER	COST EFFECTIVENESS OF HEIGHT GROWTH AT THE VARIOUS APPLICATION RATES TESTED (expressed as cm/cent)		
	5 g P/plant	10 g P/plant	15 g P/plant
Super-Urea	1.90	1.00	0.56
Super-Agran 34	1.19	0.81	0.69
Magamp	0.18	0.17	0.08
Agras No. 1	1.17	0.51	0.47
Vigran 9:9:9	0.87	0.37	0.27

Source : Schuster (1982)

TABLE 16b

Cost effectiveness of diameter growth of karri seedlings for each fertilizer type and application rate tested.

TYPE OF FERTILIZER	COST EFFECTIVENESS OF DIAMETER/GROWTH AT THE VARIOUS APPLICATION RATES TESTED (expressed as cm/cent)		
	5 g P/plant	10 g P/plant	15 g P/plant
Super-Urea	2.03	0.95	0.64
Super-Agran 34	1.35	0.94	0.58
Magamp	0.21	0.15	0.08
Agras No. 1	1.02	0.50	0.41
Vigran 9:9:9	0.69	0.32	0.22

Source : Schuster (1982)

TABLE 16c

Cost effectiveness of above ground biomass production of karri seedlings for each fertilizer type and application rate tested.

TYPE OF FERTILIZER	COST EFFECTIVENESS OF INCREASED SHOOT WEIGHT AT THE VARIOUS APPLICATION RATES TESTED (expressed as cm/cent)		
	5 g P/plant	10 g P/plant	15 g P/plant
Super Urea	713.5	301.7	200.1
Super-Agran 34	355.0	292.3	142.4
Magamp	76.9	55.0	24.5
Agras No. 1	477.8	180.2	171.7
Vigran 9:9:9	213.2	120.2	71.8

Source : Schuster (1982)

A new experiment was begun by Breidahl in 1984, (unpublished). This attempted to identify the most cost effective fertilizer treatment for planted karri seedlings. The trial tested eight readily available granular fertilizers, including Agras No. 1. Each fertilizer contained varying concentrations of P, while some also contained varying concentrations of N, potassium (K) and sulphur (S). In addition, there was an unfertilized control.

Each fertilizer was applied at the rate at which 5 g/plant of P was supplied to the seedlings, after the research of Christensen (1974) and Schuster (1982). This varied from 22 to 71 g/plant of fertilizer. The fertilizers were applied in July 1984 in a shallow hole 10 cm uphill from the seedlings, four weeks after planting. Height growth was measured 18 months after application (Table 17).

All of the fertilizers tested resulted in significantly greater height growth of the seedlings compared with the unfertilized control. Greatest height growth was achieved using fertilizers containing both P and N. Neither K nor S had any effect on the growth of the seedlings. No benefit was gained by increasing the rate of N above 2.5 g/plant, thus the Agras No.1 treatment (11.5 g N, 16 g S) was wasteful of both N and S.

Two fertilizers - MAP (monoammonium phosphate) and DAP (diammonium phosphate) - resulted in at least as good early height growth as Agras No.1 at less than half the cost. Although these fertilizers are more expensive per tonne than Agras No.1, their much higher concentrations of P means that far less is required per seedling. This leads to cost savings in both purchasing and application.

As a result of this experiment, operational practice now is to fertilize planted karri seedlings with 25 g/plant of DAP.

Planting and fertilizing are combined into one operation. Planters carry a bag of DAP tablets as well as their normal bag of plants. Tablets are placed in a spear hole approximately 10 cm uphill from the planted seedling. The DAP tablets are compressed granules of normal DAP fertilizer combined with a binding agent, sodium stearate (<1.0 per cent). Alcoa of Australia have been using these tablets in revegetating their bauxite pits for a number of years and have found that they at least match granulated fertilizer in terms of growth. Observations have shown that the tablets break down quite readily with water, but release is slow enough to allow roots to establish before the nutrient is leached.

No fertilizing experiments have been monitored over a long period, so information about the effect of fertilizer application at establishment on long term growth or on other site factors is not available. Research is required in this area.

Spacing

A karri spacing experiment was established in 1971 and measured in 1977 (Schuster 1978). Spacings tested were 1.2 m x 1.2 m (6727 s.p.ha), 1.83 m x 1.83 m (2990 s.p.ha), 2.74 m x 2.74 m (1329 s.p.ha), 3.66 m x 3.66 m (747 s.p.ha), 4.57 m x 4.57 m (478 s.p.ha) and 6.09 m x 6.09 m (269 s.p.ha). At each spacing the largest 12 trees were measured. This corresponds to a 100 per cent sample at the widest spacing, but only a 4 per cent sample at the closest spacing.

TABLE 17

Effect of fertilizer type on mean height growth and cost effectiveness, 18 months after application to recently planted karri seedlings.

TREATMENT	P	N g/PLANT	K	S	FERT. COSTS (\$/ha)	TOTAL COSTS (\$/ha) ^a	MEAN HT GROWTH (cm)	COST EFFECTIVENESS ^b
Control	0	0	0	0	0	0	117	-
Agras No. 1 (65 g/plant)	5	11.5	0	10.5	20.4	40.4	192	59
Agras No. 2 (48 g/plant)	5	6	0	6	14.2	31.2	194	78
DAP (25 g/plant)	5	4.5	0	0	9.9	14.9	194	163
MAP (22 g/plant)	5	2.5	0	0	12.8	17.8	205	144
Potato E (71 g/plant)	5	2.5	4.5	0	15.8	35.8	199	70
5-1 Super-pot (68 g/plant)	5	0	5	0	12.3	32.3	178	69
TSP (25 g/plant)	5	0	0	0	8.6	13.6	180	165
Superphosphate (55 g/plant)	5	0	0	0	8.1	26.1	180	86

Source : Bredahl (unpublished internal report)

^a calculated by adding fertilizer costs to the following estimated application costs (costs at 1 April 1985):

- (a) 65-71 g/plant = \$20/ha (requires separate fertilizer application)
 (b) 55 g/plant = \$18/ha (requires separate fertilizer application)
 (c) 48 g/plant = \$17/ha (requires separate fertilizer application)
 (d) 22-25 g/plant = \$5/ha (fertilize at same time as planting)

^b Cost effectiveness = $\frac{\text{mean height growth (cm)}}{\text{cost of fertilizing (cents/plant)}}$

No significant differences between treatments in terms of crop tree height and diameter growth were found, though there was a trend towards increased height growth in the closer spacings (Table 18a). The lack of any diameter increment response with increased spacing could be owing to one of two reasons. The advantage of increased growing space at wider spacings may be offset by greater genetic selection and occupancy of favourable microsites at closer spacings, or the dominant trees may be effective at utilizing their site even in dense stands.

TABLE 18a

Effect of initial spacing on diameter and height growth of karri at six years of age (Muirillup Experiment).

SPACING (m)	HEIGHT (m)	DIAMETER (cm)
1.22	9.06	9.22
1.83	9.17	10.43
2.74	8.19	9.95
3.66	7.72	8.97
4.57	7.55	10.57
6.09	7.31	10.12

Source : Schuster (1978)

TABLE 18b

Effect of initial spacing on the length of clean boles at six years of age (Muirillup Experiment).

Spacing (m)	1.22	1.83	2.74	3.66	4.57	6.09
Height to crown base (m)	3.35	2.38	2.18	1.77	1.04	1.18

Source : Schuster (1978)

Trees in the two widest spacings had significantly lower crowns than those in any other treatment. This is owing to a higher crown density at the closer spacings which obstructs light from the lower branches. Schuster (1978) noted that mean values of stem height to the base of the crown can be used as a measure of form and, therefore, future suitability for sawlog use (Table 18b). This experiment was located on former farmland and early scrub development was controlled by cultivation. Under normal forest conditions the dense scrub which is usually present would help shade the lower branches thus producing trees with longer boles and better form.

Although trees in the closest spacings had the highest crowns and the best form, stem mortality was high (Table 19). The suppressed stems indicated in Table 19 are those that were considered likely to die before the first commercial thinning, which will probably take place at about age 30 (Schuster 1978). These suppressed stems have resulted in the trees in the closer spacings having excellent form, yet the suppressed stems will not form part of the yield at first thinning. It must, therefore, be decided whether the cost of planting them is worth the improved yield on the crop trees as a result.

TABLE 19

Effect of initial spacing on stand health of karri (Muirillup Experiment).

SPACING (m)	INITIAL STOCKING (s.p.ha)	STEM SURVIVAL ^a (%) AT AGE 6 YEARS	SUPPRESSED STEMS ^b (%)	PRESENT STOCKING (VIGOROUS s.p.ha)
1.22	6727	90.8	25.1	4575
1.83	2990	90.7	16.6	2262
2.74	1329	96.5	17.0	1064
3.66	747	94.0	-	702
4.57	478	98.7	-	472
6.09	269	87.5	-	235

Source : Schuster (1978)

^a stem survival expressed as a percentage of initial stocking.^b suppressed stems expressed as a percentage of surviving stems.

In planted karri stands, a compromise has to be made between close spacing which promises good form, and wider spacing, which is cheaper to establish and requires less thinning, but which results in heavy branching, lowering the future sawlog value of crop trees. Current operational practice is to plant karri seedlings at a spacing of 2.5 m x 2 m (2000 s.p.ha).

Another spacing experiment was established in 1982 on a lower quality clear felled karri coupe at Nairn Block. The four spacings established were: 2 m x 2 m (2500 s.p.ha), 4 m x 2 m (1250 s.p.ha), 4 m x 3 m (833 s.p.ha) and 5 m x 4 m (500 s.p.ha). This experiment was measured in 1988 when the trees were six-years-old. Trees in the closest spacing (2 m x 2 m) were significantly shorter than those in the other spacings (Table 20a). This contrasts with Schuster's noted trend of taller trees with closer spacing. Of the largest 100 trees/ha, the mean diameter of trees in the closest spacing (2 m x 2 m) was significantly less than all other spacings. The mean diameter of the largest 100 trees/ha in the widest spacing (5 m x 4 m) was significantly greater than all other spacings. This trend is repeated with the largest 200 s.p.ha.

The height to the first live branch is significantly greater in the closest spaced plots indicating that, at this stage, these trees are shedding branches more efficiently than in the widely spaced plots (Table 20b). Height to the first live branch was smallest in the most widely spaced plots (47 per cent less than closest spacing). Stem mortality did not vary significantly between spacings.

This experiment is continuing to further quantify the effect of initial spacing on growth and form under operational conditions. Further refinement of spacing for operational planting can then be made if necessary.

Combined Effect of Fertilizer and Spacing

A fertilizing and spacing experiment was established in a one-year-old seed tree regenerated stand in Gray Block, west of Manjimup by Christensen in 1968. It consisted of four treatments with no replication. The treatments were:

- (1) spaced and fertilized (+S, +F)
- (2) spaced and not fertilized (+S, -F)
- (3) not spaced and fertilized (-S, +F)
- (4) not spaced and not fertilized (-S, -F)

The spacing treatment reduced stocking from over 5000 seedlings/ha to 1500 s.p.ha. This was achieved by placing bags over selected stems and then spraying unwanted stems with herbicide (2 per cent 2,4,5 T). The fertilizer treatment was 150 g of Nutrifert per tree (8 g N, 17 g P, 7 g K). Height and diameter of the largest 125 s.p.ha were measured nine years after treatment.

TABLE 20a

Effect of initial spacing on diameter and height growth of karri at six years of age (Nairn Experiment).

SPACING (m)	HEIGHT (m)	d.b.h.o.b. (cm) of largest 200 s.p.ha
2 x 2	6.99 ^a	9.62 ^a
2 x 4	7.68 ^b	11.56 ^b
3 x 4	8.07 ^b	11.37 ^b
5 x 4	8.02 ^b	12.32 ^c

Source: Hewett (unpublished data)

Data annotated with the same letter are not significantly different at $p = 0.05$ (Tukey test)

TABLE 20b

Effect of initial spacing on the length of clean boles at six years of age (Nairn Experiment).

Spacing (m)	2 x 2	2 x 4	3 x 4	5 x 4
Height to 1st live branch (m)	2.55 ^a	1.95 ^b	1.93 ^b	1.34 ^c

Source: Hewett (unpublished data)

Data annotated with the same letter are not significantly different at $p = 0.05$ (Tukey test)

Dominant trees in the spaced and fertilized plot were significantly larger in terms of both total height (40 per cent) and d.b.h.o.b. (50 per cent), than dominant trees in the unspaced and unfertilized plot, the unspaced and fertilized plot, and the spaced and unfertilized plot (Table 21). Fertilizing without spacing significantly increased height growth (14 per cent) (Chi-squared test). Spacing without fertilizing led to small non-significant increases in both height and diameter growth.

These results must be viewed with considerable caution because of the lack of replication of treatments. Nevertheless, the response to spacing and fertilizing is too great to be explained solely by site differences. Fertilizer application to the spaced plots appears to have stimulated the retained trees to take full advantage of their increased growing space. Without this stimulus the retained trees do not appear to have responded to increased space. Perhaps the extra space was more readily utilized by the competing understorey. This experiment highlights that a response to both increased growing space and fertilizer addition is possible at a very early age.

TABLE 21

Effect of spacing, fertilizing, and a combination of both treatments on the growth of young even-aged karri regeneration. Data are mean (± 5 cm) for each plot.

TREATMENT	HEIGHT (m)	DIAMETER AT BREAST HT (cm)
Not spaced (-S)		
Not fertilized (-F)	11.15 (± 0.74)	10.17 (± 1.02)
Not spaced (-S)		
Fertilized (+F)	12.66 (± 0.68)	11.32 (± 0.88)
Spaced (+S)		
Not fertilized (-F)	11.99 (± 0.74)	11.13 (± 1.05)
Spaced (+S)		
Fertilized (+F)	15.58 (± 0.75)	15.25 (± 1.16)

Source : Schuster (unpublished)

SEED PRODUCTION AND IMPROVEMENT

A program for karri seed production and improvement was established in 1972 to produce a regular, long-term supply of readily collected, high quality karri seed at reasonable cost. The scarcity of karri seed and the high cost of its collection is a long standing concern. The cost of pure seed collected from felled trees in routine logging operations in 1988 was at least \$3 100/kg.

Seed tends to be collected from most trees, regardless of form or vigour, so the chance of attaining worthwhile genetic gains is small. With the area of virgin karri forest being logged decreasing every year

and the resulting regrowth producing little or no seed for at least 50 years, karri seed is becoming more scarce and more expensive. As a consequence, karri seed orchards and seed production areas need to be developed to ensure the long-term supply of adequate quantities of seed at reasonable cost.

A breeding program for karri needs to be developed to ensure that the genetic quality of seed produced in seed orchards and seed production areas is maintained. Provenance trials of karri have been planted to enable the identification of superior provenances and families from throughout the karri range. In addition, progeny trials associated with each seed orchard will enable the culling of families displaying poor form or low seed production from the breeding program.

The ability to vegetatively propagate (clone) karri would lead to the potential for large improvements in the productivity of regenerated karri stands. The first step would be the establishment of clonal seed orchards. Eventually regeneration of logged stands could be carried out using clonal material. Early results using air-layering, grafting and cuttings were poor, but success was later achieved with grafting, cuttings and tissue culture.

Provenance Trials

The discontinuous nature of karri occurrence and the occurrence of outlier populations suggest that there may be some genetic variability in karri. These differences in genotype, if present, would result in differences in phenotype if trees from different populations were grown in the same environment. This leads to the possibility of improving yield from the karri forest by regenerating an area with seed or seedlings grown from seed of a provenance that grows best in that area.

Provenance trials were thus established in 1970. Since then Coates and Sokolowski (1989) have shown that in the karri forest 'geographic range is not necessarily an accurate predictor of genetic variability' p. 153. They showed that 'Most of the genetic variation in karri is due to variability within populations [...] rather than differentiation between populations' p. 151. Nevertheless, provenance trials were established to test the performance of seed collected from 'superior' trees throughout the karri range. The selection criteria of the parent trees were: dominance, a high branch-free bole, crown vigour and the absence of stem defect, except where caused by an external agency such as fire (Schuster 1979b). Various tree parameters were measured for each tree from which seed was collected. The first trial plantings were established on two sites, formerly farmland, in the Warren and Gardner valleys, half being planted in 1972 and the other half in 1973 to give a total of four trial plantings. Despite good site preparation, survival was poor owing to both competition from grass and browsing by rabbits. Five superior trees in every plot of

ten (plots based on forest blocks and river systems) were measured at age four for height and diameter. Analysis of differences in height growth between the families is limited owing to poor survival. Individual families were therefore grouped according to forest block. In all four plantings, the families exhibiting superior growth came from within the main, higher rainfall range of the species, with the exception of the Porongurup Range families in the 1972 trials. Families collected from within the main karri range also showed a trend towards greater diameter growth. Within-family and within-block variations were as great as any between-block variations. Early results from these provenance trials indicate that breeding from superior families may result in an increase in timber volume production. However, further assessment of provenance variation would be required before decisions could be made based on these results.

These provenance trials were thinned heavily (to 100 s.p.ha or 200 s.p.ha) both within and between families in 1978 (age five to six) to form the first karri seed orchards. A new set of provenance trials was established in 1979, involving 120 families from the main karri range and the major outliers. These trials will enable the long term assessment of provenance variation with regard to vigour, form and wood quality (Breidahl 1983a).

Seed Orchards and Seed Production Areas

A seed orchard (SO) is a plantation of selected clones or progenies which is isolated or managed to avoid or reduce pollination from outside sources, [and] managed to produce frequent, abundant and easily harvested crops of seed. (Feilberg and Soegaard 1975, p. 1)

A seed production area (SPA) is a plantation or natural stand managed to produce frequent, abundant and easily harvested seed (Breidahl 1983a).

Since the early conversion of provenance trials to seed orchards, other areas have been specifically planted as seed orchards. Progeny trials have been planted in conjunction with the seed orchards to test the growth and form of the various families under normal operational conditions. Results from the progeny trials will be used to cull the poorest performing families from the seed orchards. A total of 34 ha of seed orchard was planted at three locations in 1980 and 6 ha were planted in 1981. A further 15 ha of seed production areas were established during the period 1976-1980. All of these plantings have been on karri sites largely within the main karri range, and early indications are that seed production on these sites will be poor.

A review of the literature and a survey of karri plantings throughout the south-west have identified a set of environmental conditions which appear conducive to heavy seed production.

Factors Affecting Seed Production in Seed Orchards

Despite Loneragan's review of the factors affecting seed production in virgin karri forest, little is really understood world-wide about conditions that are conducive to flowering and seed production. In an even-aged regrowth stand very little seed is produced for at least the first 50 years. However, in artificial conditions such as off-site seed orchards and widely spaced stands, karri may seed as young as five years of age.

Between 1972 and 1981 a total of 65 ha of karri seed orchards and seed production areas was established. Most of these are located within the main karri occurrence on karri sites. The oldest of these seed orchards and seed producing areas have reached an age at which they should be producing reasonable quantities of seed. At this stage, however, seed production is below expectations and this will affect the economics of seed collection.

An extensive literature review (Breidahl 1983b) indicates that a separate set of environmental conditions is required, firstly for bud initiation, and secondly for seed development. Bud initiation appears to be favoured by low summer soil moisture levels, high summer and possibly low winter temperatures and high levels of light energy. Bud and capsule development appears to be favoured by high winter and spring soil moisture levels and high soil nutrient levels.

Soil Moisture Levels - Most literature indicates that while some moisture stress is required at exactly the right time to promote flower initiation, soil moisture levels must be high both before initiation (the preceding winter and spring), and for flower retention and seed development after initiation (Breidahl 1983b). Daniel *et al.* (1979) working on conifers state that above-average cone crops are associated with unusually warm, dry conditions at the time of initiation of primordia [...] and unusually high rainfall at the time of flowering (p. 141)

Matthews (1963) lists numerous references that show a reduction in water supply in summer is frequently associated with flower-bud formation in woody plants.

Sweet (1975) reviewed numerous studies and noted that a warm dry summer in any year favours flower initiation and determination in that year. This knowledge has probably influenced the siting of seed orchards in the Pacific north-west region of the USA. Growth room, and moisture stress experiments support this and emphasize the importance of the timing of the moisture stress (Sweet 1975).

There has been much disagreement about the effects of moisture stress in promoting flower initiation. Much of this seems to stem from differences in the timing of the moisture stress and differences between species in the season when flower buds are initiated

(Breidahl 1983b). Overall, it seems that flower bud initiation is increased when summer moisture stress coincides with the normal time for initiation. Flower buds in karri and many other eucalypts are initiated in mid-summer. After bud initiation in karri there is potential for enormous losses of buds and capsules (Loneragan 1979). He found that 90 per cent of hypanthia were shed between flowering and maturity. In mountain ash the majority of buds may also be lost before maturity (Griffin 1980). Moisture stress is likely to be the major cause. Sweet (1975) acknowledges the effect of site on post initiation losses and concludes that in the light of all the evidence available 'it would be sensible to deliberately choose orchard sites which enjoy dry summers, and to irrigate following flower determination' p. 77.

Soil Nutrient Levels - Evidence from fertilizer experiments indicates a strong correlation between soil nutrient levels and seed production (Breidahl 1983b). Fertilizer application artificially increases flower initiation and seed production in orchards, although we do not understand how it works (Sweet 1975). After reviewing a number of experiments, Sweet found that:

- (1) seed orchards must be kept adequately supplied with all the main and trace elements necessary for growth; and
- (2) orchards should, at the time of flower initiation, receive an added application of nitrogen to stimulate flower determination.

The effectiveness of a nitrogen source is likely to be linked to its ability to increase the proportion of arginine and other guanidines in the soluble nitrogen pool of the shoot at the time of flower initiation (Sweet 1975). This is a similar effect to that of moisture stress (Jackson and Sweet 1972).

Light - Photoperiod does not affect flowering in many fruit and forest trees, but light intensity does (Jackson and Sweet 1972). There is considerable evidence that equates flowering with large levels of light energy (Sweet 1975). For example, it is usually the edge, open grown or dominant trees in a stand (i.e. those with well lit crowns) that flower; and that within these trees flowering is often heaviest on the side of the crown facing the sun. This has been confirmed by thinning and shading experiments (Jackson and Sweet 1972) and has been observed in karri (Breidahl 1983b).

The mechanism by which light promotes flowering is not well understood. Giertych (1977) found that high light intensity is necessary for floral induction in short-day plants, but not in long-day plants, and the effect is not fully explained by photosynthesis. Baxter (1970) suggests that light acts by decreasing the action of a floral inhibitor.

Temperature - Higher than average spring/summer temperatures are important for flower bud initiation (Matthews 1963; Jackson and Sweet 1972; Giertych 1977; and Daniel *et al.* 1979). Many years of observations on the flowering of *Pinus ponderosa* in

California showed that when the mean monthly temperature for April and May was unusually high, abundant flowering followed. With low temperatures few flowers appeared (Maguire 1956). Giertych (1977) found that if internal nutritive conditions were favourable, abundant flowering could be induced by some external stimulus. He mentions light intensity and temperature as likely stimuli. Tompsett and Fletcher (1977) found that moving trees into a greenhouse favours flower initiation.

Brondbo (1970) theorizes that warm temperatures in late spring increase production of a flowering hormone. This was also found to be the case in some herbaceous plants (Leopold 1951). The observed relationship between high summer temperatures and bud initiation may be indirect, being caused by moisture stress or high levels of light associated with high temperatures.

In addition to the apparent need for high summer temperatures, some fruit trees have an additional winter chilling requirement for good flowering. This is almost certainly true for a number of forest tree species (Sweet 1975).

Planting Design

Karri seed orchards are planted at a spacing of 5 m x 2 m (1000 seedlings/ha). Families are planted in lines of ten seedlings, randomly distributed throughout the seed orchard. The high initial stocking allows for two or three heavy thinnings, primarily aimed at removing the poorest individuals in each family.

Seed for the establishment of karri seed orchards is collected from trees of good form from the main range. Seed is collected in roughly equal proportions from the Donnelly, Warren and Shannon River Systems (Schuster unpublished). Ideally, in each river system at least five tributaries including the main valley, should be sampled. About five families (single trees) should be collected from each, with the aim being to collect from 100 separate trees for each seed orchard (Schuster, unpublished).

In practice 40-50 families have been collected to plant in each seed orchard. This is greater than the recommended minimum required to minimize inbreeding.

Seedlings from only one river system are included in any one karri seed orchard. This is to ensure that all logged areas are regenerated with seed or seedlings of the original area.

Maintenance

The major maintenance operations performed in the karri seed orchards are thinning, fertilizing, scrub or grass control and pollarding. These operations are designed to ensure that each tree receives high levels of nutrients, moisture and light to aid early and heavy seed production, and to promote development of heavy, low branching to facilitate seed collection.

Thinning - Thinning aims to give the best trees (i.e. best formed and most vigorous) optimum supplies of nutrients, water, space and light to promote growth and seed production. Thinning is to be carried out before any competition for lateral branch development occurs.

It reduces stocking from 1000 to 400 s.p.ha, and should not be done until the trees are tall enough to enable a reasonable assessment of their form. This corresponds to eighteen months to two years after planting. This first thinning removes the least vigorous and most poorly formed individuals. A second thinning to 200 s.p.ha at age four years and a third thinning to 100 s.p.ha at age six to eight years should retain those trees with the best branching framework on which the future seed crops will be carried.

The third thinning should result in just one of the original ten trees remaining in each family line. Removal of whole families based on the results of progeny trials may be carried out at a later date. Eldridge (1975) states that

genetic gain from a seedling seed orchard depends largely on effective selection within the orchard. For characters of low heritability (little additive variance), worthwhile genetic gain can only be obtained by selecting the best families. For characters of high heritability, selecting the best individuals within families can be so effective that selection of the best families is unnecessary. Heritability values are still largely uncertain for most characters and therefore it is prudent to assume that they will be low. Thus provision should be made for selections both among and within seedling seed orchard families (p. 135)

Only the poorest 10 per cent of the families are likely to be removed from any of the karri seed orchards in an effort to maintain as broad a genetic base as possible. This 'between-family' thinning could not occur until about age 12 years when trends from the progeny trials become evident.

Fertilizing - Fertilizer provides trees with a good supply of nutrients to promote growth and seed production. After the initial application at planting, follow-up applications should be made at four-yearly intervals and involve a broadcast application of initially 50 kg ha⁻¹ of N and P (age four) and subsequently (greater than eight-years-old) 100 kg ha⁻¹ of N and P. Until recently only P was used. However, it is suspected that a fertilizer containing at least some N would be more effective. Unfortunately, fertilizers with a nitrogen component are expensive. Experiments using clover under the seed orchards are needed. Apart from supplying N, the clover should reduce the scrub control problem that occurs on recently cleared land.

Scrub and Grass Control - These operations are designed to minimize competition with trees for nutrients, moisture, space and light; help the development of large, low branches; and minimize the risk posed by fire. They are currently programmed for two-yearly intervals (on all areas except those where a grazing lease has been established). They should be

carried out whenever the scrub or grass is shading out the lower branches or causing a fire risk.

Scrub control should, where possible, coincide with fertilizing and thinning so that maximum benefit can be obtained from these operations. Scrub control is usually achieved by inter-row slashing using either a tractor or handslashers. The method used ultimately depends on the availability of labour and machines. The hydro-ax has proved to be very effective in scrub control operations.

Pollarding - Pollarding (or branch lopping) is currently being tested experimentally. Pollarding aims to promote the development of heavy, low branching to facilitate seed collection. Very little research has been done on pollarding eucalypt seed orchards in Australia. Matheson and Willcocks (1976) found that pollarding a *Pinus radiata* seed orchard in New South Wales not only extended the life of the orchard, but may also have increased its average annual production. Pollarding increases the life of a seed orchard by keeping the seed-bearing branches at a reasonable height for seed collection. In some cases, however, pollarding simply rejuvenates the crown rather than encouraging the development of lower limbs.

A small karri seed production area was pollarded in spring 1981 (age five years). One year later the lower branches had thickened noticeably and appeared much more vigorous. Early pollarding should be carried out just below the height at which branches start becoming vertical. This should enable the lateral branches below this point to become dominant. Further pollarding experiments will be carried out to determine the effect of pollarding at different ages.

Seed Collection - The older karri seed orchards were not thinned until they were six-years-old and hence lack large, low branches. This, combined with the height of the trees (25 m), makes non-destructive forms of seed collection very difficult. Collection from these orchards will involve either pollarding and collecting the seed from the rest of the tree by non-destructive methods, or by felling the tree. It is hoped that in the more recently established seed orchards collection will be almost entirely non-destructive. It should be possible for the first four or five collections to be made from an elevated platform, before the trees become too large and have to be felled. Successful trials have been conducted at Hayles seed orchard using the 'Squirrel' and 'Cherrypicker'. Costs were found to be very reasonable for both machines (approx. \$500/kg) when collecting from the most productive trees (Fig. 3); however, cost per kilogram rose dramatically as yields per tree dropped (Braidahl 1983b).

The four-year floral cycle in karri hampers seed collection in seed orchards. Branches with mature capsules on them may also carry crops of three separate immature stages: pin buds, fat buds and immature capsules. A pin bud is made up of a floral bud and pedicel. Its length may vary from 0.5 to 1 cm. As growth of the bud continues through spring, the bud fattens and green conical bud caps are formed. When

they reach about 2 cm in length, they are called cylindrical buds. By the third summer buds are clavate and plump (fat buds). Once the fat buds have turned yellow-green, they are known as immature capsules which then mature to a brown colour and caps (opercula) become reddish-brown (Loneragan 1979). These would be wasted if the whole branch were removed. It is likely that the exact method of collection will be determined by the condition of the individual trees. For example:

- (1) large crop of mature capsules, no pin or fat buds. Prescription - remove capsule-bearing branches;
- (2) moderate crop of mature capsules, large crops of pin and fat buds. Prescription - if collection is necessary, individual twigs must be picked, to retain the pin and fat buds; and
- (3) small crop of mature capsules, large crops of pin and fat buds. Prescription - do not collect capsules, wait for pin/fat bud crops to mature.

The management prescription for seed orchards is as follows:

YEAR	TASKS
0	Plant seedlings at 1000 s.p.ha (5 x 2 m). Fertilize seedlings with (5 g P, 2.5 g N).
2	Thin within families to 400 s.p.ha. Pollard retained trees at 1.5 m.
4	Thin within families to 200 s.p.ha. Pollard retained trees at 1.5-2.0 m.
4	Broadcast fertilize (50 kg ha ⁻¹ of P, N).
6-8	Thin within families to 100 s.p.ha.
8	Broadcast fertilize (100 kg ha ⁻¹ of P, N).
8-10	Non-destructively collect the first good seed crop.
12	Broadcast fertilize (100 kg ha ⁻¹ of P, N).
12-14	Thin between families to 80 s.p.ha (collect seed). Collect non-destructively the second good seed crop.
16	Broadcast fertilize (100 kg ha ⁻¹ of P, N).
16-18	Collect non-destructively the third good seed crop. Thin between families to 60 s.p.ha (collect seed).
20	Broadcast fertilize (100 kg ha ⁻¹ of P, N).
20-30	Clear fell and collect seed when a vast crop occurs.

Note: Scrub and/or grass control to be carried out when required.

Survey of Karri Plantings in WA

Karri has been widely planted outside its natural range in trial plots and arboreta throughout the south-west. A survey of these plantings for flowering and seed production was undertaken in 1982. Levels of flowering and seeding were generally very low. This was not unexpected as most of the sites planted closely resembled karri sites, i.e. valley-bottom, red gravelly-loam soil and high rainfall (≥ 1000 mm yr⁻¹) (Breidahl 1983b).

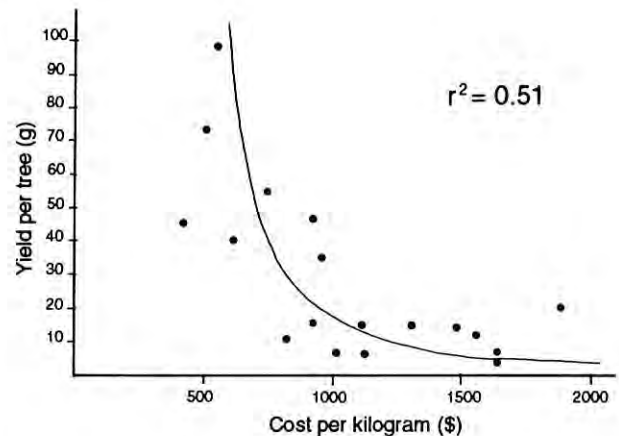


Figure 3. Effect of seed yield per tree on the cost/kg of seed collected at Hayles seed orchard.

Only three of the plots assessed exhibited heavy flowering and seeding and these were not on 'typical' karri sites. Two of the plots are on dry sites in a high rainfall area near Jarrahdale 60 km SE of Perth. The other plot is on a wet site in a low rainfall area at Talling 50 km east of Manjimup. Despite the trees in the Talling plots being only 12-years-old nearly 500 g of seed was collected from one of only about thirty trees. This is five times the highest yield recorded at Hayles seed orchard where there are 500 trees (Breidahl 1983b).

The Jarrahdale plots are located on a well drained site with a high percentage of gravel in the soil. The rainfall, although high (1200 mm yr⁻¹), is concentrated strongly in the winter months. As a result, soil moisture levels are high during winter but low during summer. In addition, summer light levels and temperatures are high while temperatures during winter are low and frosts are relatively common.

The Talling plots are located on a treeless blackboy flat. The soil is a shallow grey sand with a clay layer at a depth of about 20 cm. As a result the site is waterlogged in winter when the majority of the rainfall (675 mm yr⁻¹) is received. During the hot, dry summer, soil moisture levels are low and light levels are high. Temperatures can be very low in winter and frosts are, again, relatively common.

Therefore, these three sites which are conducive to bud initiation and capsule development have the following environmental conditions in common:

- (1) low summer soil moisture levels;
- (2) high summer temperatures;
- (3) high light levels;
- (4) high winter soil moisture levels; and
- (5) low winter temperatures.

These conditions, along with high nutrient levels, are most likely the important environmental factors affecting flowering and seed production in forest trees. Seed production on these sites may have been even greater if they had been more fertile.

Based on these assumptions, environmental conditions in the main karri range do not favour bud initiation. Summers are mild and relatively wet and the moisture stress required for bud initiation is unlikely to occur. Winters are very mild and a chilling requirement, if present, is also unlikely to be met. In addition, light levels are relatively low.

The literature review and survey of karri plantings has resulted in a better understanding of how site factors can affect karri seed production. Seed orchards in the future will be located only on sites that favour the regular initiation of heavy bud crops while also favouring the retention and development of these crops. In 1984 two such areas were planted, one being on the seasonally wet flat at Talling which was already proven in terms of seed production. The other was nearby on a dry former pasture site at the Perup Fauna Ecology Research Station.

Apart from the obvious benefit of increased seed production these sites have other advantages when compared with the karri sites used previously. These include:

- (1) isolation from outside pollen sources;
- (2) greatly reduced scrub control; and
- (3) easier site clearing.

Apart from planting seed orchards on sites conducive to heavy seed production, a large number of seed production areas are being established on a wide range of sites throughout the south-west. It is hoped that practical knowledge of the environmental conditions affecting bud initiation and capsule development will be improved by observing what happens in these areas.

This information will be enhanced by an experiment planned for the Perup seed orchard. This trial will test the effect of fertilizing (nil, high P + N) on bud initiation and subsequent capsule development.

Progeny Trials

Each of the families planted in a seed orchard is planted in associated progeny trials. The progeny trials are used to gauge the performance of the families under operational conditions. A seed orchard is a highly artificial situation and it is impossible to assess trees in a seed orchard for vigour, stem straightness or branching under normal conditions, particularly when the seed orchard is planted off site.

The progeny trials are a standard design with ten replications of each family planted in a completely randomized block design. Each family is planted in a five-tree single row necessitating an area of 2 ha for the progeny testing of a 50-family seed orchard.

An assessment at age 8-10 years will give some indication of the relative performance of the families and can be used to remove the poorest families from the seed orchards after the within-family thinning has finished.

Vegetative Propagation

The ability to propagate karri vegetatively has potential for improving the genetic quality of karri stands.

Clonal seed orchards incorporating clones of mature trees with outstanding qualities would be the first stage in an intensive breeding program for karri. Clones of trees observed to be seeding heavily in seed orchards and of outstanding individuals in progeny trials could also be included. Eventually clonal material (e.g. cuttings) could be used to regenerate areas of logged forest.

Research begun by Schuster at the Manjimup Research Station in 1978 investigated various ways of vegetatively propagating karri. Four basic techniques were used: air layering - on young flowering stock; cuttings - of young and old stock; grafting - cleft (tip) approach, and bud (patch); and tissue culture.

1. Air layering

With this technique, 'roots form on the aerial part of a plant after the stem is girdled or slit at an angle and enclosed in a moist rooting medium at the point of injury' (Hartman and Kester, 1968, p. 488). This was partially successful with karri, but no roots developed. The technique holds little promise.

2. Cuttings

In 1984 renewed interest was shown by Breidahl in research aimed at vegetatively reproducing karri by cuttings.

A small, commercial propagating unit was used to maintain the bottom heat unit to within 1°C, with a range from 5°C to 40°C. Misting was controlled by a time clock which allowed spray bursts to be programmed in 15 minute multiples. The length of spray bursts was step adjustable from 2 to 120 seconds.

Cuttings material was obtained from coppice, originating from stumps of 50-year-old trees felled in a routine thinning operation. This material was chosen because it is generally recognized that in *Eucalyptus* propagation by cuttings is easy, provided leafy cuttings are taken from very young seedlings or epicormic (coppice) shoots from the base of the tree (Durand-Cresswell *et al.* 1982).

The coppice was collected before dawn and prepared in a glasshouse. Apical material was discarded and cuttings of between 7-10 cm in length and 5-7 mm in diameter were prepared. Each cutting had a single pair of leaves which were cut in half to reduce evapotranspiration while the cutting was producing new roots. The bases of the cuttings were dipped in Benlate solution (200 ppm) for 15 minutes.

The cuttings were then dipped in indolebutyric acid (IBA) solution for about five seconds, and planted in the propagation unit. A total of 90 cuttings were prepared with three replications of each IBA treatment (3000 and 6000 ppm) and 15 cuttings per replication.

The propagation unit which was set up in a glasshouse was adjusted to give a bottom heat temperature of 25°C. Mist frequency was every 15 minutes for four seconds duration during daylight hours. Night misting frequency was decreased to 30 minute intervals. A time-controlled fluorescent light gave an extra two hours morning light. The bedding material was coarse, washed quartz sand dampened with Benlate solution.

Two months after the cuttings were planted in the propagation unit an assessment was made of rooting success. Of the 90 cuttings 15 (*ca* 17 per cent) were considered successful with roots being produced, 37 (*ca* 41 per cent) had failed, while it was too early to determine the fate of the other 38 (*ca* 42 per cent).

A final assessment was made three months after the cuttings were placed in the unit. Of the 90 cuttings, 22 (*ca* 25 per cent) had produced roots, most of which were about 15 cm long.

Although this initial success rate was not very high, the results are an improvement considering the earlier total lack of success.

After reviewing this experiment, a new one aimed at improving the strike rate of cuttings in the heated bed began. The cuttings used in this follow-up trial were also from coppice collected from the stumps of 50-year-old trees, but were thicker (10 mm diameter) than in the initial experiment, because most of the failed cuttings appeared too soft.

The cuttings were prepared in the field and immediately submerged in a 200 ppm Benlate solution. This was done to control fungal attack and also because soaking in Benlate has been found to promote rooting of cuttings (Hodges⁵, personal communication). Three IBA treatments were used: 0 ppm, 3000 ppm and 6000 ppm, with 30 cuttings per treatment and no replications. The cuttings were assessed after 45 days and just over half (55 per cent) were showing signs of rooting, while only 8 per cent had died. The 3000 ppm IBA treatment was the most successful with 75 per cent of cuttings showing signs of rooting compared with 50 per cent at 6000 ppm and 35 per cent for the control.

Further research is required before cuttings could be produced on an operational scale. This should aim to determine the optimum:

- time of year for root initiation;
- potting medium;
- rates of IBA; and
- soil and air temperatures.

Research is also required to discover ways of initiating basal coppice in trees without damaging them. This would enable outstanding trees to be cloned without them having to be cut down.

3. Grafting

Karri plants have been successfully grafted at Wanneroo, 25 km north of Perth. Scion material was collected from the same basal coppice used in the cutting trials previously described, as well as from young seedlings (< two-years-old) and from 12-year-old trees in a seed orchard. In this experiment the tip cleft grafting technique was used.

Successful grafts were obtained using each of the three sources of scion material; however, greatest success was obtained using scions collected from basal coppice and young seedlings (*ca* 75 per cent). It is difficult to reconcile the success of this experiment with the failures in earlier experiments at Manjimup (300 km south of Perth). One possible reason is the difference in climate between Wanneroo and Manjimup. These experiments were done from late winter to early spring when it is very cold in Manjimup. The much milder conditions at Wanneroo may be responsible for the success achieved there.

Despite this success, grafting is receiving less attention than cuttings because of its higher cost, as well as the likelihood of long term problems with graft incompatibility.

4. Tissue Culture

A technique that holds promise for vegetative propagation of karri is tissue culture. Scientists at Murdoch University have succeeded in vegetatively propagating karri from tissue culture. Material collected from young seedlings (one-year-old) was used to produce multiple shoots which rooted very well. Nodal explants from an older tree (seven-years-old) also yielded multiple shoots and 60 per cent of these rooted.

The effect of tree age on the success of tissue culture was also studied. Samples of leaf and bud material were collected from five trees ranging in age from 10 to 200+ years. Reasonable success was achieved with the ten-year-old material, but the older material was largely a failure. Research in this field has low priority at present.

⁵ C. S. Hodges Jr., US Department of Agriculture Forest Service.

SOIL DISTURBANCE AND REHABILITATION

Rehabilitation of soils disturbed by logging is an important aspect of karri silviculture. Although the major part of a logged area will be free from soil disturbance, areas of concentrated machine movement (snig tracks and landings) can be seriously affected. Concern over possible effects of soil disturbance on regeneration, aesthetics and long term productivity prompted the initiation of research into prevention of excessive disturbance and rehabilitation methods.

However rehabilitation on a large scale is both expensive and difficult, and efforts are currently being made to reduce the amount of soil disturbance and damage through a modification of logging techniques. (Schuster 1979a, p.2)

The area of pure karri stands on deep red loams being logged has decreased, whereas logging of mixed karri-marri stands on podzolic duplex soils with heavy clay near the surface has increased. Logging operations tend to disturb podzolic soils more severely than red loams. These stands generally support a larger number of smaller trees, thereby requiring more machinery movement. The difference is owing not only to differences in the two soil types but also to the higher intensity of logging on podzolic soils (Schuster 1979a).

How Soil Disturbance Occurs

Snigging logs from the forest can cause soil disturbance by (Bradshaw 1978):

- (1) compaction of the soil *in situ* by the wheel pressure of the machine and to some extent the log;
- (2) removal or displacement of the topsoil by the gouging effect of the log;
- (3) the mixing and puddling of the topsoil and subsoil by the repeated movement of the skidder and the log when the soil is very wet; and
- (4) the subsequent erosion of the topsoil by the action of water along the snig tracks.

Type (4) is not a serious concern and generally results in displacement of 1 per cent of topsoil from the affected snig tracks.

Much of the soil disturbed by logging in a karri coupe is compacted on major snig tracks and landings because of repeated machine passes. The degree to which compaction occurs depends on the weight of the load, the number of passes, soil type and soil moisture content. As soil moisture increases, fewer passes are required to achieve the same degree of compaction. Sometimes the soil can become so weak that the machines break through the surface causing gouging, puddling, rutting and mixing.

Disturbance of the types described above will occur at any time of the year depending on soil moisture levels (Bradshaw 1978). Disturbance can occur in summer in low lying areas, but is potentially most severe during winter, especially when it is actually raining.

Effects of Soil Disturbance

Disturbance caused by logging activity on snig tracks and landings can degrade soil structure. Bulk density can be increased, owing to compression of the soil (Table 22). Pore space can be decreased, which results in reduced root growth and increased resistance to infiltration by water. This compaction can extend to a depth of at least 40 cm on a severely disturbed site (Bradshaw 1978).

Wronski (1984) has found that a skidder working in karri thinnings caused compaction to a depth of 30-40 cm. Compaction by a forwarder extended to a depth of 50-60 cm. Disturbance caused by the forwarder working in summer is much less severe than in winter.

The sheer surface hardness of compacted areas yields very few suitable sites for germination: the compacted profile is impenetrable to water and roots. Even when the tap root can penetrate, the fine feeder roots have difficulty in developing and exploring the soil mass containing the nutrients.

Schuster (1979a) found that

up to 20-35 per cent of the ground surface of a coupe may be disturbed by logging operations but the proportion of this that would be classed as damage varies with the season of logging and from site to site (p. 2)

Why is Soil Disturbance a Potential Problem?

'Chipwood cutting, wheeled skidders and an absence of good winter sites virtually coincided' (Bradshaw 1978, p. 4). Soil disturbance is now more common because:

- (1) the logging for sawlogs and chipwood in the mixed forests involves a somewhat greater volume, and many more stems than logging for sawlogs only in pure karri forest;
- (2) more stems to remove means more of the forest floor is traversed;
- (3) well drained, pure karri sites available for cutting are virtually exhausted and logging is now confined to less well drained karri sites and the shallower podzols.

TABLE 22

Soil bulk density eight years after logging.

SOIL DEPTH [cm]	BULK DENSITY [g cm ⁻³]	
	PRIMARY DISTURBANCE	UNDISTURBED
10	1.35	0.82
20	1.38	0.90
40	1.43	1.15
80	1.32	1.30
160	1.38	1.50

Source : Bradshaw (1978 unpublished)

The type or severity of soil disturbance has not changed over the years, but rather the percentage of the coupe so affected has changed (Bradshaw 1978). Disturbance levels of up to 50 per cent of coupe area have been recorded, and would be commonplace and higher if left uncontrolled.

Rehabilitation of Disturbed Soils

A system of classifying soil disturbance was introduced in CALM's Southern Forest Region in 1979 in an attempt to unify communication throughout the region. This system recognized three classes of soil disturbance:

1. Class 1 or primary soil disturbance has occurred when either
 - (1) the A and B soil horizons have been mixed or partly mixed;
 - (2) the A soil horizon has been completely removed;
 - (3) machine activity has slopped or puddled the soil; and
 - (4) combinations of (1), (2) and/or (3) have occurred.
2. Class 2 or secondary soil disturbance has occurred when the topsoil has been compacted *in situ*.
3. Class 3 or tertiary soil disturbance includes all soil not in a virgin state, following logging, and not falling under Class 1 or 2.

These classes are used in assessing coupes for soil disturbance in order to decide whether the operation should continue and which areas require rehabilitation.

In most situations natural amelioration of compacted soils gradually restores them to their original structure. Frost heave, the accumulation of litter, and the gradual breaking up of the profile by small mammals and soil fauna and the roots of plants which become established, are some of these natural processes (Bradshaw 1978). In areas where primary disturbance has occurred and where the B horizon is exposed or mixed with the A horizon, it is reasonable to assume that these processes would take a very long time to restore the soil to its original condition (Bradshaw 1978).

Schuster (1979a) experimented with a number of methods of rehabilitating compacted landings and snig tracks. He found that the best height growth on landings occurred when they had been ripped, fertilized and bark mulched. Ripping and fertilizing each increased height growth individually, but mulching resulted in a trend towards better height growth only when in combination with the other two treatments. Ripping was found to be the only treatment to increase survival; however, all survival rates were satisfactory. Ripping also significantly increased the percentage of *Acacia pulchella* seeds germinating and surviving the first year.

On snig tracks both deep ripping (to 1 m) and debris heaping and burning greatly increased height growth, and the two treatments combined gave large

increases in height growth for both planted and naturally regenerated seedlings (Schuster 1979a). Ripping and debris heaping both gave survival results that were operationally acceptable.

Further work was initiated to examine whether cultivating a snig track to a depth of 30-50 cm could provide a better tilth for unimpeded root growth. The depth of soil cultivated was 10-15 cm. Pelleted karri seed was sown on the cultivated snig track, on untreated control areas, and on an undisturbed ashbed site. Germination on the cultivated snig track was almost as good as on the undisturbed ashbed, but was very poor on the uncultivated snig tracks (Ritson, unpublished).

All coupes are inspected regularly by the Forest Officer in Charge to determine whether soil disturbance is occurring. Limits on the percentage of the total area affected are set. These vary according to the operation. In clear fell coupes, soil disturbance up to 20 per cent of the total area (with not more than 5 per cent on landings) is permissible.

If the Forest Officer believes that soil disturbance is approaching these limits, the officer must conduct a thorough survey to determine what the actual level of disturbance is. If it is above the set limit, the operation is ceased immediately and cannot recommence until the Forest Officer in Charge determines that the soil is dry enough (Soil Dryness Index > 250 in the karri forest).

When logging is completed, disturbed soils are rehabilitated by ripping and levelling of affected areas along with heaping or windrowing of debris around the landings. In thinned areas, rehabilitation is done by raking the soil to promote germination, but no ripping that is likely to damage crop tree roots is carried out (CALM 1987a).

Erosion control is also an essential part of the logging operation. Interceptor banks and drains must be constructed across snig tracks (CALM 1987c) to minimize erosion.

THINNING OF REGROWTH STANDS

The release of the Department of Conservation and Land Management's Timber Strategy - *Timber Production in Western Australia* (1987a) - saw a new era of forest management in this State. CALM now enters into legally binding contracts with sawmills to provide agreed volumes of timber. An integral portion of this volume in the short-to-mid term will be made up of thinnings from even-aged karri and karri-marri regrowth stands.

Bradshaw and Lush (1981) described the silvicultural benefits of thinning: a newly regenerated forest may contain up to 100 000 seedlings per hectare, which is reduced to about 150 trees over 100 years as a result of natural selection. Thinning removes and uses trees that would otherwise die owing to the effects of competition, thereby increasing yield, and provides the remaining 'crop' trees, which will produce

the bulk of the sawlog yield, with additional space, light, nutrients and moisture to encourage their growth. Sometimes this increases sawlog yields at the expense of total yield (biomass).

Thinning is already being carried out on an operational scale in the 50-plus-year-old regrowth stands near Pemberton and Manjimup. The operation began in 1980 and has been covering an area of approximately 400 ha/year. The thinning prescription is based on top height and basal area (Table 23) and selection is from below. This thinning removes about 100 m³ of utilizable wood/ha, consisting of approximately 65 per cent chipwood and approximately 35 per cent sawlogs and peeler logs. The trees removed are impeding the growth rate of the retained trees and are believed to be likely to die before the full rotation length of 100 years is reached. Defective trees not suitable for milling are also removed in this operation.

Future karri sawlog yields have been based on the assumption that some post-1967 regrowth stands are likely to be thinned for the first time when they are 30 years old. However, research results suggest that by the time the stand is 30 years old, the crop trees have already lost a significant amount of their potential growth owing to competition. Recent experiments indicate that on high quality sites, regrowth stands may be commercially thinned from as young as 12-15 years of age (depending on their height). On low quality sites, commercial thinning may not be viable until the stands are 25 years old or more.

Application of fertilizer at the time of thinning might increase the growth of retained trees. There are a number of examples around the world where fertilizing has led to a marked increase in the response to thinning (e.g. Brix 1983). Nitrogen appears to be the major element involved, as it stimulates the production of new foliage, and therefore enables the tree to make better use of its growing space (Ballard 1980). Phosphorus may be equally as important in karri forests, because the soils on which they grow are deficient in this element (McArthur and Clifton 1975).

TABLE 23
Thinning intensity of even-aged regrowth karri stands.

TOP HEIGHT ^a (m)	BASAL AREA RETAINED (m ² ha ⁻¹)
30	14
35	17
40	18
45	20
50	21
55	22

Source : CALM (1990)

^a Top height is defined as the mean of the height of the two tallest crop trees within a radius of 16 m.

If fertilizer is used to boost the thinning response it should be applied as soon after thinning as possible, as any delay will reduce the response period under conditions of free crown growth. This presupposes that there is no undue damage to the roots or stems of the retained trees as a result of the thinning. Such damage may leave the trees in a poor condition to intercept and use nutrients applied immediately after thinning (Ballard 1980).

Many thinning and fertilizing experiments are required in karri regrowth to cover the range of sites and ages. A number have already been established. The immediate aims of this research are to determine the growth response of regrowth karri, and the effect of thinning and fertilizing on other factors (e.g. understorey, insect populations, soil nutrient status). These experiments are also providing invaluable silvicultural data for a karri growth model, which will enable managers to predict accurately the long term effect on yield of various silvicultural treatments.

Past Thinning Experiments

Many experiments have been initiated in karri regrowth in the past, including the Quartz Road experiment in 1977. Five others, although unreplicated, yield interesting results which serve as guidelines for developing silvicultural regimes for karri regrowth. These five experiments cover a wide range of ages (1-53 years) on areas ranging from prime karri sites on deep red loam soils to marginal karri sites on gravelly podzols.

Mattaband Early Thinning Experiment

This experiment was initiated in 1962 in pure high quality karri on a red loam soil type. Plots were thinned to 900 s.p.ha at age two and four by covering retained trees with plastic bags and spraying unwanted stems with 2, 4, 5, T. Fertilizer treatments (ranging from 250 kg ha⁻¹ to 8000 kg ha⁻¹ rock phosphate and trace elements) were superimposed on the thinning treatments. Thinning at age two gave unusual results with total volume growth increasing after thinning (Table 24). This is probably owing to a reduction in scrub competition from spraying of 2, 4, 5, T on unwanted stems. This would also explain the large response to fertilizer application in the thinned plots, but not in the unthinned plots. Reduction in scrub competition allowed young karri to take full advantage of their increased supply of nutrients. In the unthinned plots, much of the added fertilizer was probably utilized by the scrub and effectively increased competition. Fertilizer response will only occur if water supply is not limiting and, in an unthinned stand, this may not be the case (McGrath⁶, personal communication).

⁶ J. McGrath, Department of Conservation and Land Management, Bussellton.

TABLE 24

Effect of thinning and fertilizing at ages two and four on volume production of young karri regeneration, on and off ashbed (measured at age 7.5 years) - Mattaband.

SEEDBED TYPE	FERTILIZER APPLICATION	THINNED AT AGE 2 VOLUME (m ³ ha ⁻¹)	THINNED AT AGE 4 VOLUME (m ³ ha ⁻¹)	UNTHINNED VOLUME (m ³ ha ⁻¹)
ashbed	none	48.11	19.59	25.19
	heavy	81.17	36.22	24.84
non-ashbed	none	7.00	0.70	-
	heavy	-	7.35	2.10

Source : Breidahl (unpublished)

Pine Creek Road Demonstration Plots

Initiated in 1972 in five-year-old regrowth, this unreplicated experiment tested five thinning intensities ranging from unthinned to 277 s.p.ha (thinned to 6 m x 6 m). The site is mid-slope with a northerly aspect and a gravelly loam soil. The original stand was a karri-marri mixture. Ten dominant trees per hectare were measured in 1972 and 1980. Thinning to more than 1100 s.p.ha (3 m x 3 m) or to 2500 s.p.ha (2 m x 2 m) significantly affected diameter increment to age 13. Diameters in the unthinned control and 1100 s.p.ha treatments were significantly smaller than diameters in the 400 s.p.ha and 278 s.p.ha treatments at age 13. Thinning to 2500 s.p.ha improved diameter growth significantly over no thinning at all. The mean diameter of the plots varied before the treatments were applied, however, therefore interpretation is limited. Percentage increments are more useful (Table 25).

While there are limitations to this experiment because of a lack of replication and small, variable plots, the results suggest that to maximize diameter growth on crop trees, the stocking of karri regrowth should be between 625 and 1111 s.p.ha at age five. However, the effect of low stocking on form was not considered in

TABLE 25

Effect of thinning karri regrowth (at age five) on subsequent crop tree diameter growth (measured at age 13) - Pine Creek Road.

PLOT	s.p.ha	MEAN DIAMETER (cm)			
		1972	1980	DIAMETER INCREMENT 1972-80 (cm)	THINNING RESPONSE (to control) (%)
1	unthinned	6.6	18.0 ^a	11.4	-
2	2500	8.8	24.4 ^{bc}	15.6	37
3	1111	6.3	20.0 ^{ab}	13.7	20
4	625	6.4	24.4 ^{bc}	18.0	58
5	400	7.8	26.2 ^c	18.4	61
6	277	7.2	25.1 ^c	17.9	57

Source : Rotheram (unpublished)

Data annotated with the same letter are not significantly different at $p < 0.05$ (Duncan's Multiple Range Test).

this experiment. It is likely that increases in diameter growth from wide spacing would be outweighed by poor form (and the persistence of large limbs) and therefore overall loss of merchantable volume. Spacing experiments have confirmed this for young trees.

Crowea Thinning Experiment

This experiment was established in 1963 in seven-year-old regrowth resulting from group selection cutting on a red loam soil. The site is moisture gaining and the original stand was almost pure karri. Four thinning intensities (unthinned, 750, 500 and 335 s.p.ha) were tested. This experiment was unreplicated and only six trees per plot (equivalent of 150 s.p.ha) were measured, so conclusions are limited. A significant crop tree response was recorded between the unthinned plot and the most heavily thinned (to 335 s.p.ha) plot. Diameter at breast height increased by 27 per cent. Thinning had no effect on height growth (Table 26). There were also some non-significant responses in the lighter thinnings, with increases of around 15 per cent in d.b.h.o.b. over the unthinned plots. No data are available for 1963 (establishment), therefore comparisons are based on the assumption that the plots were uniform at the time of establishment.

TABLE 26

Effect of thinning karri regrowth (at age seven) on the growth of crop trees (measured at 24 years) - Crowea.

PLOT	s.p.ha	d.b.h.o.b. (cm)	HEIGHT (m)	MEAN TREE VOLUME (m ³)
1	750	29.1 ^{ab}	29.9 ^a	0.73 ^a
2	500	29.5 ^{ab}	29.9 ^a	0.75 ^a
3	335	33.4 ^a	30.4 ^a	0.95 ^b
4	unthinned	26.4 ^b	29.5 ^a	0.57 ^a

Source : Breidahl (unpublished)

Data annotated with the same letter are not significantly different at $p < 0.05$ (Duncan's Multiple Range Test).

Quartz Road Thinning and Fertilizing Experiment

The Quartz Road experiment, was established in 1978 when the trees were 11 years old. The soil is a gravelly yellow podzol.

There were two thinning levels (unthinned: stocking approximately 2500 s.p.ha and thinned to 1000 s.p.ha) and five levels of fertilizer treatment (ranging from nil to 800 kg ha⁻¹ of Urea and 3825 kg ha⁻¹ Superphosphate, with a consistent N:P ratio of 1:1). The most recent measurement was of the 15 dominant or codominant trees (corresponding to 660 s.p.ha) and was completed in 1986. Measurements were also made in 1978, 1979, 1980, 1982 and 1983. Responses reported in 1983 showed an average 41 per cent increase in the diameter at breast height of equivalent trees for the thinned plots at all fertilizer levels (Table 27).

TABLE 27

Effect of thinning and fertilizing a dense, even-aged karri stand (age 11) on diameter growth of the largest 375 s.p.ha (measured at age 16) - Quartz Road.

FERTILIZER TREATMENT	DIAMETER INCREMENT 1978-1983 (cm)		DIFFERENCE (cm)	RESPONSE (%)
	Thinned	Unthinned		
1	5.19 ^a	3.66	1.53	41
2	5.45 ^a	4.02	1.43	36
3	5.75 ^b	3.78	1.97	51
4	6.86 ^b	4.61	2.25	49
5	5.99	4.67	1.32	28
Mean	5.85 ^b	4.15	1.70	41

Source - Inions (unpublished)

^a significantly different ($p = 0.05$) from unthinned counterpart

^b significantly different ($p = 0.01$) from unthinned counterpart

Greatest d.b.h.o.b. increment occurred two years after treatment. All thinned plots (regardless of fertilizer treatment) had d.b.h.o.b. increases of 60 per cent or more two years after treatment.

All treatments with both thinning and fertilizing had periodic mean annual increments greater than the control. Increasing fertilizer from level three to level four did not give an increase in diameter increment.

Further data analysis following the 1986 measurement has shown that there were significant differences in tree size prior to treatment. This means that while there are still significant gains in diameter and volume growth owing to thinning, fertilizing and combinations of the two, it is impossible to gauge the exact magnitude of the response.

The 1986 analysis does show, however, that the response to treatment is diminishing with time, and that while some growth advantage persists, the magnitude of the response is much less than in the few years directly after treatment.

Figure 4 shows periodic mean annual diameter increment for a number of treatments for each measurement year (calculated over the life of the experiment to that year).

Maximum response in all treatments occurred a year after treatment. Thinned treatments showed larger responses than unthinned treatments, except at the heaviest rate of fertilizer application where the unthinned trees kept up with the thinned trees that had not been fertilized. Fertilizer seems to have enabled the largest trees to maintain their increased growth rate above that of smaller, less dominant trees with the same thinning treatment but to which less or no fertilizer had been applied.

The thinning intensity in this experiment was very light (2500 s.p.ha to 1000 s.p.ha) and response cannot be expected to persist. The stand has quickly filled the extra growing space and trees are competing for limited resources.

A heavier thinning may have maintained the response until the next thinning was due, but the resulting form of trees in the heavily thinned plots may have outweighed this response.

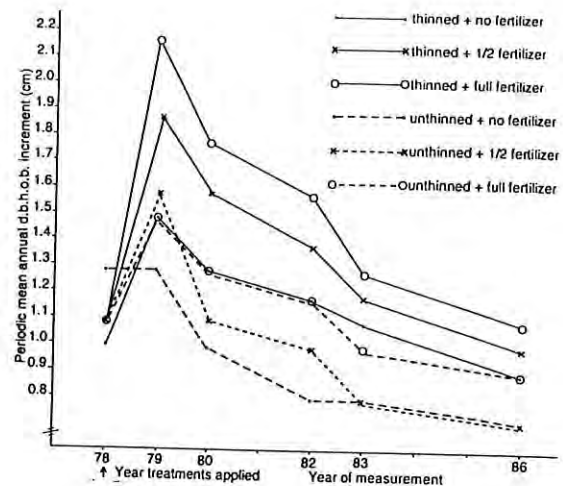


Figure 4 Periodic mean annual diameter increment. Quartz road experiment.

Big Brook Thinning Experiment

This experiment was established on a pure karri site on a deep red loam soil. The trees were thinned in 1955 when they were 25 years old.

Five plots were established with the following treatments:

- plot one : thinned to 50 dominant s.p.ha;
- plot two : thinned to 100 dominant and codominant s.p.ha;
- plot three : thinned to 150 dominant and codominant s.p.ha;
- plot four : thinned to 200 dominant and codominant s.p.ha;
- plot five : dominants removed leaving 150 codominant s.p.ha.

Analysis is based on the largest 50 s.p.ha in each plot. The mean d.b.h.o.b. of trees in plot one was significantly larger than all other plots. This trend has continued and percentage increment is greatest, though not significantly so, in this plot (Table 28).

Percentage d.b.h.o.b. increment was smallest for plot five, suggesting that removing the dominants did not benefit the stand. Plot three was thinned to the same residual stocking (150 s.p.ha) but retained dominants and codominants, the dominants probably having more capacity to respond to release than the codominants.

Once again the trend shows that the initial response to thinning appears to decrease gradually as competition commences again, indicating the need for follow-up thinning. The Big Brook Experiment is also useful because it shows that a response in 25-year-old regrowth is possible.

Lefroy Brook Thinning Experiment

Lefroy Brook was regenerated in 1875. The soil is a gravelly loam and the site is on a ridge top. A single

TABLE 28

Comparison of the diameter increment of crop trees in a karri regrowth stand thinned at age 25 to different densities - Big Brook.

PLOT	s.p.ha	LARGEST 50 s.p.ha 1955 d.b.h.o.b. (cm)	LARGEST 50 s.p.ha 1965 d.b.h.o.b. (cm)	LARGEST 50 s.p.ha 1985 d.b.h.o.b. (cm)	LARGEST 50 s.p.ha TOTAL INCREMENT 1955-1985 (cm)	LARGEST 50 s.p.ha INCREMENT (%)
1	50	39.5 ^a	51.2 ^a	69.3 ^a	29.9 ^a	76
2	100	36.3 ^b	47.2 ^b	63.5 ^b	27.2 ^b	75
3	150	34.0 ^c	43.4 ^c	58.2 ^{bc}	24.2 ^{bc}	71
4	200	35.2 ^{bc}	44.1 ^c	59.5 ^c	24.4 ^c	69
5	150	35.2 ^{bc}	43.4 ^c	56.5 ^c	21.3 ^c	60

Source - Hewett (unpublished)

Data annotated with the same letter are not significantly different at $p > 0.05$ (Duncan's Multiple Range Test)

plot was thinned to 110 s.p.ha (approximately $39 \text{ m}^2\text{ha}^{-1}$ basal area in 1967) in 1928 when the regeneration was 53 years old and an unthinned control plot was established nearly 20 years later (stocking approximately 178 s.p.ha and basal area approximately $50 \text{ m}^2\text{ha}^{-1}$ in 1967).

Poor design means that interpretation is difficult. The unthinned plot was initially measured 20 years after the thinning, so it is not known whether the plots were homogeneous before thinning. The small difference in crop tree diameter in 1971 (Table 29) may simply reflect a difference already present at thinning. These measurements were made 43 years after thinning and the response may have diminished with time as was the case in the Big Brook experiment.

In summary, all these experiments show responses to both thinning and fertilizing at various ages. The magnitude of the response is variable and the duration is generally short-lived. The exact magnitude of the responses needs to be clarified and as a result new experiments have been established.

TABLE 29

Effect of late thinning (age 53) of karri regrowth on the mean diameter of crop trees 43 years later - Lefroy Brook.

	MEAN DIAMETER (cm)		
	10 largest stems (25 s.p.ha)	20 largest stems (50 s.p.ha)	30 largest stems (75 s.p.ha)
Thinned	97.0	86.6	78.7
Unthinned	91.7	83.1	77.7
Difference (%)	6	4	1

Source : Breidahl (unpublished)

Current Thinning Experiments

Two thinning experiments are being maintained. Both are on high quality sites.

Warren Thinning and Fertilizing Experiment

This experiment is on a red loam karri soil and the stand was regenerated with seed trees in 1972. A fully replicated experiment, it was established in 1984 when the trees were 12 years old.

The Warren experiment is testing four thinning intensities (nil, 600 s.p.ha, 400 s.p.ha and 200 s.p.ha), two fertilizing intensities (nil and 400 kg ha^{-1} of nitrogen) and two coppice control treatments (nil and full control).

Nitrogen only was used for this experiment because it is available in more concentrated forms than phosphorus, and because evidence from other forests suggests that nitrogen is the major element involved in responses following thinning (Ballard 1980). Nitrogen stimulates growth of new foliage, which enables the retained trees to make better use of their increased growing space.

Subsequent research by CSIRO (O'Connell and Menage 1982) indicates the advantages of adding phosphorus to promote a leguminous understorey, and to increase the effectiveness of the added nitrogen. Future fertilization experiments will include both nitrogen and phosphorus fertilizers.

Analysis of data from three measurements yielded interesting results. Coppice control had not been implemented at this stage. Thinning produced significant increases in diameter, volume and basal area growth for all thinning levels over both growing

seasons (1984-85 and 1985-86). Significant responses to fertilization for the largest 100 s.p.ha were not detectable until the second growing season (Hewett, unpublished) (Table 30). Groot *et al.* (1984) have documented such a 'lag' in fertilization response. The nitrogen application probably did cause an increase in foliage biomass in the first increment period, but the resulting bole response would not be detected until the second increment period.

The significant response owing to thinning reflects the ability of the residual stems to take immediate advantage of reduced competition and increased growing space. Analysis of the effect on growth of the interaction between thinning and fertilizing shows that there was significant interaction for mean d.b.h.u.b. increment for the largest 100, 200 and 300 trees/ha (Table 31).

The stocking where maximum volume increment is achieved is approximately 300 trees/ha (corresponding basal area over bark is 12.6 m² ha⁻¹). This applies to high quality, even-aged 12-15 year old regrowth only, and is likely to change with time. The influence of stand density on volume increment is greatly influenced by the stand age and site quality.

The Warren experiment will continue to be measured to further refine the thinning and fertilizing response over time.

Treen Brook Thinning Experiment

Another large thinning experiment was established in 1985 in 50-year-old regrowth at Treen Brook about 10 km south-west of Pemberton. This experiment examines the effect of four thinning intensities (to residual basal areas of 30 m² ha⁻¹, 20 m² ha⁻¹, 15 m² ha⁻¹ and 10 m² ha⁻¹) and unthinned controls (43m² ha⁻¹) on subsequent volume growth.

This will provide information on how the large area of regrowth, resulting from clear felling during the late 1920s and 1930s, should be thinned to maximize sawlog production. It is also providing basic thinning response data. All thinned plots are showing improved annual diameter increments over the unthinned plots, in all size classes (Table 32).

These stands will provide an important sawlog resource from 2040 to 2060. Thinning of these stands should aim to maximize the final yield of sawlog volume. At this stage it appears that thinning more heavily than a residual basal area over bark of 20 m² ha⁻¹ will reduce overall sawlog yield (Hewett, unpublished).

These treatments have been replicated six times to allow future thinning treatments based on measured responses.

Operational Thinning of Young Karri Regrowth

The Warren thinning experiment indicated that it may be possible operationally to thin young regrowth stands on high quality sites (where a top height of 25 m or more had been reached). In 1985, an area of regrowth adjacent to the experiment was thinned in this way.

TABLE 30

Effect of thinning and fertilizing on annual diameter increment of young karri regrowth - Warren.

Thinning and Fertilizing Combined	MEAN d.b.h.u.b. INCREMENT (cm yr ⁻¹)			
	LARGEST 100 s.p.ha		LARGEST 200 s.p.ha	
	84/85 increment	85/86 increment	84/85 increment	85/86 increment
Unfertilized				
unthinned	1.9	1.42	1.68	1.24
600 s.p.ha	2.02	2.14	1.92	2.1
400 s.p.ha	2.38	1.89	2.28	1.73
200 s.p.ha	2.54	2.39	2.45	2.19
Fertilized				
unthinned	1.64	2.26	1.54	1.5
600 s.p.ha	2.05	2.64	1.94	2.33
400 s.p.ha	2.47	2.62	2.4	2.45
200 s.p.ha	2.63	2.82	2.42	2.53

Source : Hewett (unpublished)

TABLE 31

Effect of thinning and fertilizing on mean annual diameter increment of young regrowth - Warren.

Thinning intensity	MEAN d.b.h.u.b. INCREMENT (cm yr ⁻¹)			
	LARGEST 100 s.p.ha		LARGEST 200 s.p.ha	
	+ Fertilizer	- Fertilizer	+ Fertilizer	- Fertilizer
Unthinned	1.95	1.66	1.52	1.46
600 SPH	2.34	2.08	2.14	2.01
400 SPH	2.54	2.13	2.42	2.0
200 SPH	2.72	2.46	2.48	2.32

Source : Hewett (unpublished)

TABLE 32

Mean over-bark diameter increment for 50-year-old trees thinned to various residual basal areas - Treen Brook.

Residual Basal area	MEAN DIAMETER OVER BARK INCREMENT (1985-1988) cm yr ⁻¹		
	largest 40 s.p.ha	largest 80 s.p.ha	largest 120 s.p.ha
42.9 (Unthinned)	0.81	0.7	0.6
30	0.9	0.86	0.76
20	1.1	0.96	0.86
15	1.14	0.85	-
10	1.13	-	-

Source : Hewett (unpublished)

Over 100 m³ha⁻¹ of chippable material was removed in the most heavily thinned stands (to 200 s.p.ha), but very little material was removed in the more lightly thinned stands (400 s.p.ha, 600 s.p.ha).

To test further the operational and economical feasibility of thinning young, high quality karri, another experiment was established in August 1986 in 13-year-old regrowth.

The thinning operation was implemented using a John Deere 743A Tree Harvester and a Kockums Forwarder. The Tree Harvester fells the trees to be removed, then draws the log through rotating drums that remove the limbs and bark. The log is then cut to desired lengths by the harvester and deposited at the edge of the extraction track.

Access for the harvester was expected to be a major problem because of the limited site preparation carried out after the original clear felling operation. However, its excellent manoeuvrability, clearance and long reach enabled the harvester to remove almost all of the unwanted trees, while causing virtually no damage to any of the retained crop trees.

The forwarding operation proved to be very efficient largely owing to the prior bunching of logs by the harvester. As a result two harvesters would be required to keep one forwarder working at full capacity.

A total of 125 m³ ha⁻¹ of chipwood was removed during this operational trial with 200 crop trees/ha being retained. A small plot was thinned to 400 s.p.ha; unfortunately, access was impeded at this higher level of stocking and damage to the retained crop trees increased markedly.

During both operations trees were marked for retention by CALM Research staff. This was a difficult and time consuming operation because dense scrub impeded access. A small area was left unmarked to establish whether the harvester operator could select the crop trees for retention. The harvester was moved into the unmarked area after completing the thinning of the marked area. Selection by the operator proved successful with the correct stocking and spacing of crop trees being retained.

Ground fuel levels are increased following thinning. Much of the fuel is fine, and decomposition of this component should be rapid (one to two years). The rest of the fuel is woody and made up of crown branches and understorey stems 1-5 cm in diameter. This will not break down quickly and constitutes a fire hazard until it does.

Fuel distribution is improved by the trampling of the scrub and trash layers, thus reducing the chance of a crown fire occurring, but fuel loads remain high and fire intensity would still be high. Thinning may reduce the need for early prescribed burning of karri regrowth stands. In addition to the trampling of the scrub and trash, thinning opens the canopy allowing for quicker drying of the fuel. This lengthens the time available for prescribed burning because quicker drying means fuels would be dry enough for burning earlier in the season (October) and would stay dry longer (until May) (McCaw 1986).

Machine Damage to Crop Trees

During the winter of 1980 an experiment was conducted at Treen Brook to measure damage by machine to the butts of crop trees during a thinning operation in a 45-year-old regrowth stand. A forwarder and a skidder were used to log 6 ha during winter, with the forwarder logging a further 2 ha in summer for comparison. Four bole damage classes were selected, based on the area of bark removed from the cambium by the logging machines. They were:

- 0 : no damage
- 1 : 10 cm x 10 cm
- 2 : up to 30 cm x 30 cm
- 3 : >30 cm x 30 cm

The logging machines damaged 20-25 per cent of crop trees to some extent in the thinning operation (Table 33). (This excludes any damage owing to skinning of crop trees by falling trees, as this is minimal.) The skidder, which skids logs out whole, causes nearly three times as much class 3 damage as the forwarder. This damage appears to be severe, although the long term effect on wood quality is not known.

In mid-1982 machine damage in operationally thinned areas was reaching unacceptable levels. A new study was therefore implemented. The aims were to determine:

- (1) the causes of damage;
- (2) the damage vectors; and
- (3) the extent of damage.

During forwarding, 20 (or 34 per cent) of the 58 stems retained in the plot (0.6 ha) received some sort of stem damage. All of the damage was in either Class 1 or Class 2 (Table 34).

TABLE 33

Machine damage to crop trees during a thinning operation in 50-year-old regrowth - Treen Brook (1980).

OPERATION	BOLE DAMAGE CLASSES				
	0 (%)	1 (%)	2 (%)	3 (%)	1+2+3 (%)
Winter Forwarder	80	10	7	3	20
Winter Skidder	76	8	8	8	24
Summer Forwarder	77	12	6	5	23

Source : Voutier (unpublished)

TABLE 34

Machine damage to crop trees during a thinning operation in 50-year-old regrowth - Big Brook (1982).

	BOLE DAMAGE CLASSES					
	0	1	2	1 + 2	3	Total (1-3)
Percentage	66	24	9	1	0	34

Source : Voutier (unpublished)

Detailed observations (Voutier⁷, personal communication) revealed that although some of the damage was still being caused by lack of care by the driver, the underlying extraction method itself was fundamentally flawed. Forwarders continually move across the coupe following the feller, sorting out and loading whatever can be easily reached, while a buncher follows behind sorting and stacking what is left. Voutier states that the amount of waste movement forced on the forwarders is large and is aggravated by the, then, policy of sorting logs in the bush.

Winter logging may also contribute to the damage to retained trees, although this was not supported by the 1980 experiment. Rubber-tyred forwarders operate under great difficulty in winter on the heavy karri soils. When soils are saturated the forwarders slip and slide, and damage to retained trees is inevitable.

Voutier concluded that significant reductions in the level of damage were unlikely to be achieved without some restructuring of the extraction process. Ideally, forwarders should be restricted to removing stacks of logs from the bush to the landing. Crop tree protection is now a standard part of coupe management. Crop trees are inspected by the Forest Officer In Charge and assessed for damage. If excessive damage occurs (> 5 per cent of trees assessed) the logging contractor may be charged for all damaged trees. This serves as an incentive for machine operators to take great care of crop trees. Driver training has also helped to minimize crop tree damage.

FUTURE DIRECTION OF KARRI SILVICULTURE RESEARCH

The overall aim of the Science and Information Division of the Department of Conservation and Land Management is 'to provide up-to-date and scientifically sound information to uphold effective conservation and land management in WA' (CALM 1995).

Future research in karri silviculture should aim to:

- (1) reduce the cost of the regeneration program;
- (2) determine the optimal initial stocking of karri regeneration to suit different management needs;
- (3) establish thinning and fertilizing experiments in karri regrowth stands of varying ages and on a range of sites;
- (4) maintain or improve the long term productivity of karri and karri-marri stands;
- (5) investigate alternative establishment techniques; and
- (6) investigate alternative silvicultural systems for integration of silviculture and other forest management requirements.

Reducing the Cost of the Regeneration Program

New Regeneration Techniques

Although the seed tree method is preferred, just over half of the karri regeneration program is carried out by planting nursery-raised seedlings. This method is relatively expensive and time consuming. Direct seeding methods have the potential to reduce regeneration costs greatly as no nursery operations are required. At present broadcast sowing requires about fifteen times as much seed (40 000 seeds/ha) as hand planting. This limits its operational usage. Methods of direct seeding that use less seed and produce consistently good results deserve investigation.

Seed Production and Improvement

Future work in this field should involve:

1. Maintaining the area of karri seed orchards and seed production areas. New plantings will incorporate families not yet represented in the seed orchards, seedlings raised from seed collected in the 'first generation' seed orchards and, eventually, clones of outstanding (in terms of form, wood quality and seed production) trees in the forest and in progeny trials.
2. Culling the seed orchards of the poorest performing families (in terms of growth rate, form and seed production), based on results achieved in progeny tests.
3. Continuing to study the effects of environmental and management factors on seed production, so that future clonal seed orchards are planted on sites that maximize seed production.
4. Determining the optimum rotation length for the karri seed orchards and developing methods of tree management and seed collection.

Determining the Optimum Initial Stocking

Karri spacing experiments need to be established on a range of sites on which karri is planted. The aim will be to determine, for a range of sites, the optimum initial stocking of karri regeneration to suit nominated management objectives. Current practice aims to produce high quality sawlogs with some pulpwood during thinning in a reasonable time frame. In the future, management priorities may change emphasis. This may result in a change in initial stocking.

Results from current experiments will help to determine what the optimum initial espacement should be, but further information from high quality sites will be required.

⁷ R. Voutier, retired, formerly Department of Conservation and Land Management, Manjimup.

Thinning and Fertilizing Experiments

All thinning and fertilizing studies provide silvicultural data fundamental to the development of growth and economic models. Using these models, managers of karri regrowth can calculate at any stage during a rotation the future yields and cost-benefit relationships for any number of treatments.

Experimental studies are needed to identify the nutrients responsible for observed response to fertilizing following thinning, and to further quantify the thinning response on a range of sites. The research should ascertain the optimum level at which nutrients should be applied, as well as the best method and season of application, the timing of first and subsequent thinnings, thinning method, degree and intensity.

The effect of thinning and fertilizing on the quality of wood produced in the regrowth karri stands should be given more attention in the future. Similarly, it should be essential to monitor the effect of early thinning on fuel loads for early prescribed burning operations, and the effect of thinning and fertilizing on the composition and abundance of understorey species.

Maintaining or Improving Stand Productivity

The effect of different rotations on the nutrient balance and nutrient cycling in the karri forest needs to be monitored. Scientists have, to 1988, published a number of papers dealing with nutrient cycling and biomass production in the karri forest (Grove and Malajczuk 1985a and 1985b; O'Connell 1988). Their results indicate that the karri forest understorey plays an important role in the nutrition of karri stands, but that more research is required about the impact of management practices on nutrient cycling.

Alternative Establishment Techniques

Fire is the main establishment technique used in karri forest at present. Some ripping and ploughing is done on snig tracks and landings, but generally slash burning to create ashbeds is the main preparation. This is favoured for a number of reasons including ease of operation and reduced costs, but mainly because the seedling growth on ashbed is excellent, and because other species are adapted to regeneration following fire.

Various operational trials using heaping and windrowing of debris and ripping or raking soil have provided interesting preliminary results, but thorough investigations into alternative methods are required. Although there are no immediate plans to forsake fire as the principal regeneration tool, the need to determine whether karri can be successfully regenerated without fire is important.

Integrated Research

While the clear felling system is undisputably successful in karri logging and regeneration, alternative systems

should continue to be examined. Investigations into these alternative systems should examine their suitability in terms of regeneration success and tree growth, health and form, and their effect on fauna, flora, water production, visual amenity, cost efficiency and fire protection.

ACKNOWLEDGEMENTS

Many people have contributed to karri silvicultural research, from the beginnings of forest management in WA, with the establishment of the Forest Department in 1918. Most notable among these—Don Stewart, John Meachem, Owen Loneragan, Barney White, Per Christensen, Cameron Schuster, Steve Quain, Pat McNamara, Don Grace, Jack Bradshaw and Roger Underwood. Likewise, many people have been involved in the production of this paper. The first author prepared the main draft in 1983.

Jack Bradshaw, George Baur, Per Christensen, Roger Underwood, Barney White and Ian Abbott have provided useful criticism.

The staff of CALM's Manjimup Research Centre have also made a large contribution with their wealth of local knowledge - in particular Tony Annels and Pete Skinner who were involved in the setting up and monitoring of many of the earlier experiments covered.

REFERENCES

- Annels, A.R. (1980). Artificial seeding of karri (*Eucalyptus diversicolor* F. Muell.). Forests Department of Western Australia, Research Paper 59.
- Ashton, D.H. (1956). The autecology of *E. regnans*. Ph. D Thesis, Botany Department, University of Melbourne.
- Ballard, R. (1980). The means to excellence through nutrient amendment. In: *Forest Plantations - The Shape of the Future*. Proceedings of Weyerhaeuser Science Symposium, Tacoma, Washington, April 30 - May 3, 1979.
- Baxter, P. (1970). The flowering process - a new theory. In: *Plant growth substances*. Proceedings of the 7th International Conference on Plant Growth Substances, Canberra, Australia. D.J. Carr (Ed). pp. 775-779. Springer Verlag, Berlin.
- Bradshaw, F.J. (1978). Soil damage and winter logging. Forest Department of Western Australia, Unpublished internal report.
- Bradshaw, F.J. and Lush, A.R. (1981). *Conservation of the karri forest*. Forests Department of Western Australia, Perth.
- Bredahl, R. (1983a). Provenance variation in karri. Paper presented at Research Working Group, No. 1 Meeting, Como, Western Australia. November 1983.

- Breidahl, R. (1983b). The effect of site on flowering and seed production of karri. Paper presented at Research Working Group No. 1 Meeting, Como, Western Australia, November 1983.
- Breidahl, R. (1984). The effect of four pre-emergent herbicides on weed control and seedling growth in the karri open rooted nursery. Department of Conservation and Land Management, Western Australia, Unpublished internal report.
- Brix, H. (1983). Effects of thinning and nitrogen fertilization on growth of Douglas fir: relative contribution of foliage quantity and efficiency. *Canadian Journal of Forest Research* **13**, 167-175.
- Brondbo, P. (1968). Flowering of forest trees. A literature review. *Tidskrift for Skogbryk*, Oslo, 1968. Vol. 76(3), 179-190. Translated for the Forestry Commission by L. Gombrich, 1970.
- Christensen, P. (1969). Planting karri wildings. Forests Department of Western Australia, *Forest Notes* 7 (3), 14-18.
- Christensen, P. (1970). Planting karri wildings II. Forests Department of Western Australia. *Forest Notes* 8 (1), 6-9.
- Christensen, P. (1971a). The purple-crowned lorikeet and eucalypt pollination. *Australian Forestry* **35**(4), 263-270.
- Christensen, P.S. (1971b). Stimulation of seedfall in karri. *Australian Forestry* **35**(3), 182-190.
- Christensen, P. (1974). Response of open-rooted karri (*Eucalyptus diversicolor*) seedlings to nitrogen and phosphorus fertiliser. Forests Department of Western Australia, Research Paper 12.
- Christensen, P.E.S. and Schuster, C.J. (1979). Some factors affecting germination of karri (*Eucalyptus diversicolor* F. Muell.) seed. Forests Department of Western Australia, Research Paper 50.
- Churchill, D.M. (1968). The distribution and prehistory of *Eucalyptus diversicolor* F. Muell., *E. marginata* Donn ex Sm., and *E. calophylla* R. Br. in relation to rainfall. *Australian Journal of Botany* **16**, 125-151.
- Coates, D.J. and Sokolowski, R.E. (1989). Geographic patterns of genetic diversity in karri (*Eucalyptus diversicolor* F. Muell.) *Australian Journal of Botany* **37**, 145-156.
- Cunningham, T.M. (1960). The natural regeneration of *E. regnans*. School of Forestry, University of Melbourne, Bulletin 1.
- Daniel, T.W., Helms, J.A. and Baker, F.S. (1979). *Principles of Silviculture*. 2nd edn, McGraw-Hill Inc., New York.
- Department of Conservation and Land Management (1987a). *Timber production in Western Australia: a strategy to take WA's south-west forests into the 21st century*. CALM, Western Australia.
- Department of Conservation and Land Management (1987c). *Manual of hardwood logging specifications: for control of hardwood logging operations in the northern, central and southern forest regions of Western Australia*. 1st edn, CALM, Western Australia.
- Department of Conservation and Land Management (1987d). *Regional Management Plan, 1987-1997, Southern Forest Region*. Plan No. 11, CALM, Western Australia.
- Department of Conservation and Land Management (1990). *Silviculture specification 2/90: Karri Thinning*. CALM, Western Australia.
- Department of Conservation and Land Management (1991). *Annual Report 1990-1991*. CALM, Western Australia.
- Department of Conservation and Land Management (1995). *Science and Information Division Strategic Plan 1995-1999*. CALM, Western Australia.
- Durand-Cresswell, R., Boulay, M. and Franclet, A. (1982). Vegetative propagation of Eucalyptus. In: *Tissue culture in forestry*. J.M. Bonga, D.J. Durzan, Martinus (eds). Nijhoff, The Hague, Netherlands.
- Eldridge, K.G. (1975). Eucalyptus species. In: *Seed orchards*. R. Faulkner (ed.). UK Forestry Commission, Bulletin 54, pp. 134-139.
- Feilburg, L. and Soegaard, B. (1975). Historical Review of seed orchards. In: *Seed orchards*. R. Faulkner (ed.). UK Forestry Commission, Bulletin 54, pp 1-8.
- Giertych, M. (1977). Role of light and temperature in flowering of forest trees. Third World consultation on forest tree breeding, Canberra 1977, pp. 1-5.
- Griffin, A.R. (1980). Reproductive biology of *Eucalyptus regnans*. CSIRO Division of Forest Research, Research Working Group No. 1 Meeting. Morwell, Victoria, November 1980.
- Groot, A., Brown, K.M., Morrison, I.K. and Barker, J.E. (1984). A 10-year tree and stand response of jack pine to urea fertilization and low thinning. *Canadian Journal of Forest Research* **14**, 44-50.
- Grove, T.S. and Malaczuk, N. (1985a). Biomass production by trees and understorey shrubs in an age-series of *Eucalyptus diversicolor* F. Muell. stands. *Forest Ecology and Management* **11**, 59-74.
- Grove, T.S. and Malaczuk, N. (1985b). Nutrient accumulation by trees and understorey shrubs in an age series of *Eucalyptus diversicolor* F. Muell. stands. *Forest Ecology and Management* **11**, 75-95.
- Hall, N., Johnston, R.D. and Chippendale, G.M. (1970). *Forest trees of Australia*. 3rd edn. Department of National Development, Forestry and Timber Bureau, Canberra.
- Hartman, H.T. and Kester, D.E. (1968). *Plant propagation: principles and practices*. 2nd edn. Prentice Hall Inc., Englewood Cliffs, NJ.

- Hatch, A.B. (1960). *Ashbed effects in Western Australian forest soils*. Forests Department of Western Australia, Bulletin 64.
- Hocevar, M. (1980). The effect of hole and angle planting on stem and root development of spruce and Japanese Larch. *Schweizerische Zeitschrift für Forstwesen* 131 (4), 297-310, EAFV Birmensdorf Switzerland.
- Incoll, W.D. (1979). Effect of overwood trees on growth of young stands of *Eucalyptus sieberi*. *Australian Forestry*, 42 (2), 110-116.
- Inions, G., Wardell-Johnson, G. and Annels, A. (1990). Classification and evaluation of sites in karri (*Eucalyptus diversicolor* F. Muell.) regeneration, 2: Floristic attributes. *Forest Ecology and Management* 32, 135-154.
- Jackson, D.I. and Sweet, G.B. (1972). Flower initiation in temperate woody plants. *Horticultural Abstracts* 42(1), 9-24.
- Jones, P. (1978). *Fuel removal, fuel conditions and seedbed preparation in karri slash disposal burns*. Forests Department of Western Australia, Research Paper 42.
- Keighery, G. J. (1982). Bird pollinated plants in Western Australia. In: *Pollination and Evolution*. J.A. Armstrong, J.M. Powell and A.R. Richards (eds.) pp.77-89. Royal Botanic Gardens, Sydney NSW.
- Kimber, P.C. and Schuster, C.J. (1979). Fire and the regeneration of karri. Symposium on the biology of native Australian plants, University of Western Australia, Perth.
- Lane-Poole, C.E. (1917). Notes on karri forests: made during a ministerial tour of inspection in January - February, 1917. Forests Department of Western Australia, Bulletin No. 6.
- Leopold, A.C. (1951). Photoperiodism in plants. *The Quarterly Review of Biology* 26(3), 247-263.
- Loneragan, O.W. (1961). Jarrah (*Eucalyptus marginata* Sm.), and karri (*Eucalyptus diversicolor* F.v.M.) regeneration in southwest Western Australia. Thesis, Master of Science, University of Western Australia, Perth.
- Loneragan, O.W. (1971). Artificial regeneration of karri (*Eucalyptus diversicolor* F. Muell.). Forests Department of Western Australia, Bulletin 78.
- Loneragan, O.W. (1979). Karri (*Eucalyptus diversicolor* F. Muell.) phenological studies in relation to reforestation. Forests Department of Western Australia, Bulletin 90.
- Loneragan, O.W. and Loneragan, J.F. (1964). Ashbed and nutrients in the growth of seedlings of karri, *Eucalyptus diversicolor* (F.v.M.). *Journal of the Royal Society of Western Australia* 47(3), 75-80.
- McArthur, W.M. and Clifton, A.L. (1975). Forestry and agriculture in relation to soils in the Pemberton area of Western Australia. *CSIRO Soils and Land Use Series* No. 54.
- McCaw, W.L. (1986). Behaviour and short term effects of two fires in regenerated karri (*Eucalyptus diversicolor*) forest. Western Australia Department of Conservation and Land Management, Technical Report 9.
- Maguire, W.P. (1956). Are ponderosa pine cone crops predictable? *Journal of Forestry* 54 (11), 778-779.
- Matheson, A.C. and Willcocks, K.W. (1976). Seed yield in a radiata pine seed orchard following pollarding. *New Zealand Journal of Forestry Science* 6(1), 14-18.
- Matthews, J.D. (1963). Factors affecting the production of seed by forest trees. *Forestry Abstracts* 24(1), 1-13.
- Meachem, J.C. (1960). *The karri forest*. Forests Department of Western Australia, Perth.
- Meachem, J.C. (1961). Evidence given In: Rodger, G.J., *Report of the Royal Commission: appointed to enquire into and report upon the bush fires of December 1960 and January, February and March 1961 in Western Australia, the measures necessary or desirable to prevent and control such fires and to protect life and property in the future, and the basic requirements for an effective state fire emergency organisation*. Government Print, Perth.
- Mount, A.B. (1964). The interdependence of Eucalypts and forest fires in southern Australia. *Australian Forestry*, 28(3), 166-172.
- O'Connell, A.M. (1988). Decomposition of leaf litter in karri (*Eucalyptus diversicolor*) forest of varying age. *Forest Ecology and Management* 24, 113-125.
- O'Connell, A.M. and Menage, P.M.A. (1982). Litter fall and nutrient cycling in karri (*Eucalyptus diversicolor* F. Muell.) forest in relation to stand age. *Australian Journal of Ecology* 7(1), 49-62.
- O'Dowd, D.J. and Gill, A.M. (1984). Predator satiation and site alteration following fire: mass reproduction of alpine ash (*Eucalyptus delegatensis*) in south eastern Australia. *Ecology* 65(4), 1052-1066.
- Pryor, L.D. (1951). Controlled pollination of Eucalyptus. *Proceedings of the Linnean Society of NSW* 76, 135-139.
- Revell, G. (1991). Managing and Sustaining visual landscape values in Western Australia's south west forests. In: *Proceedings of a Seminar - A review of Road, River and Stream Zones in Southwest Forests*. July 1991. p. 43-55. Lands and Forest Commission.
- Rotherham, I. (1983). Suppression of growth of surrounding regeneration by veteran trees of karri (*Eucalyptus diversicolor*). *Australian Forestry* 46(1), 8-13.

- Schuster, C. (1978). The effect of plant spacing on the early development of karri (*Eucalyptus diversicolor* F. Muell.). Forests Department of Western Australia, Research Paper 44.
- Schuster, C.J. (1979a). Rehabilitation of soils damaged by logging in south-west Western Australia. Forests Department of Western Australia, Research Paper 54.
- Schuster, C.J. (1979b). An initial study of provenance variation in karri (*Eucalyptus diversicolor* F. Muell.). Forests Department of Western Australia, Research Paper 55.
- Schuster, C.J. (1979c). Regeneration and plant succession in the karri forest. Symposium, Forests Department of Western Australia, and CSIRO Division of Land Resources Management.
- Schuster, C.J. (1980a). Aerial seeding of karri. Forests Department of Western Australia, *Forest Notes* 17 (2).
- Schuster, C.J. (1980b). Aspects of spot seeding and seed pelleting for the regeneration of karri (*Eucalyptus diversicolor* F. Muell.). Forests Department of Western Australia, Research Paper 63.
- Schuster, C.J. (1982). Fertilising planted karri (*Eucalyptus diversicolor* F. Muell.) seedlings. Forests Department of Western Australia, Research Paper 70.
- Schuster, C.J. and Fremlin, R.R.A. (1980). Herbicides for use in Western Australian Forest Nurseries. Forests Department of Western Australia, Research Paper 61.
- Skinner, P.R. (1972). Planting karri wildings III. Forests Department of Western Australia, *Forest Notes* 10(3), 1-4.
- Sweet, G.B. (1975). Flowering and seed production. In: *Seed orchards*. Forestry Commission of Great Britain. R. Faulkner (ed.) Bulletin 54. pp. 72-82.
- Talbot, L. (1973). Karri thickets, before settlement. Forests Department of Western Australia, *Forest Notes* 11(2), 6-17.
- Tompsett, P.B. and Fletcher, A.M. (1977). Increased flowering of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in a polythene house. *Silvae Genetica* 26, pp. 84-86.
- Underwood, R.J. (1978). Natural fire periodicity in the karri (*Eucalyptus diversicolor* F. Muell.) forest. Forests Department of Western Australia, Research Paper 41.
- Walker, A. W. (1980). Recent developments at West Manjimup Nursery. Forests Department of Western Australia, *Forest Notes* 17(1).
- White, B.J. (1971). Regeneration methods in mixed marri-karri stands. Forests Department of Western Australia, Research Paper 4.
- White, B.J. (1974a). Clear felling with seed trees in karri (*Eucalyptus diversicolor*). Forests Department of Western Australia, Research Paper 13.
- White, B.J. (1974b). Karri silvics. Forests Department of Western Australia, Research Note 1.
- White, B.J. and Underwood, R.J. (1974). *Regeneration in the karri forest community*. Forests Department of Western Australia, Perth.
- Woods, R.V. (1976). Early Silviculture for upgrading productivity on marginal *Pinus radiata* sites in the South-Eastern Region of South Australia. Woods and Forests Department, South Australia, Bulletin 24.
- Wronski, E.B. (1984). Impact of tractor thinning operations on soils and tree roots in a karri forest, Western Australia. *Australian Forest Research* 14, 319-332.