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Annual waterfowl counts in south-west Western Australia - 1991/92

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ABSTRACT

Totals of 255 976 waterfowl, 99 nests and 766 broods were counted at 1102 wetlands in south-west Western Australia in November 1991 in a program conducted jointly by the Department of Conservation and Land Management and the Royal Australasian Ornithologists Union. In March 1992, 212 353 waterfowl, 3 nests and 21 broods were counted in 1084 wetlands. Black Swans, Eurasian Coots, 11 species of native ducks, and four species of exotic ducks, geese and swans were counted. Extrapolation of November and March counts suggests that there were *c.* 1 400 000 waterfowl in south-west Western Australia during the 1991/92 summer. Grey Teal were the most abundant species in both November (356 178 ± 105 648) and March (277 424 ± 136 150). Lakes supported 76 per cent of waterfowl in November and 65 per cent in March. Esperance and Wagin regions each contained approximately 20 per cent of the total estimated waterfowl population.

INTRODUCTION

In 1988 the Department of Conservation and Land Management (CALM) and the Royal Australasian Ornithologists Union (RAOU) began a four-year program of biannual waterfowl counts in south-west Western Australia (WA) to provide additional information about numbers and distribution of waterfowl in WA. Although counts of waterfowl numbers had previously been made for individual wetlands (e.g. Ford 1958; Sedgewick 1973), the only large-scale surveys in south-west WA were those of Jaensch *et al.* (1988) and Jaensch and Vervest (1988a,b). In addition to the biannual waterfowl counts, CALM and the RAOU conducted a more intensive three-year study of all waterbirds on *c.* 250 wetlands on the Swan Coastal Plain, near Perth, from 1989 to 1992 (Storey *et al.* 1993).

The program of biannual waterfowl counts was an extension of the March surveys conducted between 1986 and 1988 by Jaensch and Vervest (1988a,b) and used a fixed set of *c.* 1250 wetlands for survey by volunteers and CALM staff in November and March of each 'summer' period, starting in November 1988 (Halse *et al.* 1990, 1992). Larger or more inaccessible wetlands were surveyed from the air. The objectives of the biannual counts were: (1) to estimate numbers of ducks, swans and coots in south-west WA; (2) to examine regional distribution of the species each year in relation to wetland conditions; and (3) to compare regional distribution and types of wetlands used during the breeding season and in late summer.

This paper reports results for 1991/92, which was the final year of counting. Earlier counts were reported in Halse *et al.* (1990,1992,1994). Results for large-scale waterfowl counting programs elsewhere in Australia have been reported by Bayliss and Yeomans (1990a,b), Kingsford *et al.* (1992) and Peter (1992).

SURVEY DESIGN

The survey design was described by Halse *et al.* (1990,1992,1994) and only brief details are given here.

Survey methods

Thirteen native and four exotic species of waterfowl were counted: Black Swan (*Cygnus atratus*), Freckled Duck (*Stictonetta naevosa*), Australian Shelduck (*Tadorna tadornoides*), Pacific Black Duck (*Anas superciliosa*), Grey Teal (*A. gibberifrons*), Chestnut Teal (*A. castanea*), Australasian Shoveler (*A. rhynchotis*), Pink-eared Duck (*Malacorhynchus membranaceus*), Hardhead (*Aythya australis*), Maned Duck (*Chenonetta jubata*), Blue-billed Duck (*Oxyura australis*), Musk Duck (*Biziura lobata*), exotic swans, geese and ducks (Mute Swan, *Cygnus olor;* Greylag Goose, *Anser anser;* and domestic varieties of Mallard, *Anas platyrhynchos*, and Muscovy, *Cairina moschata*) and Eurasian Coot (*Fulica atra*).

Counts were made during nine-day periods (two weekends and the intervening week) towards the end of the breeding season in 1991 (16-24 November), and in early autumn 1992 when the birds were concentrated at 'summer' refuges (7-15 March).

The surveyed area in the South-West and the south-western part of the Eucla Land Divisions in south-west WA was divided into 20' blocks (Fig. 1). As far as possible, two permanent lakes with potential as summer refuges, two lakes (often seasonal) with potential as breeding sites, five farm dams and two sections of river were surveyed in each 20' block. All major estuaries[1] between Perth and Esperance were surveyed. Table 1 summarizes the number of wetlands surveyed in November 1991 and March 1992. For analysis of the distribution of waterfowl and its relation to rainfall, 20' blocks were grouped into 11 'regions' (Fig. 1) (Halse *et al.* 1990,1992).

Most wetlands were surveyed from the ground by 120 volunteer RAOU observers or by CALM staff. Some larger inland lakes, some lakes and river sections with difficult access, and all larger estuaries were surveyed from the air over a four-day period using a Cessna Cutlass 172 flying at about 70 knots at a height of 25-30 m. Wetlands counted from the air are marked in Appendix 2[2]. Observers recorded the number of birds, the number of nests containing eggs and the number of broods they saw at each wetland. They also recorded water depth (dry, <0.5 m, 0.5-<1.0 m, ≥1.0 m). Emergent vegetation in the inundated part of the each wetland was recorded during earlier surveys and the wetland assigned to a category reflecting the dominant type of vegetation (Halse *et al.* 1992). The categories were live trees, live trees and sedges, sedges, dead trees, samphire and open wetland (no vegetation).

[1] We use the term 'estuary' colloquially to include several wetlands, most notably Vasse-Wonnerup Estuary, that are not truly estuarine.

[2] Appendix 2 is lodged in the Wildlife Sciences Library, Department of Conservation and Land Management, PO Box 51, Wanneroo 6065.

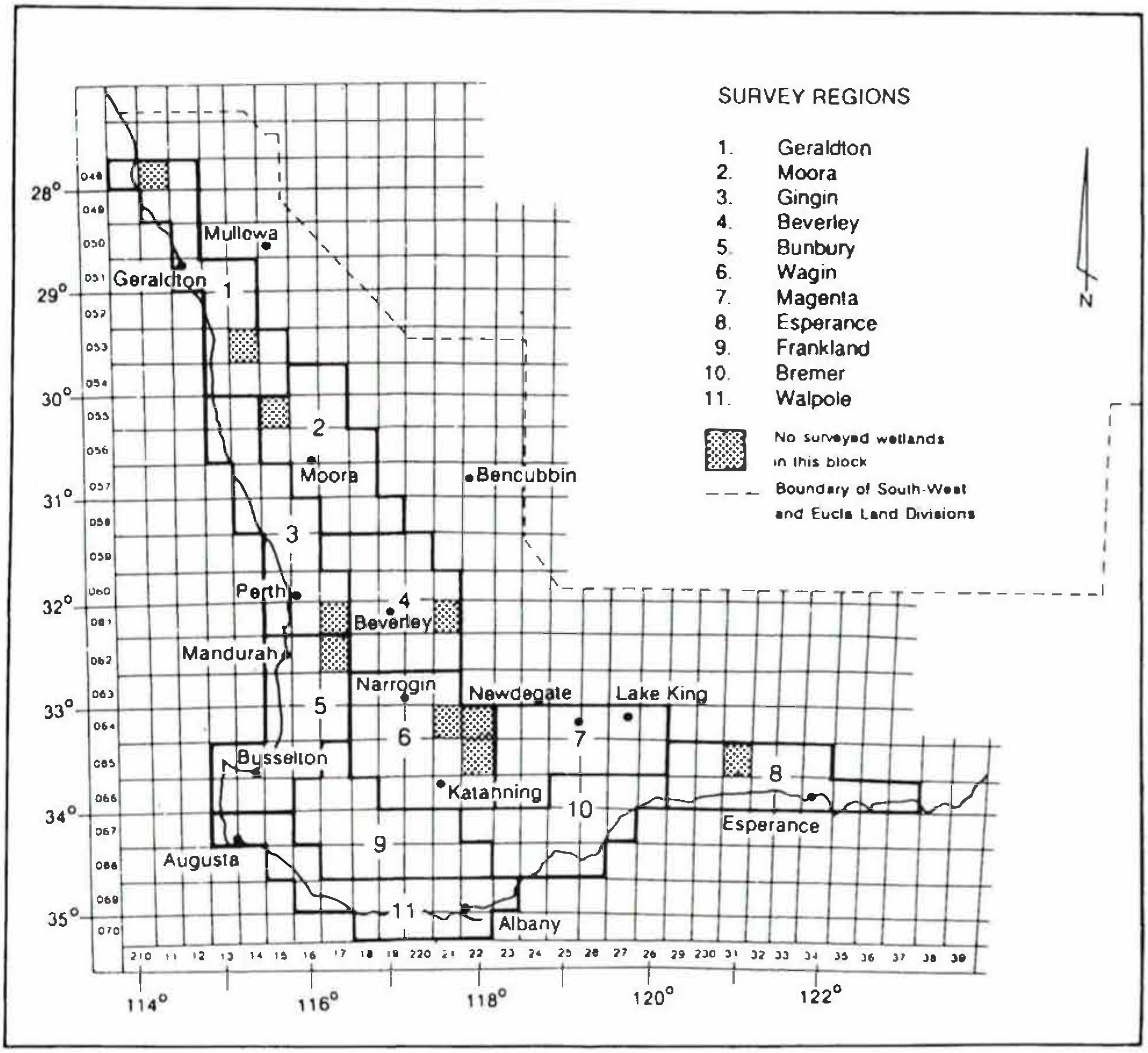


Figure 1. The area surveyed in the biannual waterfowl counts and regions recognized within the surveyed area. The 20' blocks, which form the basis of the survey design, are marked.

TABLE 1

Numbers of wetlands surveyed in each region in November 1991 and March 1992 compared with the number of wetland 'units' (see text) of each type identified from topographic maps. Figures in parentheses represent numbers of atypical waterbodies counted. Counts from atypical wetlands were added directly to the extrapolations.

REGION	LAKE			RIVER			DAM			ESTUARY		
	Nov 91	Mar 92	Units	Nov 91	Mar 92	Units	Nov 91	Mar 92	Units	Nov 91	Mar 92	Units
Geraldton	25	34	464	9	11	69	13	22	100	2	2	6
Moora	54(2)	40(2)	651	2	2	42	46	41	1000	-	-	-
Gingin	77(4)	76(4)	400	11	11	110	28	27	100	1	-	3
Beverley	31(2)	31(2)	102	15	15	105	59	57	1500	-	-	-
Bunbury	37(4)	41(4)	384	16(2)	17(2)	198	35	36	200	3	3	6
Wagin	46(8)	43(8)	209	19(1)	17(1)	112	61	67	1500	-	-	-
Magenta	45	46	350	1	1	5	57	57	1500	-	-	-
Esperance	49(5)	51(5)	650	7(3)	7(3)	57	40	42	1500	4	4	4
Frankland	34(1)	28(1)	343	23	22	288	55	48	3000	-	-	-
Bremer	36	32	232	19(3)	18(3)	219	35	35	1500	10	10	10
Walpole	39	37	206	14(1)	11(1)	135	37	35	2000	8	8	13
TOTAL	473(26)	459(26)	3991	136(10)	132(10)	1340	466	466	13900	27	27	42

Estimating numbers

Number of waterfowl in each region was estimated separately for lakes, rivers and dams by multiplying the mean number of birds counted per wetland by the total number of wetland 'units' of that type in the region. Topographic maps (1:100 000) were used to estimate the number of lakes and river sections in each region. Sometimes groups of small salt lakes were counted as one unit because this reflected the nature of the surveyed wetlands more closely than counting individual lakes. Similarly, long sections of flowing river were broken into several units or, in some cases, small pools were combined. Anon (1971) was used to provide information on the number of farm dams in each region and these data were converted to estimates of the numbers of dam units after correcting for bias in selection of surveyed dams (Halse *et al.* 1992). The estimated numbers of wetland units in each region are shown in Table 1.

The formula used to extrapolate from counts to estimated numbers of waterfowl is given below, estimating the number of Grey Teal on lakes in Beverley region as an example

$$\text{Estimated number} = \frac{\text{Count}}{N_S} \times N_T + C_A$$

where Count = number of Grey Teal counted in typical lakes in Beverley, N_T = total number of lake units in Beverley, N_S = number of typical lakes surveyed in Beverley, and C_A = number of Grey Teal counted in atypical lakes in Beverley.

Approximately 30 lakes and river sections supported much larger waterfowl populations than other wetlands in the same region. These 'atypical' wetlands were excluded from extrapolations, and counts at them were added directly to population estimates. Similarly, counts at estuaries were not extrapolated: all major estuaries were surveyed and our observations showed that most, if not all, of the remainder did not support significant numbers of waterfowl.

Ninety-five per cent confidence limits (C.L.) of estimates of waterfowl numbers were calculated using formulae derived from Snedecor and Cochran (1967, pp. 520-523) for standard errors associated with stratified sampling

$$S(\text{mean no. of birds/wetland}) = \frac{\sqrt{MS_{error}}}{\sqrt{N_S}} \times \sqrt{1 - \frac{N_S}{N_T}}$$

$$\text{C.L.} = 1.96 N_T \times S(\text{mean no. of birds/wetland})$$

where MS_{error} = mean square of the within-regions term in a one-way ANOVA of number of birds per wetland according to region.

RESULTS

Rainfall and wetland conditions

Annual rainfall in 1991 in the area covered by the biannual waterfowl counts was 'average', except in the Gingin region where it was 'above average' and the Esperance region where it was 'very much below average' (Table 2, Fig. 2). In absolute terms, Walpole, Bunbury, Frankland and Gingin were the wettest regions; Magenta and Esperance were the driest (Fig. 3). Rainfall decreased along a north-easterly gradient.

TABLE 2

Annual rainfall for 1991 in the five meteorological districts of south-west WA within the surveyed area of the biannual waterfowl counts (Bureau of Meteorology 1991).

District	1991 rainfall (mm)	Average rainfall (mm)	Decile range[a]
North Coastal	412	396	6
Central Coastal	946	849	8
South Coastal	896	909	5
North Central	341	357	6
South Central	402	435	4

[a] decile range 8-9 = above average rainfall
4-7 = average rainfall

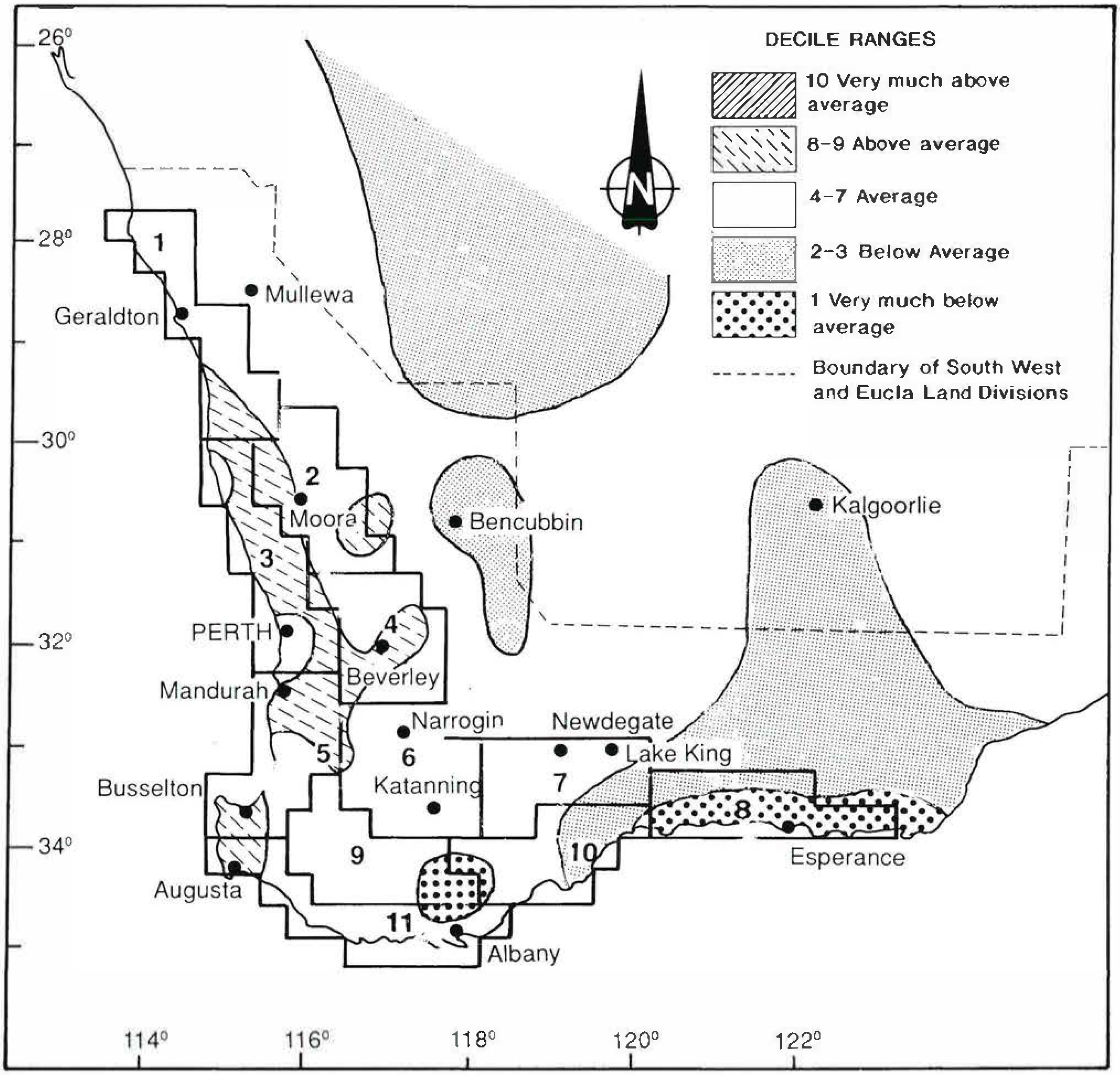


Figure 2. Decile ranges of the rainfall in south-west WA between January and December 1991 (Bureau of Meteorology 1991).

Ninety per cent of waterbodies (lakes, dams, etc.) contained water in November 1991. The regions where the largest numbers of waterbodies held water were Walpole (100 per cent), Frankland (100 per cent), Bunbury (99 per cent) and Gingin (98 per cent), while the driest regions were Geraldton (69 per cent) and Esperance (73 per cent) (Fig. 4).

Many wetlands in the survey area dried between November 1991 and March 1992 so that only 76 per cent of waterbodies contained water in March. Lakes were the wetland type showing greatest reduction in water levels (Fig. 5). Heavy rainfall (Fig. 6) and localized flooding in the Gingin region in February were not reflected by depths of the wetlands surveyed in that region in March (Fig. 4) although many small waterbodies filled. There was also heavy rainfall in the northern Goldfields (north-east of the surveyed area) in February and extensive rainfall on the eastern margin of the surveyed area from 13 to 19 March (Bureau of Meteorology 1992).

The most common types of vegetation in lakes were live and dead trees, fringing trees or trees and sedges predominated in rivers, most estuaries were fringed by sedges and most dams lacked vegetation (Table 3).

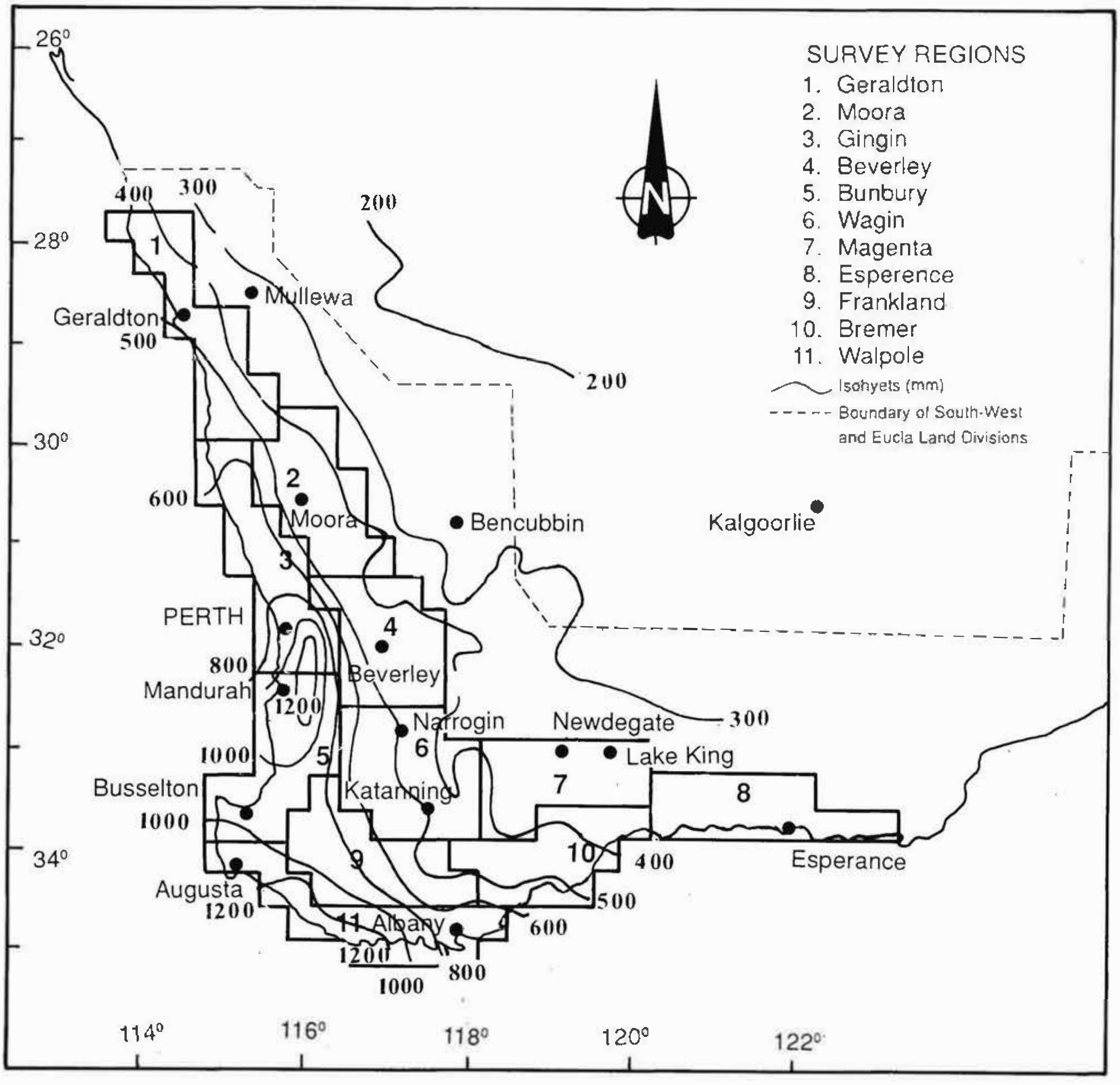


Figure 3. Rainfall (mm) in south-west WA between January and December 1991 (Bureau of Meteorology 1991).

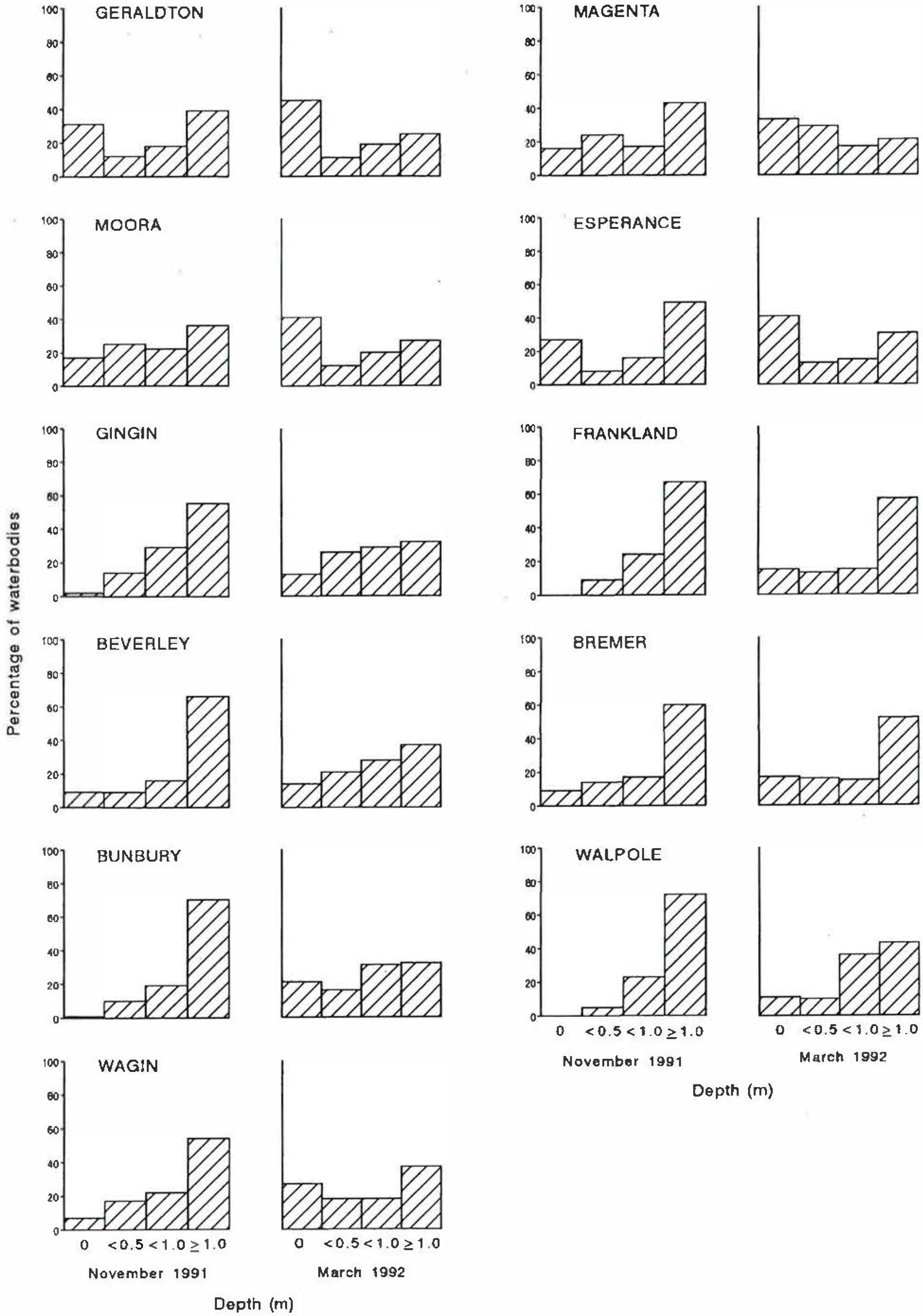


Figure 4. Percentage of waterbodies in each region containing various depths of water in November 1991 and March 1992.

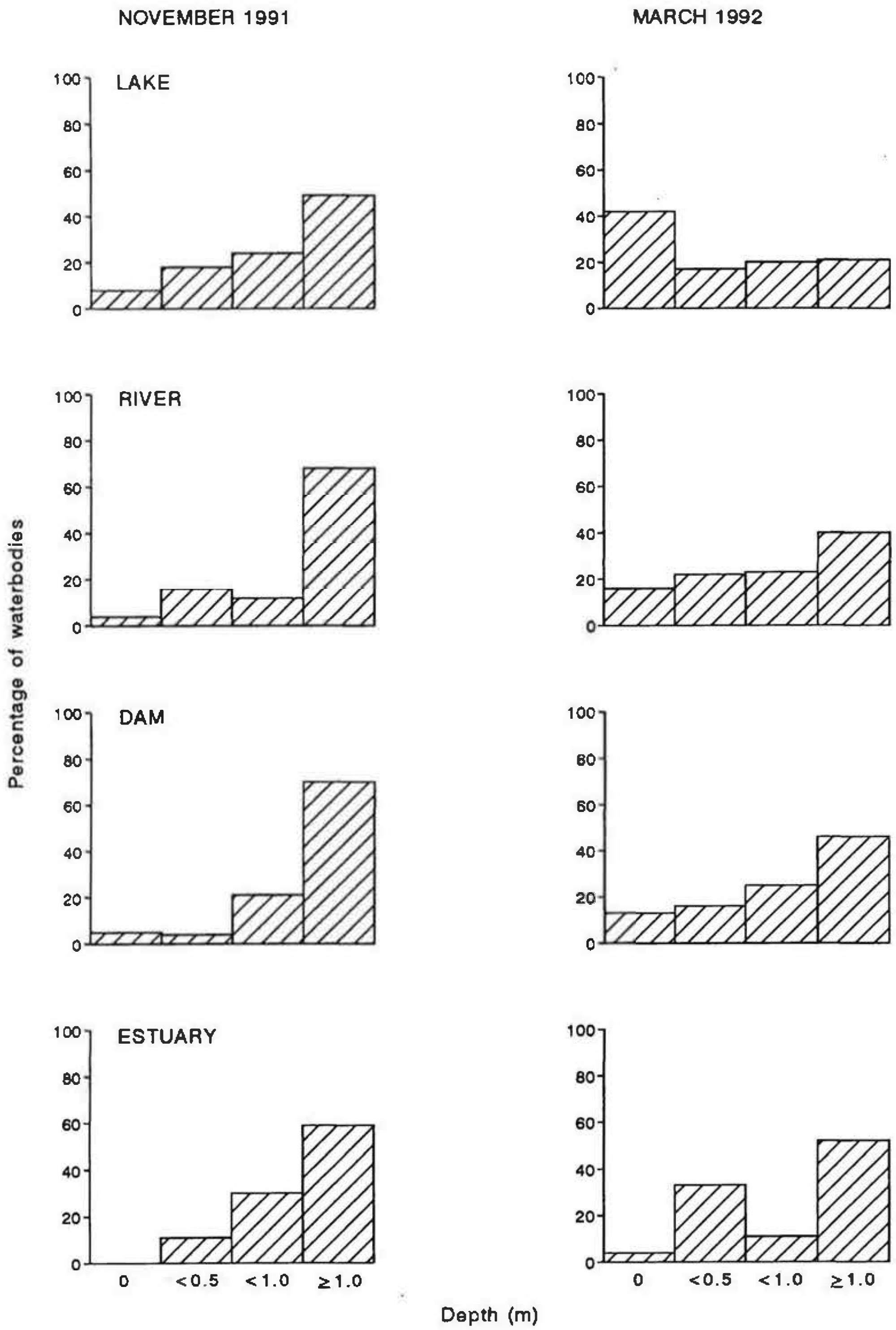


Figure 5. Percentage of waterbodies of each type containing various depths of water in November 1991 and March 1992.

Number of birds

Totals of 255 976 waterfowl were counted at 1102 wetlands in November 1991, and 212 353 at 1084 wetlands in March 1992 (Table 4). Extrapolations suggested that there were 1 154 645 ± 46 404 waterfowl in the surveyed area in November and 1 075 154 ± 65 496 in March (Table 5). The six more abundant species during both surveys were Grey Teal, Australian Shelduck, Eurasian Coot, Pacific Black Duck, Maned Duck and Black Swan. They accounted for 93 per cent of the estimated waterfowl population in November and 92 per cent of the estimated March population (Table 5).

Population estimates of half the species differed significantly between November and March (Table 5). Estimates for Australasian Shoveler (5.6 times more, t=2.82, P<0.01), Musk Duck (2.2, t=2.29, P<0.05) and Pacific Black Duck (2.0, t=2.02, P<0.05) were higher in March; estimates for Pink-eared Duck (2.7 times more, t=2.28, P<0.05), Australian Shelduck (1.8, t=2.83, P<0.01) and Maned Duck (1.6, t=2.72, P<0.01) were higher in November.

Summing the higher of the November and March estimates for each species suggested the total waterfowl population in south-west WA during summer of 1991/92 was approximately 1 400 000.

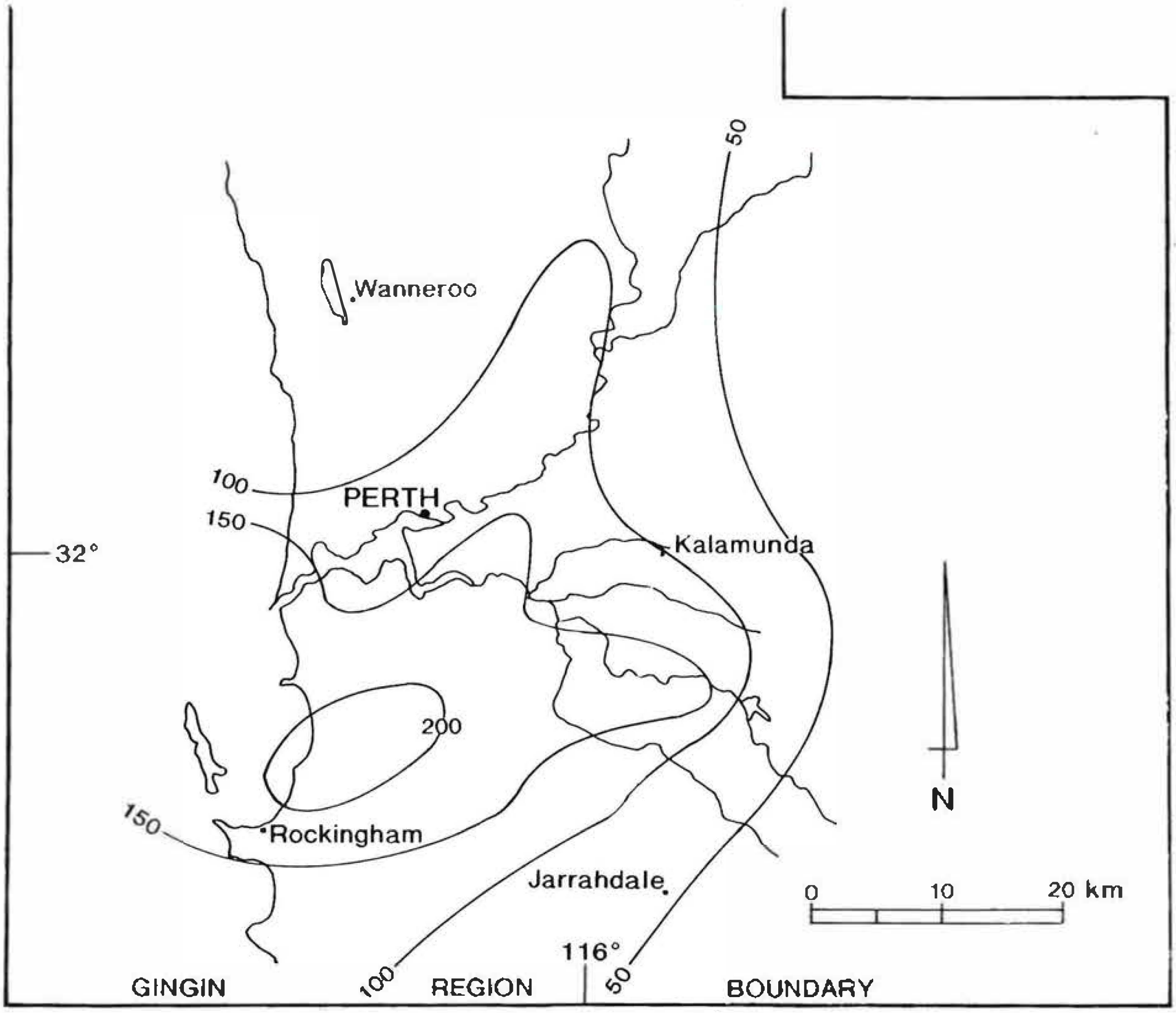


Figure 6. Rainfall (mm) around Perth in the Gingin region in February 1992 (Bureau of Meteorology 1992).

TABLE 3

Percentage of the different types of waterbody surveyed in biannual waterfowl counts in 1991/92 supporting various categories of vegetation.

	NOVEMBER 1991				MARCH 1992			
Vegetation	Lake	River	Dam	Estuary	Lake	River	Dam	Estuary
Live trees	33	37	4	4	33	36	4	4
Trees/sedges	14	26	3	26	14	26	3	26
Sedges	17	7	8	44	15	7	8	44
Dead trees	20	7	3	-	21	8	2	-
Samphire	5	-	-	11	5	-	-	11
Open	11	23	82	15	12	23	83	15
N	473	136	466	27	459	132	466	27

TABLE 4

Number of birds, nests and broods counted for each waterfowl species in November 1991 and March 1992 in south-west WA.

	NOVEMBER 1991			MARCH 1992		
Species	Birds counted	Nests counted	Broods counted	Birds counted	Nests counted	Broods counted
Black Swan	15279	6	236	14953	-	4
Freckled Duck	12	-	-	88	-	-
Australian Shelduck	99147	-	24	42924	-	-
Pacific Black Duck	19322	13	107	26811	-	-
Grey Teal	69986	31	100	78512	-	3
Chestnut Teal	2714	3	-	6960	-	-
Australasian Shoveler	732	-	5	3576	-	-
Pink-eared Duck	13613	7	27	3356	1	1
Hardhead	1228	-	9	433	-	1
Maned Duck	4901	4	64	2556	-	-
Blue-billed Duck	228	1	8	691	-	1
Musk Duck	1111	-	13	2810	-	-
Exotic ducks	390	3	4	323	-	3
Unidentified ducks	6	-	-	-	-	-
Eurasian Coot	27327	31	169	28360	2	8
TOTAL	255976	99	766	212353	3	21

TABLE 5

Estimated number of birds (± 95 per cent confidence limits) of each waterfowl species in November 1991 and March 1992 in south-west WA.

SPECIES	NOVEMBER 1991	MARCH 1992
Black Swan	44461 ± 14954	54877 ± 20438
Freckled Duck[a]	118	670
Australian Shelduck	333501 ± 74826	181911 ± 73500
Pacific Black Duck	104938 ± 32579	215555 ± 102233
Grey Teal	356178 ± 105640	277424 ± 136150
Chestnut Teal	17360 ± 10214	26746 ± 16198
Australasian Shoveler	3587 ± 1738	20190 ± 11411
Pink-eared Duck	36886 ± 18089	13887 ± 8051
Hardhead	7249 ± 8607	2721 ± 3667
Maned Duck	103288 ± 22363	62869 ± 18668
Blue-billed Duck	1338 ± 1199	2368 ± 2693
Musk Duck	6715 ± 1726	14452 ± 6399
Exotic ducks	2896 ± 5113	1990 ± 2058
Unidentified ducks[a]	33	-
Eurasian Coot	139491 ± 54730	199495 ± 74318
TOTAL	1154645± 46404	1075154 ± 65496

[a]Confidence limits could not be calculated because of too few occurrences.

Distribution

In November 1991 and March 1992, 76 and 65 per cent, respectively, of the estimated waterfowl population in south-west WA occurred on lakes, 15 and 21 per cent on dams, 4 and 10 per cent on river pools and approximately 5 per cent on estuaries (Table 6).

Maned Ducks were the only species that occurred mostly away from lakes - approximately 80 per cent were on dams during both counts. Pacific Black Ducks were most flexible in their use of wetland types: in March 49 per cent of them occurred on lakes, 30 per cent on rivers, 18 per cent on dams and 2 per cent on estuaries. Other species, especially Australasian Shovelers, Pink-eared Ducks, Blue-billed Ducks and Musk Ducks, were found mainly at lakes (Table 6).

The important regions for waterfowl during surveys in 1991/92 were Esperance, Wagin, Bunbury and Gingin (Tables 7 and 8). In November, the Wagin region contained 22 per cent of the estimated population in south-west WA, Esperance 21 per cent and Bunbury 11 per cent. In March, Wagin held 19 per cent, Esperance 16 per cent and Bunbury 15 per cent, while six of the 14 taxa were most abundant in Gingin.

Chestnut Teal exhibited the most pronounced geographical bias in distribution, with 63 and 86 per cent of the species occurring in the Esperance region in November and March, respectively, and 28 and 13 per cent in the Bremer region (Tables 7 and 8). More than half the Maned Duck population occurred in the Wagin and Frankland regions during both surveys. Gingin supported 87 per cent of Blue-billed Ducks in March but only 47 per cent during the wetter November survey period. Hardheads (60 per cent) were also concentrated in Gingin in March. Exotic waterfowl were virtually restricted to the Gingin, Beverley and Bunbury regions.

The number of birds counted at wetlands with different categories of vegetation is shown in Table 9. As a group, waterfowl appeared to prefer wetlands of the 'dead trees' and 'sedges' categories in both November and March (each category represented approximately 12 per cent of wetlands and supported 27 and 30 per cent, respectively, of birds in November and 26 and 35 per cent of birds in March[3]). There was also a disproportionately high number of birds on wetlands of the 'trees/sedges' category in March (11 per cent of wetlands and 18 per cent of birds). 'Open' wetlands, which represented 44 per cent of all waterbodies, were strongly avoided by most species and supported only 7 per cent of birds in November and 3 per cent in March.

The distribution of species at lakes, which supported the greatest range of vegetation categories of all the wetland types surveyed, showed that most species had strong associations with some vegetation categories (Fig. 7). Australian Shelducks and Grey Teal appeared to prefer lakes of the 'dead trees' category during both surveys, Pacific Black Ducks and Blue-billed Ducks were associated with 'sedges' or 'trees/sedges', Chestnut Teal preferred 'live trees' and Musk Ducks showed positive association with lakes of the 'sedges' category. There was a tendency for all species except Black Swans to avoid open lakes; similarly all species, except Pacific Black Ducks in November, were negatively associated with wetlands of the 'samphire' category.

[3] Results of statistical tests of habitat preferences are not presented because valid hypotheses could not be constructed. If occurrence of each bird was treated as an independent event, then deviations from expected frequencies were significant even when they constituted a very small percentage deviation. Analysis based on presence/absence also seemed flawed because if only one bird of a species was seen in a wetland that supported vast numbers of other waterfowl, the habitat was probably less suitable for the rare species than the abundant ones.

TABLE 6

Estimated number of waterfowl of each species at each wetland type in November 1991 and March 1992.

	NOVEMBER 1991				MARCH 1992			
Species	Lake	River	Dam	Estuary	Lake	River	Dam	Estuary
Black Swan	37028 ± 14102	468 ± 401	586 ± 451	6380	45447 ± 18795	1186 ± 891	1213 ± 752	7032
Freckled Duck	68	-	50	-	670	-	-	-
Australian Shelduck	305100 ± 71374	1378 ± 741	7356 ± 2711	19765	128045 ± 53193	2337 ± 1528	46807 ± 18779	4682
Pacific Black Duck	61118 ± 15947	17873 ± 10242	18259 ± 6390	7688	105742 ± 29435	65591 ± 55200	39705 ± 17598	4517
Grey Teal	274103 ± 80011	14526 ± 6789	52585 ± 18848	14963	191596 ± 106636	13956 ± 9236	53521 ± 20278	18351
Chestnut Teal	11110 ± 8741	664 ± 585	1112 ± 1388	1080	23070 ± 15119	1418 ± 845	96 ± 234	2162
Australasian Shoveler	3034 ± 1386	95 ± 91	284 ± 261	175	19989 ± 11374	73 ± 37	-	128
Pink-eared Duck	33487 ± 17557	43 ± 51	737 ± 481	2620	13430 ± 7427	-	457 ± 624	-
Hardhead	5830 ± 7124	279 ± 437	1049 ± 1048	91	2217 ± 3109	62 ± 146	441 ± 412	-
Maned Duck	16357 ± 6180	9275 ± 3314	77618 ± 12869	39	5299 ± 2715	5166 ± 2829	52392 ± 13124	12
Blue-billed Duck	1126 ± 702	170 ± 153	43 ± 344	-	2362 ± 2673	6 ± 20	-	-
Musk Duck	6356 ± 1483	99 ± 81	249 ± 162	11	13308 ± 5309	192 ± 174	894 ± 916	59
Exotic ducks	1545 ± 1102	754 ± 1037	596 ± 2974	-	1553 ± 1154	437 ± 904	-	-
Unidentified ducks	33	-	-	-	-	-	-	-
Eurasian Coot	115532 ± 42243	4069 ± 4225.	17723 ± 8262	2167	147434 ± 47746	17866 ± 10151	33240 ± 16421	954
TOTAL	871827 ± 35280	49691 ± 3844	178147 ± 7280	54979	700160± 38344	108332 ±16258	228765 ± 10894	37897

TABLE 7

Estimated number of waterfowl of each species in each region in November 1991.

	REGION										
Species	Geraldton	Moora	Gingin	Beverley	Bunbury	Wagin	Magenta	Esperance	Frankland	Bremer	Walpole
Black Swan	60	1254	7723	772	5054	2810	1159	16719	4057	2003	2851
Freckled Duck	50	-	5	-	-	-	62	-	-	-	-
Australian Shelduck	3486	24455	23330	10924	26338	35049	10522	137534	14908	28495	18460
Pacific Black Duck	4332	4015	20551	5091	22332	2569	357	14013	15785	3047	12846
Grey Teal	15407	62669	11951	35305	51294	109912	17217	17859	21047	4050	9469
Chestnut Teal	-	-	115	-	5	12	23	8862	1091	3847	11
Australasian Shoveler	1415	238	506	7	369	233	-	258	46	305	210
Pink-eared Duck	217	7095	1789	1816	2817	15011	93	7064	718	239	26
Hardhead	217	426	2078	1147	320	2570	-	118	-	103	269
Maned Duck	2616	1672	8796	12010	6922	38035	3928	2977	20832	2034	3467
Blue-billed Duck	56	-	644	53	281	-	-	57	64	26	158
Musk Duck	445	175	1011	49	711	187	86	2379	976	185	510
Exotic ducks	-	250	2196	294	145	-	-	-	-	-	10
Eurasian Coot	1890	17726	19546	3723	5528	43717	3516	30787	7610	4606	842
TOTAL[a]	30191	119975	100274	71191	122116	250105	36963	238627	87134	48940	49129

[a] includes unidentified waterfowl

TABLE 8

Estimated number of waterfowl of each species in each region in March 1992.

	REGION										
Species	Geraldton	Moora	Gingin	Beverley	Bunbury	Wagin	Magenta	Esperance	Frankland	Bremer	Walpole
Black Swan	246	2139	7728	587	5260	1617	23	20524	5431	921	10400
Freckled Duck	-	-	-	-	-	-	670	-	-	-	-
Australian Shelduck	4089	14054	8267	21351	10103	54926	972	10996	44811	7479	4863
Pacific Black Duck	7153	1595	29987	12904	73909	12392	221	31014	24770	8010	13601
Grey Teal	10537	6472	15808	49526	44469	87087	906	36395	10742	9405	6077
Chestnut Teal	-	34	6	-	35	52	-	22868	185	3567	-
Australasian Shoveler	3182	522	4466	18	1934	540	-	3158	1187	3262	1921
Pink-eared Duck	1633	1637	4828	334	1373	744	1636	539	-	740	423
Hardhead	48	17	1640	60	88	71	-	152	26	312	308
Maned Duck	268	2604	2859	4721	4833	20676	1825	3581	11992	6742	2770
Blue-billed Duck	6	-	2062	120	42	-	-	28	-	-	111
Musk Duck	671	171	2464	98	1686	250	99	1942	5908	392	771
Exotic ducks	-	-	1529	301	159	-	-	-	-	-	-
Eurasian Coot	1322	20558	39216	5628	19953	23249	784	35968	18578	8938	25301
TOTAL	29155	49803	120859	95648	163843	201603	7136	167164	123629	49768	66546

TABLE 9

Number of waterfowl counted on wetlands of each vegetation category in 1991/92.

CATEGORY	NOVEMBER	MARCH
Live trees	56718	36239
Trees/sedges	26363	37679
Sedges	68154	54941
Dead trees	76435	73693
Samphire	9108	2379
Open	19198	7422
TOTAL	255976	212353

Numbers of birds

The number of surveyed wetlands without birds increased between November 1991 and March 1992, usually because the wetlands were dry (Fig. 8a). Just over 30 per cent of the waterfowl occurred on wetlands containing 10 000 or more birds in both November and March (Fig. 8b).

The 15 wetlands supporting highest numbers of waterfowl in November 1991 and March 1992 are listed in Table 10. Peel-Harvey Estuary supported most birds in both November (23 060) and March (21 826). Jerdacuttup West Lake, Coyrecup Lake, Lake Dumbleyung, Culham Inlet and Lake Gundaring were also in the top 15 wetlands in both surveys. Eleven of the major wetlands during November counts were lakes, three were estuaries and one was a river; there were two estuaries, one river and twelve lakes in March. Wetlands with high numbers of birds were concentrated in the Wagin region in both November and March (six and five, respectively).

Wetlands with the three highest counts for each species in November and March, respectively, are listed in Appendix 1. Thirty-one wetlands were lakes, seven were estuaries, six were river sections and two were dams. All regions except Moora were represented although listed wetlands were concentrated in Gingin and Bunbury.

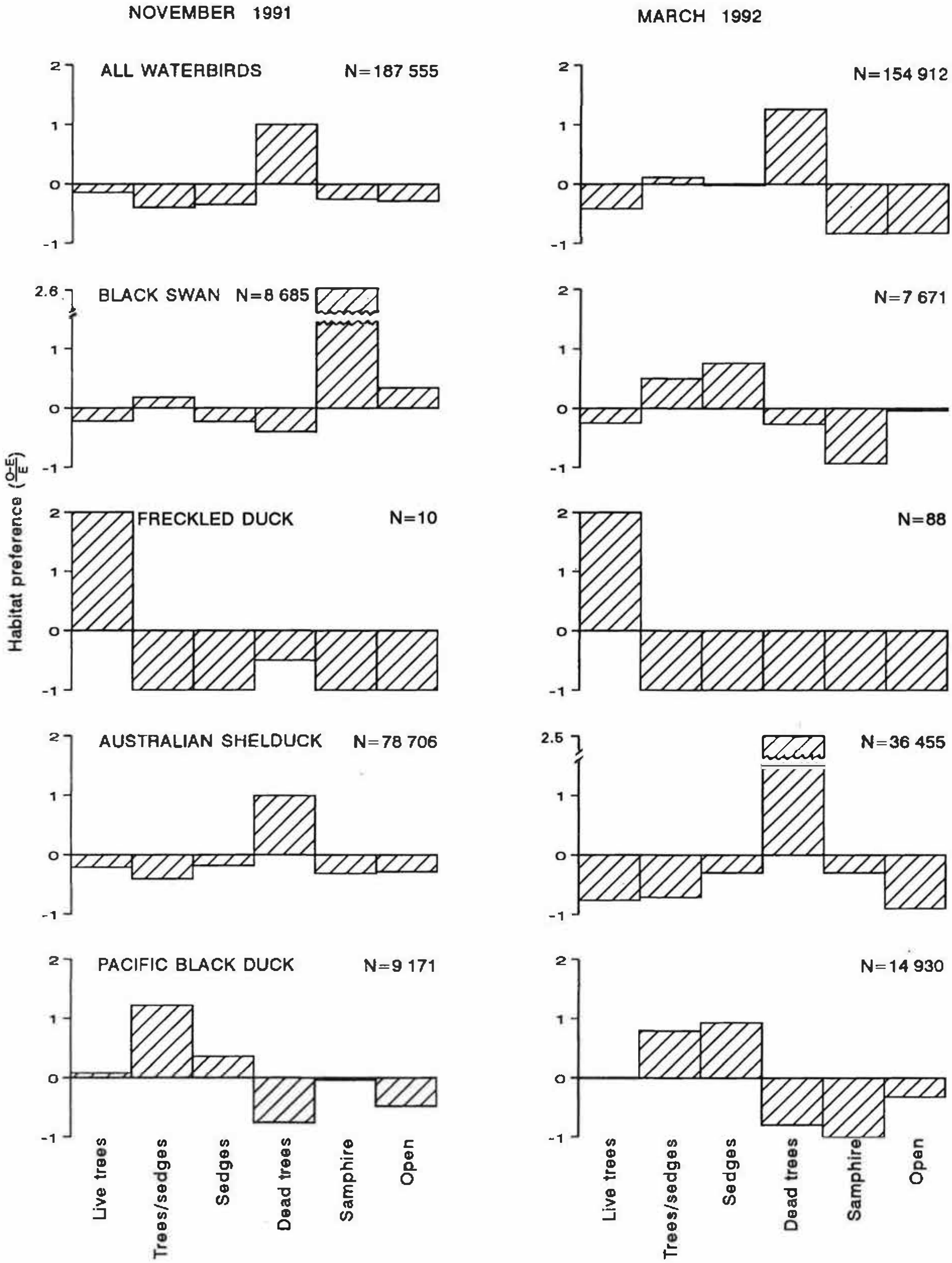


Figure 7. Preferences of waterfowl species for wetlands of different vegetation categories during biannual waterfowl counts in 1991/92. Preference for each wetland vegetation category calculated as (O-E)/E where O was number of birds counted at wetlands of each category and E was number expected if occurrences were proportional to the number of waterbodies of each category. Values of (O-E)/E are not symmetrical about zero.

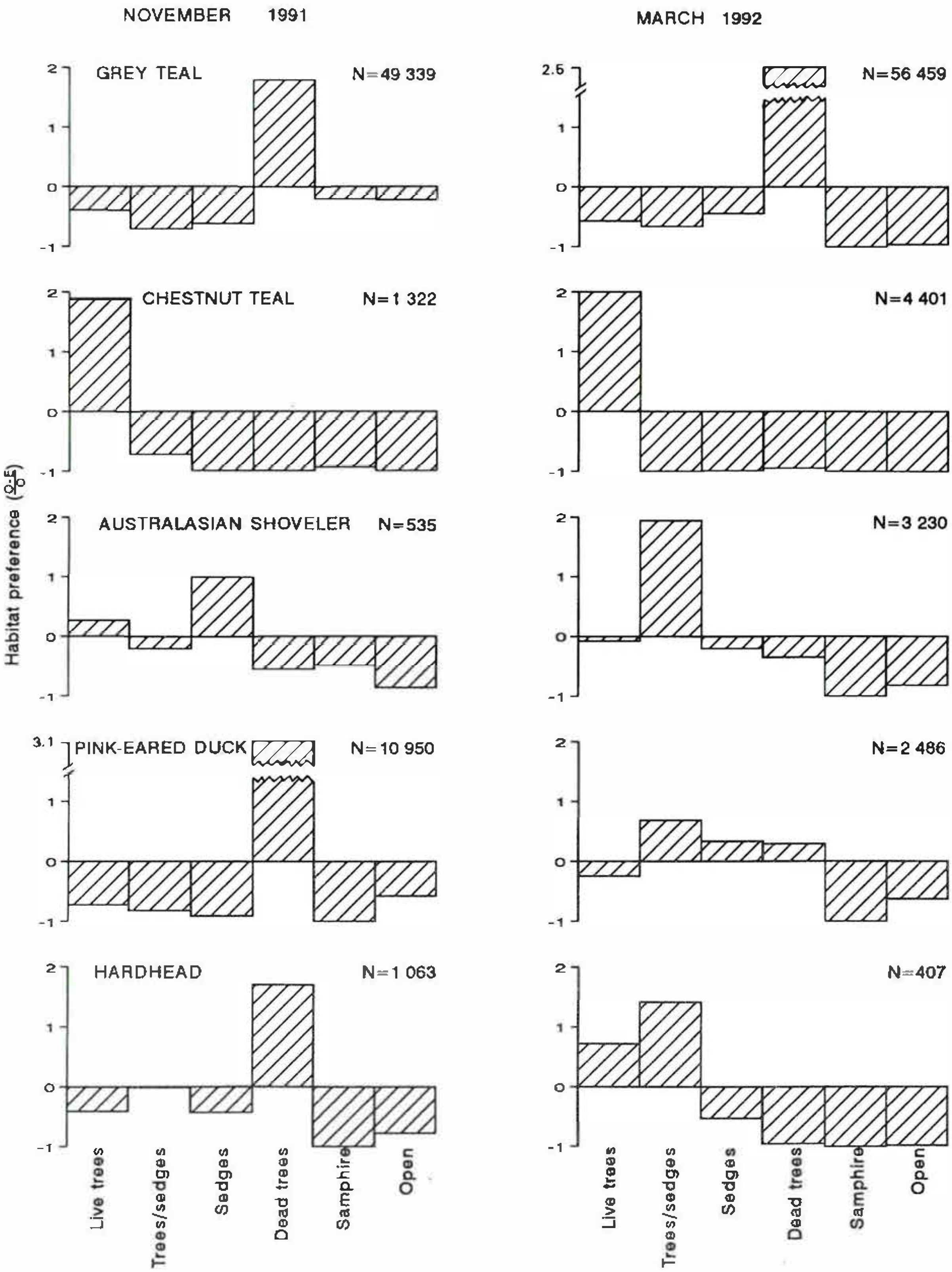
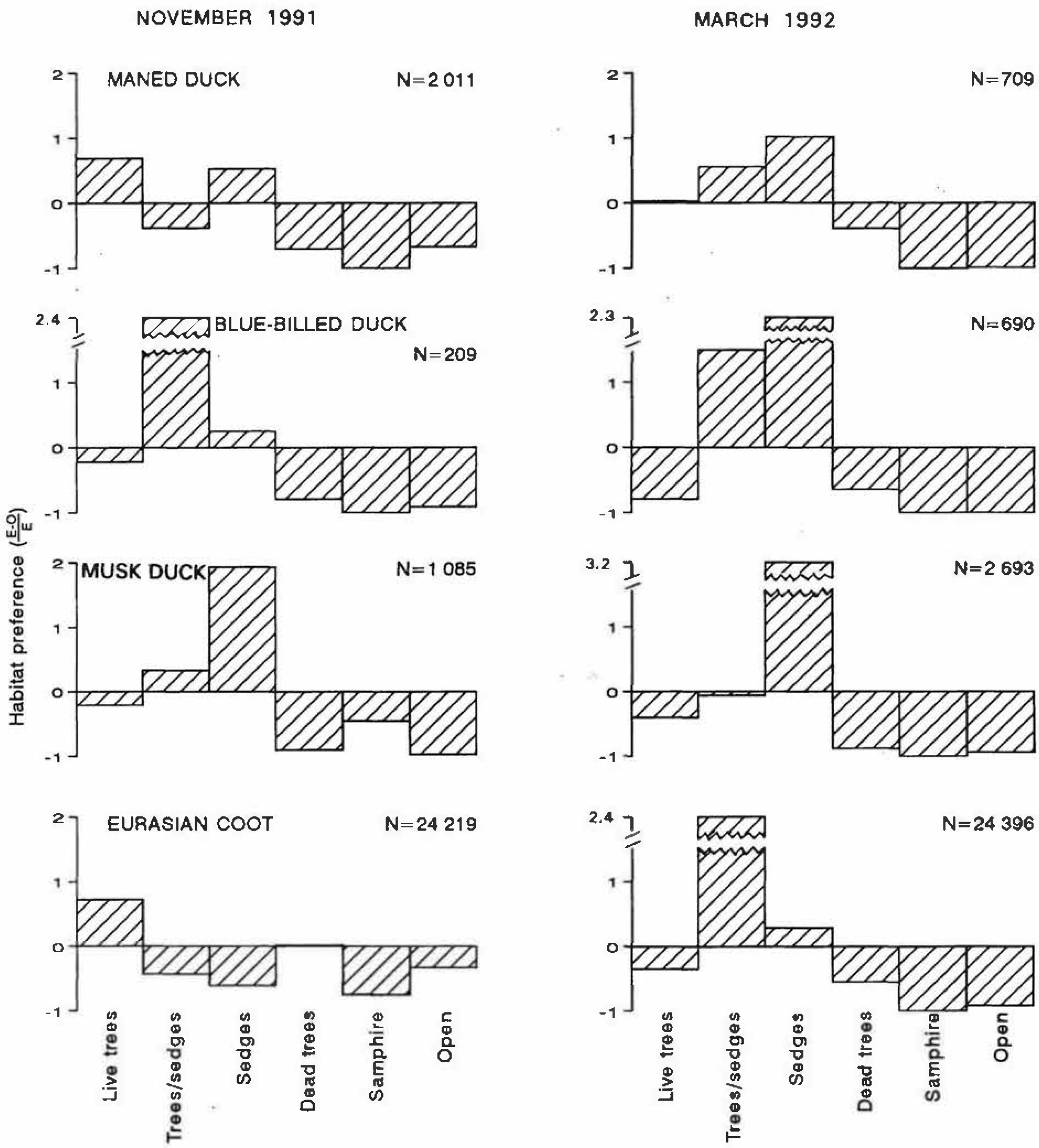


Figure 7 (continued).



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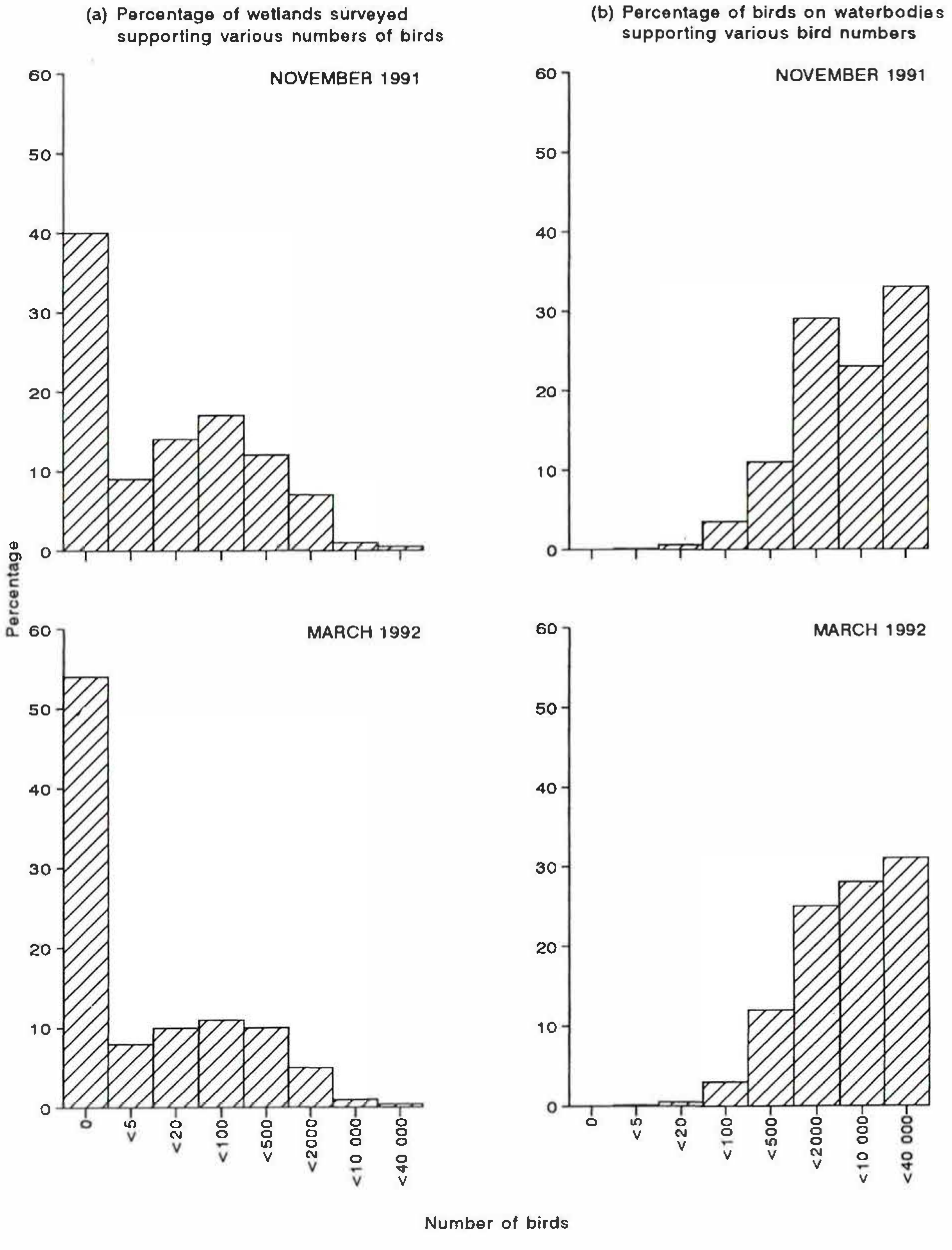

Figure 8. Number of birds at surveyed wetlands during the 1991/92 biannual waterfowl counts. (a) The percentage of waterbodies supporting various numbers of birds. (b) The percentage of birds at waterbodies supporting various bird numbers.

TABLE 10

The 15 wetlands supporting highest numbers of waterfowl in November 1991 and March 1992.

	NOVEMBER 1991				MARCH 1992			
	Wetland	Number	Region	Type	Wetland	Number	Region	Type
1	Peel Harvey Estuary	23060	Bunbury	E[a]	Peel-Harvey Estuary	21826	Bunbury	E
2	Vasse-Wonnerup Estuary	14150	Bunbury	E	Lake Dumbleyung	15636	Wagin	L
3	Jerdacuttup West Lake	13017	Esperance	L	Coyrecup Lake	15594	Wagin	L
4	Coyrecup Lake	11855	Wagin	L	Lake Yealering	13493	Beverley	L
5	Lake Guraga	10764	Gingin	L	Lake Forrestdale	7335	Gingin	L
6	Lake Dumbleyung	10421	Wagin	L	Lake Brown	6030	Beverley	L
7	Lake Preston	7436	Bunbury	L	Jerdacuttup West Lake	4530	Esperance	L
8	Casuarina Lake	6327	Wagin	L	Mullet Lake	4074	Esperance	L
9	Lake Gore	6147	Esperance	L	Wilson Inlet	3809	Walpole	E
10	Culham Inlet	5060	Esperance	E	Lake Gundaring	3794	Wagin	L
11	Lake Muir	4955	Frankland	L	Lake Clifton	3731	Bunbury	L
12	Beverley Lakes	4298	Beverley	L	Lake Towerinning	3635	Wagin	L
13	Lake Parkeyerring	3713	Wagin	L	Clarkes Lakes A & B	3602	Beverley	L
14	Lake Gundaring	3594	Wagin	L	Ewlyamartup Lake	3055	Wagin	L
15	Coblinine River Flats	3125	Wagin	R	Goegrup Pool (Serpentine R)	2894	Bunbury	R

[a]Wetland types: E = estuary, L = lake, R = river

Breeding

Ninety-nine nests and 766 broods were found in November 1991. Three nests and 21 broods were recorded in March 1992 (Table 4). No nest of Freckled Duck, Australian Shelduck, Australasian Shoveler, Hardhead or Musk Duck was found in either survey. The most commonly found nests belonged to Eurasian Coots and Grey Teal, and the most commonly seen broods belonged to Black Swans, Eurasian Coots, Pacific Black Ducks and Grey Teal. In relation to number of birds counted, Blue-billed Duck broods were found most frequently (ratio of 1 brood : 28 adults). Broods of Black Swans (1:65), Maned Ducks (1:76) and Musk Ducks (1:85) were common. Broods of exotic ducks (1:98), Hardheads (1:136), Australasian Shovelers (1:146) and Pacific Black Ducks (1:181) were less common, as were broods of Pink-eared Ducks (1:504) and Grey Teal (1:700). Australian Shelduck broods (1:4131) were scarce. No brood of Freckled Duck or Chestnut Teal was seen.

Distribution of breeding

Lakes were the most important breeding areas surveyed in 1991/92: 59 per cent of nests and 66 per cent of broods found in November occurred there. River sections contained 19 per cent of nests and 8 per cent of broods, dams contained 20 per cent of nests and 11 per cent of broods. Estuaries contained 2 per cent of nests and 15 per cent of broods (mostly Black Swans) (Table 11). Most nests and broods seen in November 1991 occurred in the Gingin (38 per cent of records), Bunbury (24 per cent) and Wagin (12 per cent) regions. The importance of Bunbury was exaggerated by the large number of breeding records of Black Swans (Table 12).

The distribution of breeding among vegetation categories was examined only for lakes, which had the most diverse vegetation of the wetland types surveyed. Wetlands of the 'trees/sedges' category appeared to be preferred breeding sites (14 per cent of wetlands *vs* 33 per cent of breeding activity), while those that were open or supported only samphire tended to be avoided (16 per cent *vs* 4 per cent) (Table 13). The breeding that did occur on open wetlands was at fresh, rather than saline, water.

DISCUSSION

Approximately 1 150 000 and 1 080 000 waterfowl, respectively, were estimated to occur in the surveyed area of south-west WA in November 1991 and March 1992, although summing the higher of the November and March estimates for each species suggests there were 1 400 000 birds during the 1991/92 summer. These figures are similar to results from previous surveys that suggest approximately 1 500 000 waterfowl occur in south-west WA (Fig. 9; Halse *et al.* 1992, 1994). The lower estimate obtained in March rather than in November is puzzling. Previous work suggests that when conditions become drier between November and March, as they did overall in 1991/92, the number of birds counted and the estimated number of birds should be higher (Fig. 9). A possible explanation for the low March estimate is that heavy rainfall in February around Perth (Fig. 6) and north-east of the surveyed area (Bureau of Meteorology 1992) caused some birds to move onto types of wetland in the Gingin region, such as roadside pools, that were not surveyed. Other birds may have moved north-eastwards out of the surveyed area. Heavy rainfall along the eastern edge of the

TABLE 11

Distribution of breeding by waterfowl species among wetland types in south-west WA in November 1991.

	LAKE		RIVER		DAM		ESTUARY	
Species	Nests	Broods	Nests	Broods	Nests	Broods	Nests	Broods
Black Swan	2	123	1	2	1	2	2	109
Freckled Duck	-	-	-	-	-	-	-	-
Australian Shelduck	-	17	-	-	-	4	-	1
Pacific Black Duck	7	71	2	18	4	14	-	7
Grey Teal	21	55	5	.21	5	23	-	1
Chestnut Teal	-	-	-	-	3	-	-	-
Australasian Shoveler	-	1	-	3	-	1	-	-
Pink-eared Duck	7	27	-	-	-	-	-	-
Hardhead	-	7	-	1	-	1	-	-
Maned Duck	-	26	-	10	4	28	-	-
Blue-billed Duck	1	8	-	-	-	-	-	-
Musk Duck	-	13	-	-	-	-	-	-
Exotic ducks	-	3	3	-	-	1	-	-
Eurasian Coot	20	148	8	9	3	12	-	-
TOTAL	58	501	19	61	20	86	2	118

TABLE 12

Distribution of breeding (nests and broods combined) by waterfowl species among regions in south-west WA in November 1991.

	REGION										
Species	Geraldton	Moora	Gingin	Beverley	Bunbury	Wagin	Magenta	Esperance	Frankland	Bremer	Walpole
Black Swan	0	6	55	2	120	25	-	1	11	1	21
Australian Shelduck	-	3	8	5	4	3	-	-	-	1	-
Pacific Black Duck	2	-	57	8	33	2	-	-	6	-	12
Grey Teal	-	7	31	12	15	33	1	2	10	-	9
Chestnut Teal	-	-	-	-	-	-	-	-	3	-	-
Australasian Shoveler	-	-	2	-	1	2	-	-	-	-	-
Pink-eared Duck	-	5	11	11	-	7	-	-	-	-	-
Hardhead	-	-	7	1	1	-	-	-	-	-	-
Maned Duck	-	1	19	2	13	11	2	-	17	-	3
Blue-billed Duck	-	-	6	-	2	-	-	-	-	-	1
Musk Duck	2	-	9	-	-	-	-	-	1	-	1
Exotic ducks	-	-	4	2	1	-	-	-	-	-	-
Eurasian Coot	2	7	123	18	17	24	4	3	1	1	1
TOTAL	6	29	332	72	207	107	7	6	49	3	48

TABLE 13
Distribution of breeding records within lakes according to vegetation category in south-west WA in November 1991. N = nests, B = broods

	LIVE TREES		TREES/SEDGES		SEDGES		DEAD TREES		SAMPHIRE		OPEN	
Species	N	B	N	B	N	B	N	B	N	B	N	B
Black Swan		28	1	46	1	20	-	18	-	4	-	7
Australian Shelduck	-	7	-	5	-	-	-	4	-	3	-	-
Pacific Black Duck	4	15	-	27	3	20	-	6	-	-	-	3
Grey Teal	11	28	-	6	2	8	8	13	-	-	-	-
Chestnut Teal	-	-	-	-	-	-	-	-	-	-	-	-
Australasian Shoveler	-	-	-	-	-	-	-	1	-	-	-	-
Pink-eared Duck	-	6	1	-	-	4	6	17	-	-	-	-
Hardhead	-	1	-	3	-	2	-	-	-	-	-	1
Maned Duck	-	9	-	7	-	8	-	1	-	-	-	1
Blue-billed Duck	-	4	-	1	-	2	1	1	-	-	-	-
Musk Duck	-	3	-	9	-	1	-	-	-	-	-	1
Exotic ducks	-	-	-	2	-	-	-	-	-	-	-	-
Eurasian Coot	5	36	10	67	-	24	5	16	-	-	-	5
TOTAL	20	137	12	173	6	89	20	77	-	7	-	18

surveyed area late in March (Bureau of Meteorology 1992) may also have caused birds to move. Halse *et al.* (1992) discussed the difficulty of estimating waterfowl numbers after summer rainfall.

Species with lower than expected population sizes in March 1992, compared with patterns observed in 1988/89 and 1990/91 (Halse *et al.* 1992,1994), were the Australian Shelduck, Grey Teal, Pink-eared Duck, Hardhead and Maned Duck. These species were also less abundant during March 1989/90, the other count after summer rainfall (Halse *et al.* 1992). The original observation that these species respond to rainfall in south-west WA was made by Bekle (1983), who found that Australian Shelduck, Grey Teal and Hardhead dispersed from wetlands in Perth after rain in January 1982. Maned Duck and Pink-eared Duck were rare in the wetlands Bekle (1983) studied.

Although winter of 1991 was the second wettest of the four winters during the waterfowl counting program (Fig. 9), it appeared to result in least breeding. There were 1801 breeding records in November 1988, 955 in 1989, 920 in 1990 and 865 in 1991 (Halse *et al.*1990,1992,1994). This pattern may be caused by declining effort spent searching for nests. Alternatively, waterfowl may have perceived 1991 as a drier year than rainfall records (Table 2) or the percentage of waterbodies containing water (Fig. 9) indicated. A higher proportion (86 per cent) of waterfowl were counted on wetlands supporting at least 500 birds in 1991 than in other Novembers (70 per cent in 1988, 80 per cent in 1989 and 1990), suggesting that birds were already congregating at summer refuges.

Most waterfowl were found in Wagin and Esperance regions during November 1991 and March 1992 surveys. Wagin was comparatively wet in 1991/92 (see Halse *et al.* 1990,1992,1994) but conditions in Esperance were comparatively dry. Large numbers of birds occurred in Wagin during all surveys between 1988 and 1992. The region is a stronghold for waterfowl in south-west WA, in spite of severe salination (Mulcahy 1978; Halse *et al.* 1993a) that makes it less favoured by salt-sensitive species such as Blue-billed Duck, Pacific Black Duck and Hardhead most years (Halse *et al.* 1993b). Numbers of waterfowl in Esperance were not high until March 1990. The region flooded extensively in the winter of 1989 (Halse *et al.* 1992) and, as water levels receded, it supported large numbers of birds (Halse *et al.* 1992,1994).

As in previous surveys (Halse *et al.* 1990,1992,1994), Bunbury and Gingin were the most important regions for breeding in November 1991. Unlike previous years, in 1991 Bunbury was less important than Gingin, perhaps because conditions were slightly drier in Bunbury.

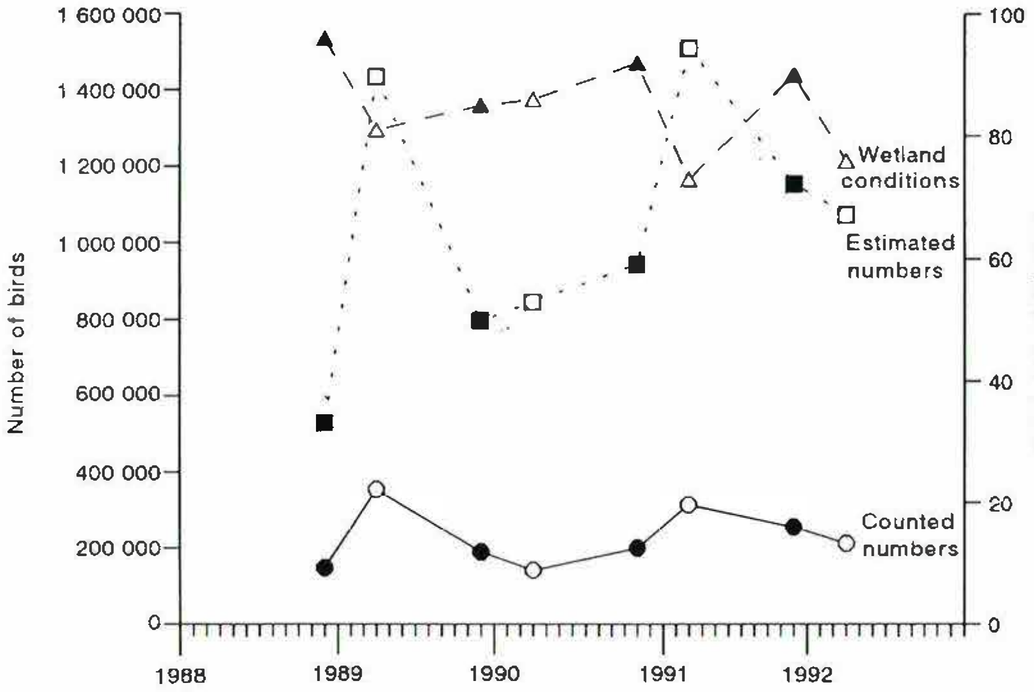

Figure 9. Numbers of birds counted, estimated numbers of birds in the surveyed area and percentage of wetlands surveyed that contained water during November and March waterfowl surveys between 1988/89 and 1991/92 in south-west WA.

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Abbott, J., Agar, G., Allan, G. & P., Barrett, B., Belfairs, B., Bennetts, P., Bentley, P., Bigwood, C., Blyth, J., Bougher, M., Bremner, M., Brockman, N., Brooke, J., Burbidge, A., Bush, T., Clark, H., Coole, J., Cotton, J., Craig, M., Curry, S., Danks, A., Davidson, J., DeCampi, G., Donohoe, J., Doyle, F., Dyer, G., Edwards, U., Ewert, J., Frederiksen, H. & K., Godfrey, N., Golos, P., Graham, M., Green, J., Green, O., Hale, B., Hamersley, B., Hamilton, N., Harrison, L., Hill, S., Howard, M., Howden, P., Hunt, J., Ingles, J., Jacoby, P., James, D., Jasper, R., Jennings, P., Jones, A. & R., Kent, T., Keogh, S., Kirkby, T., Kneebone, B., Lane, J., Leighton, P., Lodge, G. & D., Lupton, L., Margrain, C. & T., Masters, J., Mattner, J. & C., McGuire, M., McRoberts, B. & K., Mercer, C., Meredith, B., Millar, D., Moir, R., Moore, A., Morgan, D., Motteram, R., Napier, C. & W., Nash, D., Nash, M., Nurick, J., Owen, M., Parker, I., Parry, C., Patterson, V., Paynter, R., Pitcher, M. & D., Richter, C., Ridley, B., Robinson, N., Roocke, A., Rooke, I., Rose, A., Rose, L., Rule, R., Sandstrom, D., Scarff, A., Shannon, P., Silvester, L., Singleton, E., Smith, R., Start, J. & H., Talbot, J. & V., Taylor, J. & A., Trethowan, C., Turpin, M. & D., Tyrer, N., Walsh, G., Watkins, G. & R., Watts, K., Webb, J., Wilder, C., Wilmot, P., Wilson, B., Worts, U., Wright, L., York, K., Zadow, W.

REFERENCES

Anon (1971). Water resources on farms at 31 March 1970. Commonwealth Bureau of Census and Statistics, Perth, Unpublished Report.

Bayliss, P. and Yeomans, K.M. (1990a). Seasonal distribution and abundance of Magpie Geese, *Anseranas semipalmata* Latham, in the Northern Territory, and their relationship to habitat, 1983-86. *Australian Wildlife Research* **17**, 15-38.

Bayliss, P. and Yeomans, K.M. (1990b). Use of low-level aerial photography to correct bias in aerial survey estimates of Magpie Geese and whistling duck density in the Northern Territory. *Australian Wildlife Research* **17**, 1-10.

Bekle, H. (1983). Effects of unseasonable rains in January 1982 on waterfowl in south-western Australia, 1: Responses of selected species on coastal summer refuges. *Western Australian Naturalist* **15**, 117-122.

Bureau of Meteorology (1991). *Monthly Weather Review, Western Australia - December 1991.* Department of Administrative Services, Perth, Western Australia.

Bureau of Meteorology (1992). *Monthly Weather Review, Western Australia - February, March 1992.* Department of Administrative Services, Perth, Western Australia.

Ford, J.R. (1958). Seasonal variation in populations of Anatidae at the Bibra Lake District, Western Australia. *Emu* **58**, 31-41.

Halse, S.A., Jaensch, R.P., Munro, D.R. and Pearson, G.B. (1990). Annual waterfowl counts in south-western Australia - 1988/89. *Western Australian Department of Conservation and Land Management Technical Report* 25.

Halse, S.A., Pearson, G.B. and Patrick, S. (1993a). Vegetation of depth-gauged wetlands in nature reserves of south-west Western Australia. *Western Australian Department of Conservation and Land Management Technical Report* 30.

Halse, S.A.,Vervest, R.M., Munro, D.R., Pearson, G.B. and Yung, F.H. (1992). Annual waterfowl counts in south-western Australia - 1989/90. *Western Australian Department of Conservation and Land Management Technical Report* 29.

Halse, S.A.,Vervest, R.M., Pearson, G.B., Yung, F.H. and Fuller, P.J. (1994). Annual waterfowl counts in south-western Australia - 1990/91. *CALMScience* **1**, 107-129.

Halse, S.A., Williams, M.R., Jaensch, R.P. and Lane, J.A.K. (1993b). Wetland characteristics and waterbird use of wetlands in south-western Australia. *Wildlife Research* **20**, 103-126.

Jaensch, R.P. and Vervest, R.M. (1988a). Ducks, swans and coots in south-western Australia: the 1986 and 1987 counts. *Royal Australasian Ornithologists Union Report* 31.

Jaensch, R.P. and Vervest, R.M. (1988b). Ducks, swans and coots in south-western Australia: the 1988 count and recommendations. *Royal Australasian Ornithologists Union Report* 46.

Jaensch, R.P., Vervest, R.M. and Hewish, M.J. (1988). Waterbirds in nature reserves of south-western Australia 1981-1985. *Royal Australasian Ornithologists Union Report* 30.

Kingsford, R.T., Porter, J.L., Smith, J.D.B. and Lawler, W. (1992). An aerial survey of wetland birds in eastern Australia - October 1991. *New South Wales National Parks and Wildlife Service Occasional Paper* 12.

Mulcahy, M.J. (1978). Salinization in the south-west of Western Australia. *Search* **9**, 269-272.

Peter, J. (1992). Waterfowl count in Victoria: February 1992. *Royal Australasian Ornithologists Union Report* 85.

Sedgwick, E.H. (1973). Birds of the Benger Swamp. *Western Australian Naturalist* **12**, 147-155.

Snedecor, G.W. and Cochran, W.G. (1967). *Statistical Methods*, 6th edn. Iowa State University Press, Ames, USA.

Storey, A.W., Vervest, R.M., Pearson, G.B. and Halse, S.A. (1993). *Wetlands of the Swan Coastal Plain*, Vol. 7: *Waterbird usage of wetlands on the Swan Coastal Plain.* Water Authority of Western Australia, Perth.

APPENDIX 1

The number of wetlands in which each native waterfowl species occurred (N) and the three wetlands supporting highest numbers (in parentheses) of each species in November 1991 and March 1992. Regions and wetland types are given below the main body of the table.

SPECIES	N	1	2	3
NOVEMBER 1991				
Black Swan	211	Vasse-Wonnerup Estuary (1873)	Lake Muir (1493)	Wilson Inlet (909)
Freckled Duck	4	East Bryde Nature Res. Lake (8)	Dam 2 054-215 (2)	Gibbs Road Swamp (1)
Australian Shelduck	286	Lake Dumbleyung (9138)	Peel-Harvey Estuary (7691)	Lake Preston (7201)
Pacific Black Duck	407	Vasse-Wonnerup Estuary (3784)	Peel-Harvey Estuary (1793)	Jerdacuttup West Lake (911)
Grey Teal	387	Peel-Harvey Estuary (10745)	Vasse-Wonnerup Estuary (3093)	Coblinine River Flats (2817)
Chestnut Teal	41	Gordon Inlet (646)	Two Mile Lake (379)	Mullet Lake (275)
Australasian Shoveler	64	Peel-Harvey Estuary (150)	Jerdacuttup West Lake (130)	White Lake (Eneabba) (75)
Pink-eared Duck	96	Coyrecup Lake (6393)	Peel-Harvey Estuary (2000)	Casuarina Lake (1012)
Hardhead	68	Casuarina Lake (415)	Lake Chittering (100)	Culham Inlet (90)
Maned Duck	299	Taylors Lakes (220)	Lake Chittering (142)	Waneragup Lake (120)
Blue-billed Duck	39	Lake Monger (23)	Yangebup Lake (20)	Bibra Lake (20)
Musk Duck	125	Lake Clifton (357)	Thomsons Lake (37)	Lake Mariginiup (34)
Eurasian Coot	248	Jerdacuttup West Lake (6932)	Casuarina Lake (2010)	Lake Guraga (1472)
MARCH 1992				
Black Swan	144	Wilson Inlet (2590)	Irwin Inlet (1340)	Mullet Lake (933)
Freckled Duck	1	East Bryde Nature Res. Lake (88)		
Australian Shelduck	235	Lake Dumbleyung (14022)	Peel-Harvey Estuary (3509)	Lake Brown (2000)
Pacific Black Duck	322	Murray River (Delta to Pinjarra) (2284)	Harvey River (Lower reach) (1554)	Lake Clifton (1199)
Grey Teal	284	Peel-Harvey Estuary (16462)	Lake Yealering (11720)	Coyrecup Lake (11040)
Chestnut Teal	47	Jerdacuttup West lake (2730)	Stokes Inlet (983)	Wheatfield Lake (848)
Australasian Shoveler	59	Coyrecup Lake (385)	Lake Forrestdale (370)	Lake Torrup (345)
Pink-eared Duck	56	Amarillo Pool (Serpentine River) (850)	Coyrecup Lake (711)	Thomsons Lake (303)
Hardhead	41	North Lake (173)	Lake Forrestdale (60)	Yellilup Swamp (40)
Maned Duck	154	Dam 1 063-217 (130)	Penwortham Pool (100)	Big SEC Swamp (82)
Blue-billed Duck	30	Thomsons Lake (318)	Lake Monger (130)	Lake Bambun (82)
Musk Duck	101	Lake Clifton (1240)	Katherine Lake (202)	Lake Preston (195)
Eurasian Coot	205	Lake Forrestdale (5750)	Goegrup Pool (Serpentine River) (1205)	Coyrecup Lake (1152)

Appendix 1 (continued)

NOTE

WETLAND	REGION	TYPE	WETLAND	REGION	TYPE
Amarillo Pool (Serpentine River)	Bunbury	R	Katherine Lake	Frankland	L
Lake Bambun	Gingin	L	Lake Mariginiup	Gingin	L
Bibra Lake	Gingin	L	Lake Monger	Gingin	L
Big SEC Swamp	Bunbury	L	Lake Muir	Frankland	L
Lake Brown	Beverley	L	Murray River (Delta to Pinjarra)	Bunbury	R
Casuarina Lake	Wagin	L	Mullet Lake	Esperance	L
Lake Chittering	Gingin	L	North Lake	Gingin	L
Lake Clifton	Bunbury	L	Peel-Harvey Estuary	Bunbury	E
Coblinine River Flats	Wagin	R	Penwortham Pool	Frankland	R
Coyrecup Lake	Wagin	L	Lake Preston	Bunbury	L
Culham Inlet	Bremer	E	Stokes Inlet	Esperance	E
Dam 1 063-217	Bunbury	D	Taylors Lakes	Gingin	L
Dam 2 054-215	Geraldton	D	Thomsons Lake	Gingin	L
East Bryde Nature Reserve Lake	Magenta	L	Lake Torrup	Bremer	L
Lake Dumbleyung	Wagin	L	Two Mile Lake	Bremer	L
Lake Forrestdale	Gingin	L	Vasse -Wonnerup Estuary	Bunbury	E
Gibbs Road Swamp	Gingin	L	Woneragup Lake	Bunbury	L
Goegrup Pool (Serpentine River)	Bunbury	R	Wheatfield Lake	Esperance	L
Gordon Inlet	Bremer	E	White Lake (Eneabba)	Geraldton	L
Lake Guraga	Gingin	L	Wilson Inlet	Walpole	E
Harvey River (Lower reach)	Bunbury	R	Yangebup Lake	Gingin	I
Irwin Inlet	Walpole	E	Lake Yearlering	Beverley	L
Jerdacuttup West Lake	Esperance	L	Yellilup Swamp	Bremer	L

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Equilibrium moisture content variations of timbers commonly used in Western Australia

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SUMMARY

An equilibrium moisture content (EMC) survey was undertaken throughout Western Australia over two years. A range of species commonly used in WA was assessed indoors and outdoors (under cover) in locations ranging from the Kimberleys to the south coast. Species assessed at all sites were: jarrah (*Eucalyptus marginata* Donn ex Sm.), karri (*E. diversicolor* F. Muell.), Tasmanian blue gum (*E. globulus* Labill. ssp. *globulus*), radiata pine (*Pinus radiata* D. Don) and Douglas fir (*Pseudotsuga menziesii* Mirb.). Additional species were assessed at Como and Harvey. EMC curves for the different species closely follow the EMC curves based on ambient conditions, indicating the sensitivity of timber to changes in ambient conditions. Mean EMCs of the five species exposed to indoor conditions were lower than the EMCs for outside conditions at a given location, except at Karratha where the indoor EMC was 0.3 per cent higher. An EMC map dividing WA into three zones is provided for the timber exposed to outdoor conditions. Models developed to predict EMC from meteorological data indicated that evaporation, rainfall, relative humidity (RH) and temperature are strongly related to EMC, with RH highly significant at predicting EMC. Data on the rates of moisture absorption of specimens exposed to outdoor and indoor conditions for eight weeks are given. Seasonal variations occur in the moisture content of timber in normal use as furniture and panelling and this is accompanied by an approximately proportional change in dimension. Furniture should be designed to allow some movement owing to shrinkage and expansion of timber components.

INTRODUCTION

The performance of wood as a raw material is largely influenced by its moisture content. Wood is hygroscopic, therefore its moisture content is subject to continuous changes with varying atmospheric conditions. Such moisture content changes are associated with dimensional changes when moisture content is below the fibre saturation point (f.s.p.), i.e. when moisture is added to or lost from the cell walls (Tsoumis 1964). The bound water in wood is in equilibrium with the relative humidity (RH) of the surrounding air, at equilibrium moisture content (EMC). Moisture in wood can exist in two forms; bound or hygroscopic water, and free or capillary water (Haygreen and Bowyer 1982).

The properties of wood are influenced by the presence of water. The moisture content is very high in living trees or freshly felled wood, varying typically from 60 to 200 per cent (Richardson 1993). The green moisture content tends to vary inversely with the normal air-dry density of a timber species, i.e. high density species have low green moisture contents and low density species have high green moisture contents. During drying, free moisture is first lost from the cell spaces and this involves little change in properties except loss of weight. The loss of bound water from the cell walls reduces the separation between adjacent cellulose chains and causes shrinkage as well as progressive changes in physical properties. The amount of bound water is approximately proportional to the relative humidity of the atmosphere, although changes in moisture content lag behind changes in relative humidity, a phenomenon known as 'hysteresis' (Richardson 1993). Changes in relative humidity result in moisture fluctuations, which cause swelling or shrinkage.

The amount of water held by wood cells is dependent not only on the equilibrium relative vapour pressure, but also on the direction from which equilibrium is approached. This phenomenon is known as 'sorptive hysteresis' (Stamm 1967) and the amount of water absorbed from the dry condition is always less than the amount retained on desorption at a fixed relative vapour pressure. When timber takes up moisture it generally assumes lower EMC than when it loses moisture to the air. Koponen (1985) claimed that EMC in absorption may be approximately 80 per cent of the value in desorption.

As the atmospheric conditions in any one place vary from day to day and season to season, the moisture content of timber will be constantly changing, even in a sheltered position, but at a much slower rate than the atmospheric conditions. Wood used where humidity fluctuates will continually change in moisture content, and therefore dimensions (Haygreen and Bowyer 1982).

Ambient temperature change has very little effect on the moisture content of wood, the main factor causing such changes is variation in relative humidity (Van Wyk 1963). For example, at a constant RH of 80 per cent and temperature changes of 10°C, 20°C and 25°C, the EMCs are 16.4, 16.2 and 16.0 per cent respectively. On the other hand, at 20°C and RH of 50, 70 and 90 per cent, the EMCs are 9.2, 13.3 and 20.3 per cent respectively. Chafe (1991) stated that EMC is determined primarily by the RH of the ambient environment, but it also depends on species of wood, specific density and other wood properties, extractive content of the wood, previous drying history of wood and hysteresis.

Problems can arise when timber is used in widely varying humidity and temperature conditions, if the design and application of that product have not anticipated changes in dimension. For satisfactory performance of timber in-service, it is essential to use timber with moisture contents close to the EMC in use. Shrinkage can result in checking and warping of timber, and swelling in humid conditions can result in jammed doors and windows, and buckled table tops.

Many EMC trials have been conducted in different countries around the world, e.g. Europe (Tsoumis 1964), South Africa (Hartwig 1959; Van Wyk 1957, 1963), Malawi (Howland and Matabwa 1971), Fiji (Gough 1977), United Kingdom (Anon. 1929), New Zealand (Orman 1955), Canada (Canada Department of Resources and Development 1952), United States (Higgins 1957; Bois 1959; United States Department of Agriculture 1973), and Australia and New Guinea (Finighan 1966). Other Australian studies were in NSW (Welsh 1936; Ellwood and Leslie 1949) and Queensland (Bragg 1986).

This paper presents results of an EMC survey undertaken throughout Western Australia (WA) over two years. A range of species commonly used in WA was assessed indoors and outdoors (under cover) in locations ranging from the Kimberleys, in the north, to the south coast. The aim of this trial was to collect information on moisture contents of timbers used in different areas of WA, which could assist timber suppliers to provide products suitable for specific areas.

MATERIALS AND METHODS

Exposure sites and timber species

The following geographic areas of WA were selected.

North to South: Kununurra, Broome, Karratha, Geraldton, Perth (Como), Harvey, Busselton, Manjimup and Walpole.

West to East: Narrogin, Kalgoorlie and Esperance.

These locations were selected because district or regional offices of the Department of Conservation and Land Management (CALM) were situated there and had staff and facilities to conduct this trial.

Species assessed at all sites were:

Jarrah (*Eucalyptus marginata* Donn ex Sm.)
Karri (*E. diversicolor* F. Muell.)
Tasmanian blue gum (*E. globulus* Labill. ssp. *globulus*) - WA grown
Radiata pine (*Pinus radiata* D. Don)
Douglas fir (*Pseudotsuga menziesii* Mirb.)

At Como and Harvey additional species were assessed.

Como:

Redwood (*E. transcontinentalis* Maiden)
Dark red meranti (*Shorea pauciflora* King)
Maritime pine (*Pinus pinaster* Ait.)

Harvey:

Marri (*E. calophylla* R.Br. ex Lindl.)
Tuart (*E. gomphocephala* DC.)
Tasmanian oak (*E. delegatensis* R.T. Bak.)
Gimlet (*E. salubris* F. Muell.)
Redwood
Wandoo (*E. wandoo* Blakely)
Mulga (*Acacia aneura* F. Muell. ex Benth.)
WA sheoak (*Allocasuarina fraseriana* (Miq.) L. Johnson)
Dark red meranti
Maritime pine
Western red cedar (*Thuja plicata* D. Don)
Nyatoh (*Payena* spp.)

At each site, moisture content was monitored in three replicates of each timber species by weighing specimens at the beginning of each month. A particular set of replicates at each site was cut from the one sample board. Specimens were randomly allocated to exposure sites.

Sample Board Preparation

Specimens from backsawn boards 750 x 100 x 30 mm cut from the outer heartwood of the log and free of sapwood were assessed for basic density, dried to 12 per cent moisture content then assessed for air-dry density. Tasmanian blue gum, Douglas fir, tuart, Tasmanian oak, wandoo, dark red meranti, western red cedar and nyatoh were assessed only for air-dry density because only dry sample boards were available. Boards were dressed to 20 mm, then three replicates 200 x 80 x 20 mm were cut from each board. A hole was drilled in one end of each specimen and a cup hook inserted. Both ends were end-sealed with two coats of enamel paint to prevent excessive rates of moisture exchange through the end grain.

The trial excluded comparisons between different timber thicknesses, quartersawn and backsawn material, planed and unplaned, and different surface coatings. Previous studies have shown that for material up to 30 mm thick, the moisture changes are independent of thickness, but above 30 mm the rate of moisture content change decreases very rapidly with increase in thickness, although they reach practically the same maximum and minimum values as that of the thinner material (Anon. 1929; Orman 1955). The moisture changes of quartersawn material occur more slowly than those of backsawn material (Anon. 1929), but the difference in final EMC, for practical purposes, is insignificant. The moisture differences that occurred in samples with rough-sawn and planed surfaces appear to be of little practical significance (Anon. 1929; Hartwig 1959). In any case, comparison is difficult because the dressed size is thinner than the rough-sawn size. Paints, varnishes and other types of coatings assist in retarding moisture changes, and in lessening the range of variation. These substances are not impervious to water, and if the relative humidity changes, the wood in time will adsorb sufficient water vapour to establish a new EMC. Although several coatings are known to be highly effective, no entirely moisture-proof coating will prevent moisture fluctuations but the changes will not be excessive in either direction (Cassens and Feist 1991), therefore the effect of coatings was not examined in this trial.

Field Placement

Specimens used outdoors were suspended by cup hooks in situations that were protected from the weather but offered unrestricted air-flow, e.g. under verandas or in open sheds. Indoor specimens were also suspended by cup hooks in air conditioned or heated offices. Specimens were weighed to an accuracy of 0.1 g on the first working day of each month for a period of two years, although some locations did not provide full data.

Meteorological Data

Meteorological data for the duration of the study, including monthly rainfall, 12.00 noon (Western Standard Time) temperature and RH and evaporation figures (if possible) were obtained for each site from CALM district offices or Bureau of Meteorology records. Indoor conditions of temperature and RH, and the duration of air-conditioning or heating were obtained from district offices. No indoor temperature and RH data are available for Busselton and Walpole. EMCs based on meteorological data were calculated using an equation given in Simpson (1971).

Regression analysis was used to relate 12.00 noon temperatures and relative humidities to meteorological readings, for the two-year study period taken at 9.00 a.m. and 3.00 p.m., for Manjimup, Narrogin, Esperance, Perth and Kalgoorlie. The other centres were excluded because of limited 12.00 noon data, e.g. Broome and Kununurra, or no meteorological data, e.g. Harvey (Wokalup) had only 9.00 a.m. readings and the nearest meteorological station to Karratha is 20 km away at Dampier and considered unrepresentative.

Determination of Moisture Content

A 30 x 30 x 100 mm piece was cut from the end of each sample and oven-dried to determine moisture content. The mass of the residual piece was then recorded and the subsequent changes in mass over the trial period were compared with the initial weight (measured at the time of assessing initial moisture content) at a known moisture content, and used to predict moisture content variation. At the completion of two years assessment, specimens were returned to the Wood Utilisation Research Centre (WURC) in Harvey, where the whole specimen was oven-dried. For the denser species up to two weeks drying was required to achieve a stable mass. The oven-dry mass and monthly weighing for each specimen allowed the exact determination of moisture content at each assessment. These moisture contents were compared with those determined during the trial, based on the moisture content of the 30 x 30 x 100 mm section. Moisture contents determined by oven-drying the whole sample (actual EMC) were compared with those determined by weight change (estimated EMC) and meteorological readings (EMC formula calculated from Simpson's (1971) equation) over the two-year study period. EMC based on oven-drying the whole specimen is the most accurate and is used throughout this report, except for the EMC map referred to below.

EMC Map

An EMC map was developed by CALM's Land Information Branch. The equation developed by Simpson (1971) and the 9.00 a.m. long term mean annual temperature and RH for approximately 160 stations in WA were used to calculate mean annual EMCs for each location. Long term meteorological data were taken from 'Climatic averages - Australia' (Bureau of Meteorology 1988). Relative humidity records at 9.00 a.m. were used as they are often taken as an estimate of the mean for the 24-hour period, and 9.00 a.m. temperatures were used because they had a strong correlation with the 12.00 noon temperatures recorded throughout the survey. Owing to the difference between the EMCs of the wood samples and the EMCs based on meteorological records, e.g. Kalgoorlie had a mean wood EMC for the combined species of 5.9 per cent compared with an EMC of 10.3 per cent based on long term 9.00 a.m. readings of RH and temperature. The respective values for Geraldton were 11.7 per cent and 9.2 per cent. The equation :

$$EMC = 1.137EMC_{9am} - 3.41 \quad r^2 = 0.7$$

was used to predict the mean EMCs of the combined species for each meteorological station, using EMC data calculated from mean long term 9.00 a.m. RHs and temperatures. EMCs determined by this equation were then plotted onto a map of WA and lines of best fit were drawn to separate the State into three EMC zones:

Zone 1 - greater than 12 per cent
Zone 2 - 10 per cent to 12 per cent
Zone 3 - less than 10 per cent

The long term climatic averages were used because the survey was over only a two-year period, and long term averages give a better indication of the atmospheric conditions experienced at the different sites. For example, over the study period some locations had weather conditions that were different from the long term averages: Kalgoorlie had an exceptionally wet period in autumn 1992, with a rainfall of 64 mm above the long term average.

Absorption Rates

The current moisture contents of exposed timber depends on actual and past moisture and temperature and humidity conditions. Moisture-sensitive species would depend on conditions of the very recent past, probably restricted to the few preceding weeks, while less reactive species would be better related to conditions for some preceding months. To determine the absorption rates of different species, samples assessed at Harvey were oven-dried after the EMC survey and exposed indoors and outdoors at Harvey in October and November 1993. Samples were weighed weekly to determine moisture uptakes and ambient temperatures, and RHs were recorded daily at 12.00 noon.

RESULTS AND DISCUSSION

Effect of Density

Mean basic and air-dry densities of specimens assessed at all sites are listed in Table 1 and densities of the additional specimens assessed at Como and Harvey are listed in Table 2. Standard deviations and ranges indicated a large variation in basic and air-dry densities, which is consistent with the results given by Kingston and Risdon (1961) and Bootle (1983), and considered representative of these timber species.

TABLE 1

Basic and air-dry densities of samples assessed at all sites.

SPECIES	BASIC DENSITY			AIR-DRY DENSITY[b]			SAMPLE SIZE
	Mean	S.D.	Range	Mean	S.D.	Range	
Jarrah	647.2 (658)[a]	22.2	602.1-682.3	840.5 (823)[a]	34.7	774.7-901.6	24
Karri	732.5 (695)[a]	18.9	676.3-756.0	967 (905)[a]	26.1	908.6-1003.5	25
Douglas fir	- (372)[a]	-	-	531.7 (449)[a]	41.8	465.4-642.5	24
Radiata pine[c]	435.7 (485)[a]	34.9	377.8-523.8	520 (593)[a]	33.1	467.5-599.7	25
Tasmanian blue gum[c]	- (561)[a]	29.7	484-634	813.0 (790)[a]	24.4	768.6-867.1	24

[a] Figures are the species average given by Kingston and Risdon (1961).
[b] Air-dry densities are before reconditioning.
[c] Specimens for Douglas fir and Tasmanian blue gum were obtained from dry timber, therefore basic densities were not measured.

TABLE 2

Basic and air-dry densities of additional samples assessed at Harvey and Como.

SPECIES	BASIC DENSITY			AIR-DRY DENSITY[b]			SAMPLE SIZE
	Mean	S.D.	Range	Mean	S.D.	Range	
Marri	582.0 (663)[a]	2.7	579.8 - 585.1	748.0 (855)[a]	3.3	745.7 - 751.8	3
Tuart	895.2 (836)[a]	-	-	1081.6 (1030)[d]	10.6	1092.3-1071.0	2
Tasmanian oak[e]	(511)[a]			770.1 (663)[a]	9.5	759.1 - 775.1	3
Gimlet	948.9 (897)[a]	17.9	936.3 - 961.6	1190.1 (1099)[a]	8.3	1184.2-1196.0	2
Redwood[c]	958.2	27.1	934.5 - 997.0	1146.9	20.6	1127.9-1166.6	4
Wandoo	856.1 (921)[a]	-	-	1094.4 (1099)[a]	0.4	1094.8-1093.9	2
Mulga	990.6	13.6	981.0-1000.2	1166.3 (1100)[d]	5.0	1162.8-1170	2
WA Sheoak	610.9 (622)[a]	17.6	598.5 - 623.3	718.0 (734)[a]	20.6	703.5 - 732.6	2
Dark red meranti[c,e]				798.0 (680)[d]	0.7	797.3 - 798.7	2
Maritime pine[c]	454.2 (490)[a]	25.4	426.3 - 487.4	573.0 (596)[a]	24.0	550.6 - 606.4	4
Western red cedar[e]				351.1 (350)[d]	2.2	349.2 - 353.5	3
Nyatoh[e]				777.3 (650)[d]	181	574.9 - 923.7	3

[a] Figures are the species averages given by Kingston and Risdon (1961).
[b] Air-dry densities are before reconditioning.
[c] Assessed at both Harvey and Como.
[d] Figures given by Bootle (1983).
[e] Specimens for Tasmanian oak, dark red meranti, western red cedar and nyatoh were obtained from dry timber, therefore basic densities were not measured.

Bootle (1983) referred to an inverse relationship between the EMC and the density of a timber. That is, the lower the density, the higher the EMC and the faster the rate of moisture exchange. However, low density timbers have an appreciably lower movement (shrinkage or swelling) per 1 per cent change in moisture content. This advantage over the dense timbers tends to be counterbalanced by their greater short-term susceptibility to large moisture content movement through greater sensitivity to humidity variations.

Features of Certain Locations

Certain features of some locations have affected the results and need clarification. Kalgoorlie had an exceptionally wet period in Autumn 1992, with rainfall 64 mm above the long term average, giving above average EMCs for that period. The Walpole indoor specimens were located above a slow-combustion fire within the district office, approximately 4 m from a major doorway, which was regularly opened and closed on working days. This presumably would have caused moist air from the outside to enter into the office and affect the EMCs of the indoor specimens. No air-conditioning was used in the Walpole district office during the summer. The indoor specimens at Narrogin were located in a small office attached to a large nursery shed, with no air-conditioning or heating. The door was constantly opened and closed on working days, resulting in conditions similar to outdoor ambient conditions. Indoor specimens assessed at Harvey were stored in a large enclosed wood-processing shed, and although the shed is partly insulated, no air-conditioning or heating was used, thus causing conditions to fluctuate with outside ambient conditions.

EMC Survey

Tables 3 and 4 list the mean monthly EMCs of specimens assessed outdoors and indoors at all sites throughout WA over a two-year period, and indicate the likely maximum and minimum EMCs that can occur. Monthly fluctuations in the EMCs of specimens and EMCs based on ambient conditions can be seen in Figures 1 and 2. Results for Broome and Kununurra are based on only eight months of data, making graphical representation difficult, but mean EMCs are presented in Table 3. EMC curves based on ambient conditions for Busselton are from Bureau of Meteorology records of yearly conditions (RH at 9.00 a.m. and the average of daily maximum and minimum temperature). No EMC curves based on ambient conditions are available for the indoor sites of Busselton and Walpole. The Esperance indoor EMC based on ambient conditions indicated a much higher than expected EMC, with conditions similar to outdoor EMCs in sub-tropical areas. For example, Brisbane has an outdoor EMC of 14 per cent (Bragg 1986).

Results for Broome and Kununurra are based on an eight-month assessment, with Broome having measurements in March, April, July, August, September, October (1991), December (1992) and January (1993). Kununurra had measurements in February, September, October, November, December (1991) and January, October and November (1992), which are spring/summer months, giving a biased overall mean EMC. Measurements for Broome are taken over all seasons and give a better indication of the mean EMC. Staff restrictions at these two locations affected the data collection over the two-year period. Broome had a combined species EMC of 10.4 per cent and an EMC of 10 per cent based on the 9.00 a.m. long term RH and temperature. Broome and Kununurra have similar climates, but the combined species EMC for Kununurra was 5.2 per cent and is lower than the EMC of 8.3 per cent based on the 9.00 a.m. long term RH and temperatures. It is difficult to recommend an EMC for Kununurra, based on results from this trial, because of no field data in autumn/winter, but an EMC based on long term meteorological records of 8.5 per cent can be predicted. An EMC based on the wood samples of 10.4 per cent can be predicted for Broome because data were available for all seasons. Adjustments were made using a regression equation to these two EMCs for developing the EMC map. Owing to the limited field data, these two locations were excluded from the statistical analysis.

Moisture Content Fluctuations

Figure 1 shows the mean outdoor and indoor EMCs of five species assessed at ten sites and EMCs based on ambient conditions averaged over a two-year period. Figure 2 shows the outdoor and indoor EMCs of the additional species assessed at Harvey and Como. No graphs are given for Broome and Kununurra owing to limited monthly data, and no EMC curves based on 12.00 noon RH and temperature data are given for Busselton and Walpole indoor sites as data are unavailable. Table 3 lists the mean EMCs, range and standard deviation of specimens assessed at all sites and Table 4 lists the EMCs of the additional specimens assessed at Harvey and Como. Fluctuations in EMC with changes in ambient conditions can be clearly seen, and these are discussed below.

Outdoor EMC

The EMC curves of the different species in most cases closely follow the EMC curves based on ambient conditions, indicating clearly how sensitive timber is to changes in the ambient conditions of the surroundings. In general, the EMCs of the wood specimens were similar to the EMCs calculated from 12.00 noon RH and temperature readings, but Busselton data indicated wood EMCs 2 to 3 per cent below the EMCs based on ambient conditions. EMCs in the south-west locations showed the greatest seasonal fluctuation, for example, Manjimup had summer EMCs from 10 to 13 per cent and winter EMCs from 16 to 19 per cent, and Perth (Como) 8 to 10 per cent (summer) and 11 to 14 per cent (winter).

Karratha and Kalgoorlie had mean EMCs for all species of 5.8 and 5.9 per cent respectively, which is approximately 4.3 per cent lower than the next highest

TABLE 3

EMCs of samples assessed at all sites throughout WA (outdoors and indoors) over a two-year period.

SITE	JARRAH			KARRI			RADIATA PINE			DOUGLAS FIR			TASMANIAN BLUE GUM			COMBINED SPECIES		
OUTDOOORS	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD
Kununurra (8)	4.8	2.2-8.6	1.6	4.8	2.4-11.4	2.7	6.0	2.2-15.1	3.2	5.6	1.8-14.8	3.5	4.5	2.2-11.8	2.1	5.2	1.8-15.1	2.7
Broome (8)	11.4	9.2-12.8	1.0	10.9	9.4-12.0	0.8	9.2	5.6-11.5	1.7	10.6	8.1-12.3	1.2	9.8	8.0-11.3	1.0	10.4	5.6-12.8	1.4
Karratha (22)	6.4	4.1-9.3	1.2	5.6	3.9-8.1	1.1	6.3	2.9-11.5	2.0	5.6	2.8-9.6	1.5	5.3	3.2-7.7	1.1	5.8	2.8-11.5	1.5
Geraldton (17)	11.8	9.6-13.2	0.8	12.4	11.3-13.4	0.6	12.3	8.6-14.2	1.3	11.4	8.9-12.9	1.0	10.6	8.8-12.5	0.7	11.7	8.6-14.2	1.1
Perth (24)	11.8	8.6-15.0	1.9	10.5	7.6-13.1	1.5	10.7	6.6-14.6	2.4	9.5	5.9-13.2	1.9	9.4	7.1-12.5	1.6	10.6	5.7-15	2.1
Harvey (27)	13.4	10.1-17.7	2.5	13.2	10.6-16.8	2.1	12.3	5.1-20.6	3.6	10.7	5.0-16.1	3.3	10.3	5.2-16.7	3.9	12.0	5.0-20.6	3.4
Busselton (26)	10.9	6.4-14.7	2.2	10.3	7.0-13.4	1.7	10.9	5.6-17.8	2.9	9.0	3.8-13.6	2.3	9.5	5.6-13.8	2.3	10.1	3.8-17.8	2.4
Manjimup (20)	14.9	10.2-18.3	2.1	15.2	12.5-17.9	1.7	14.7	7.7-19.8	2.8	12.9	8.8-16.9	2.2	14.0	9.2-17.8	2.4	14.4	7.7-19.8	2.4
Walpole (24)	15.4	13.1-17.8	1.2	15.2	11.9-17.6	1.2	15.0	12.0-18.2	1.7	12.4	10.3-14.6	1.2	13.1	10.8-15.2	1.1	14.2	10.3-18.2	1.8
Narrogin (23)	13.0	9.6-17.6	2.4	11.8	8.9-15.4	2.0	12.2	7.3-18.3	3.2	10.8	7.1-15.3	2.4	10.6	7.2-15.0	2.4	11.7	7.1-18.3	2.7
Esperance (24)	11.0	8.6-12.6	0.9	10.3	8.8-11.5	0.6	11.0	8.2-13.4	1.3	8.9	6.3-10.7	1.0	9.1	6.6-10.6	0.9	10.1	6.3-13.4	1.3
Kalgoorlie (26)	6.2	3.4-9.6	2.0	5.9	4.2-8.4	1.4	6.6	1.4-11.8	2.9	5.4	1.9-9.7	2.3	5.4	2.9-8.6	1.8	5.9	1.4-11.8	2.2
INDOORS																		
Kununurra (7)	6.3	4.1-9.6	1.4	4.9	2.6-9.5	1.7	7.4	3.7-10.8	1.9	6.7	2.9-11.5	2.1	4.7	2.5-6.2	1.0	6.0	2.5-11.5	1.9
Broome (8)	11.4	9.3-12.7	1.1	11.3	10.2-12.1	0.6	9.3	6.0-11.2	1.7	10.6	8.2-12.0	1.2	9.5	7.8-10.6	0.9	10.4	6.0-12.7	1.4
Karratha (22)	6.9	5.5-7.9	0.7	5.9	4.7-8.1	0.8	7.1	4.5-8.8	0.9	5.6	3.9-7.2	0.8	5.0	3.9-6.0	0.6	6.1	4.0-8.6	1.1
Geraldton (17)	10.5	9.4-11.2	0.4	10.2	9.3-11.5	0.5	10.1	8.1-11.2	0.7	8.4	6.7-9.4	0.6	8.2	7.3-8.7	0.3	9.5	6.7-11.5	1.1
Perth (25)	10.3	8.7-11.7	0.7	10.6	8.7-12.0	0.8	9.7	7.5-11.6	1.0	10.3	7.7-12.1	1.1	8.8	7.4-10.0	0.7	10.3	7.4-13.3	1.2
Harvey (27)	11.8	10.0-13.7	0.9	11.5	10.1-13.0	0.7	10.8	5.5-13.0	1.5	8.7	5.1-11.2	3.3	8.4	5.1-10.9	2.1	10.2	5.1-13.7	2.1
Busselton (26)	9.6	7.3-12.0	1.0	9.2	7.5-10.4	0.7	9.5	5.6-12.6	1.3	7.8	4.8-10.2	1	8.2	6-10.8	1.1	8.8	4.8-12.6	1.3
Manjimup (20)	11.2	10.1-11.9	0.4	11.9	11.2-12.4	0.3	10.9	9.9-12.0	0.5	9.7	8.6-10.6	0.5	8.4	6.6-9.0	0.4	10.4	6.6-12.4	1.3
Walpole (24)	13.9	11.4-18.0	1.5	12.3	10.0-14.9	1.1	11.4	8.3-16.1	1.8	10.2	7.7-14.1	1.5	11.1	9.1-14.1	1.2	11.8	7.7-17.6	1.9
Narrogin (23)	12.6	9.3-16.5	2.3	11.4	9.0-14.1	1.6	10.9	6.4-15.6	2.7	9.9	6.5-13.7	2.2	9.7	6.5-13.6	2.2	10.9	6.4-16.5	2.5
Esperance (24)	9.4	7.8-11.1	0.7	8.8	7.3-10.1	0.6	9.0	7.1-10.9	0.9	8.3	6.9-10.0	0.7	7.2	5.7-8.5	0.6	8.6	5.7-11.1	1.0
Kalgoorlie (26)	6.0	5.1-7.4	0.5	5.5	4.8-6.7	0.5	6.2	5.0-7.9	0.7	5.7	4.8-7.0	0.6	4.6	3.8-5.8	0.5	5.6	3.8-7.9	0.8

Notes: Number of months assessed are given in parentheses.
The mean EMCs (outdoor and indoor) for Kununurra are lower than expected as only spring/summer months were assessed.

TABLE 4
EMCs of additional wood samples assessed at Harvey and Como (outdoors and indoors) over a two-year period.

SPECIES	OUTDOORS			INDOORS		
	Mean	S.D.	Range	Mean	S.D.	Range
HARVEY (27)[a]						
Marri	14.1	2.4	10.5-19.6	11.4	0.9	9.7-13.1
Tuart	13.3	1.5	11.1-15.7	12.8	0.7	11.4-14.1
Tasmanian oak	12.8	1.6	10.3-15.6	12.0	0.7	10.4-13.4
Gimlet	14.5	2.0	11.0-18.0	14.6	0.8	12.9-16.9
Redwood	14.3	1.9	11.8-18.0	12.9	1.0	11.1-15.6
Wandoo	12.4	1.5	10.5-15.1	11.9	0.6	10.6-13.7
Mulga	12.4	1.6	10.2-15.4	11.1	0.7	9.6-12.4
WA sheoak	12.5	2.0	9.5-15.8	11.4	0.8	9.8-12.6
Dark red meranti	12.7	2.1	9.6-16.2	11.4	0.8	9.8-13.2
Maritime pine	12.2	3.7	5.1-19.6	10.3	1.8	5.3-13.3
Western red cedar	9.1	3.0	5.0-14.1	6.8	1.0	5.0-8.0
Nyatoh	11.6	2.8	5.3-16.0	10.1	1.3	5.6-11.5
Combined	13.0	2.6	5.0-19.6	11.6	2.1	5.0-16.9
COMO (24)[a]						
Redwood	11.8	1.6	9.0-14.4	12.0	0.8	10.3-13.3
Dark red meranti	11.2	1.6	8.3-13.8	10.8	0.7	9.3-12.0
Maritime pine	9.5	2.3	5.7-13.8	9.8	0.9	7.7-11.6
Combined	10.8	2.1	5.7-14.4	10.9	1.2	7.7-13.3

[a] Number of months assessed are given in parentheses

EMC (Busselton and Esperance) and 8.6 per cent lower than the EMC for Manjimup. Kalgoorlie had exceptionally high rainfall in March, April, May and June 1992, with 3.5 times the average for those months, giving a higher EMC than the expected long term figure. In comparison, Lamond and Hartley (1991) reported that in the very dry western areas of New South Wales, such as Broken Hill, timber will dry down to approximately 7 per cent moisture content during summer. Bragg (1986) found a mean EMC of 14 per cent for coastal areas of Queensland and Lamond and Hartley (1991) reported EMCs for coastal areas of New South Wales between 12 and 15 per cent. The coastal town of Karratha has ambient conditions of mean yearly 9.00 a.m. RH and temperature of 45 per cent and 26.3°C (EMC 8.2 per cent) indicating dry conditions and low EMCs. CALM staff describe climatic conditions for Karratha as similar to those in drier inland areas of WA. For example, the inland town of Kalgoorlie has a mean yearly 9.00 a.m. RH and temperature of 56 per cent and 18.3 °C respectively, giving an EMC of 10.3 per cent.

Busselton, Esperance and Geraldton, and Perth (Como) and Harvey had similar EMCs for the combined species, ranging from 10.1 per cent to 11.7 per cent (Table 3). Busselton, Esperance and Geraldton are located on the coast, whereas Como is 15 km and Harvey 20 km inland. The combined species mean EMC for Como is 10.6 per cent and Harvey 12.0 per cent. Como has a mean annual rainfall of 756 mm, whereas Harvey is on the edge of the Darling Scarp, surrounded by forest, with a higher rainfall (mean annual rainfall of 996 mm) and twelve more raindays per year, giving a slightly higher EMC for Harvey. Busselton and Esperance have slightly lower EMCs than Como, Harvey and Geraldton. The annual EMC for Busselton, based on ambient conditions from Bureau of Meteorology records, is approximately 2 per cent higher than the specimen EMCs, indicating that the conditions in which the specimens were stored had a lower humidity.

The EMC based on long term meteorological data for Esperance is 13.4 per cent, 3.3 per cent greater than the combined specimen EMC and the EMC based on the 12.00 noon RH and temperature figures supplied by CALM staff, indicating that the location of the specimens under a sheltered verandah is at a lower EMC. Manjimup and Walpole's EMCs are similar and the highest recorded in this trial. High mean annual rainfalls (between 1000 and 1040 mm), a large number of raindays (156 and 186 respectively) and high humidities (mean 9.00 a.m. RH of 75 per cent) would result in high EMCs.

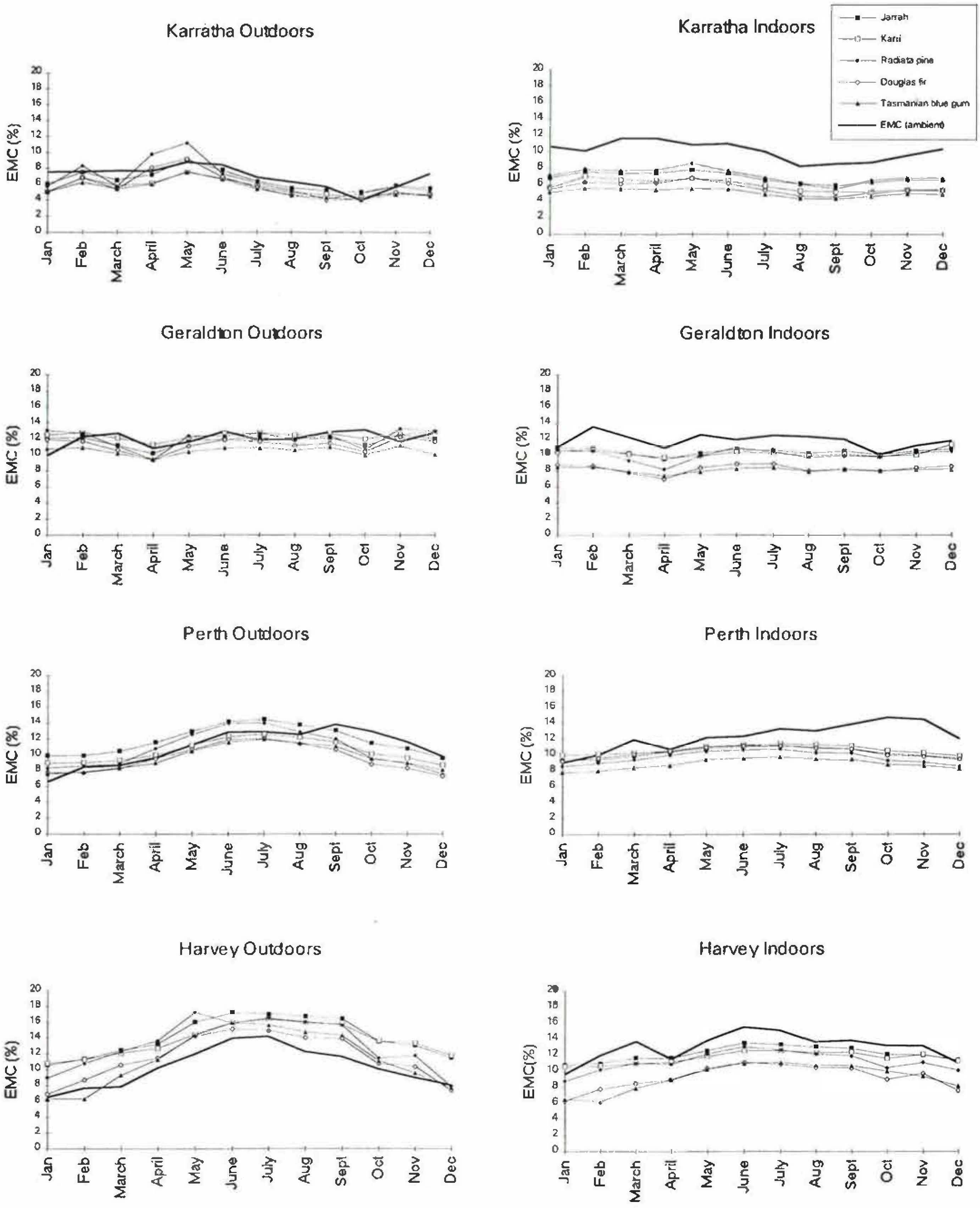

Figure 1. Mean outdoor and indoor EMCs of five species assessed at ten sites and EMCs based on ambient conditions averaged over a two-year period.

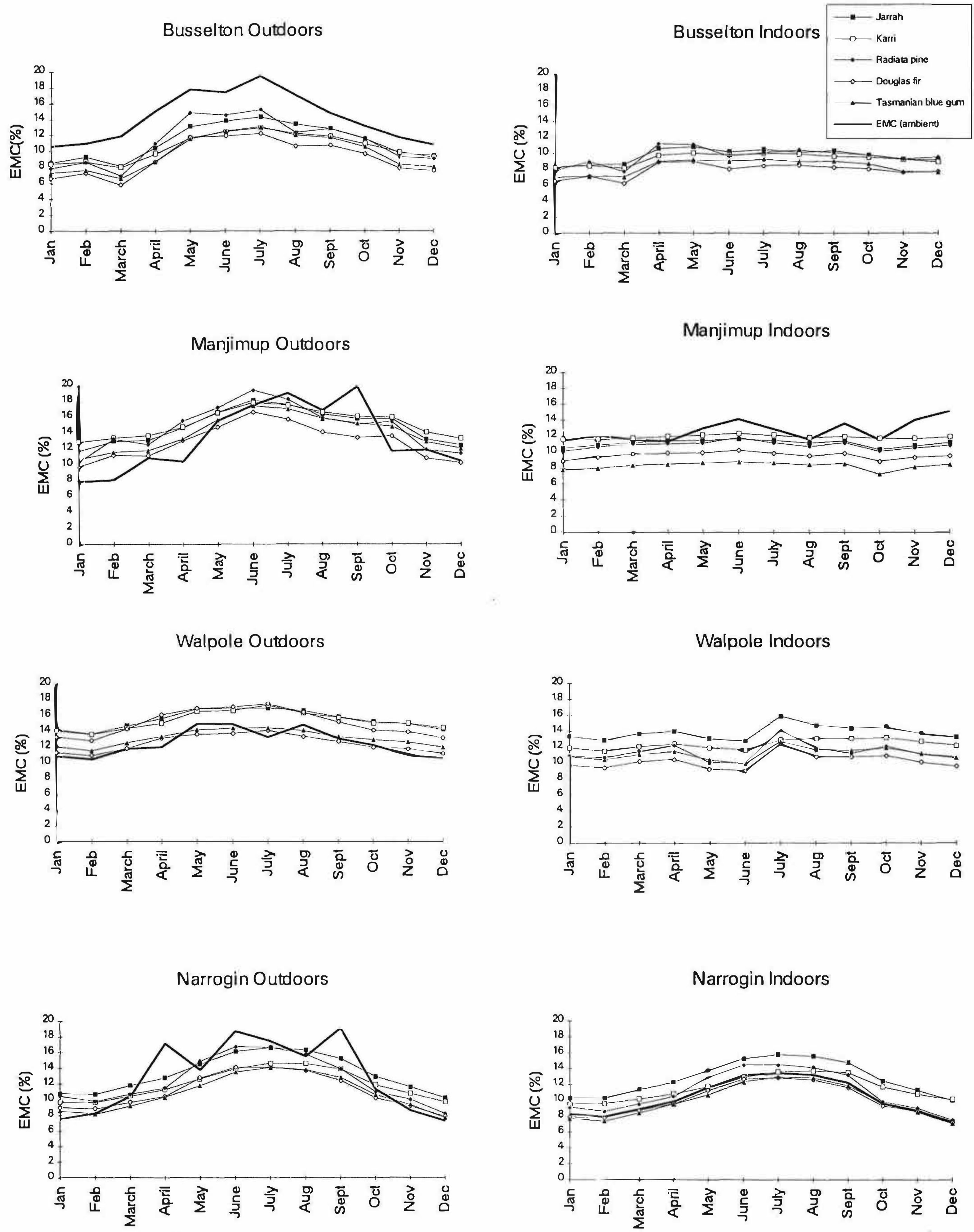

Figure 1 (continued)

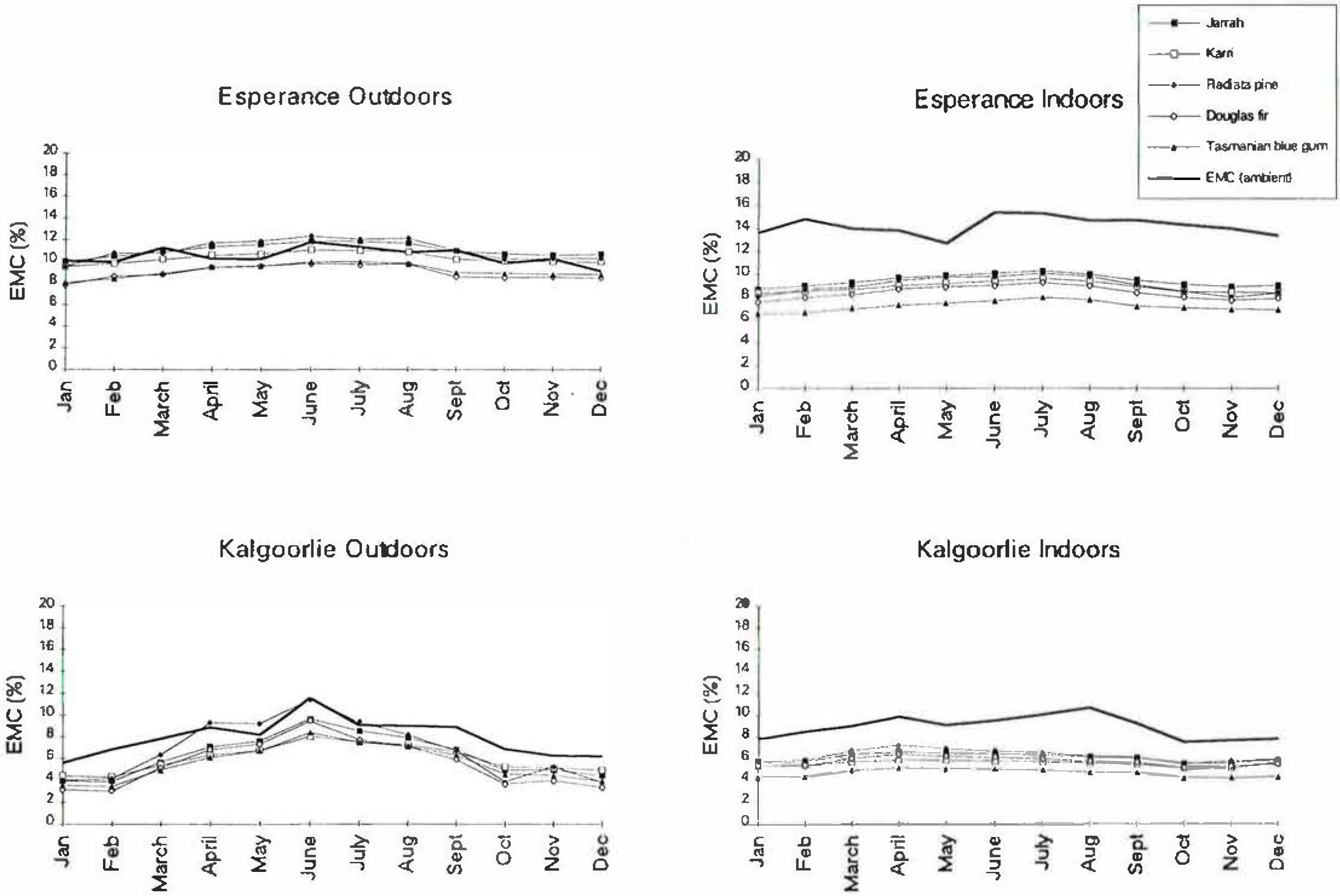

Figure 1 (continued)

Finighan (1966) found the mean annual EMC and ranges for 20 mm jarrah and radiata pine based on monthly readings at the following WA towns were :

Town	Jarrah Mean (%)	Jarrah Range (%)	Radiata pine Mean (%)	Radiata pine Range (%)
Albany	18	18 - 19	16	15 -17
Bridgetown	16	15 - 19	15	12 - 17
Perth	16	13 - 18	13	10 - 16

In this survey EMCs at Albany and Bridgetown were not assessed. Walpole has a similar climate to that of Albany, and Manjimup is similar to Bridgetown, and the following mean annual EMCs were recorded in this survey:

Town	Jarrah Mean (%)	Jarrah Range (%)	Radiata pine Mean (%)	Radiata pine Range (%)
Walpole	15.4	13.1-17.8	15.0	12.0-18.2
Manjimup	14.9	10.2-18.3	14.7	7.7-19.8
Perth (Como)	11.6	8.6 -15.0	10.7	6.6-14.6

These figures indicate lower means, particularly those for Perth, than the EMCs given by Finighan 30 years previously, but the ranges indicate high EMCs do occur. The lower density pine specimens indicate large fluctuations in EMC, with Manjimup having an EMC fluctuation of 12.1 per cent between summer and winter.

The greatest amount of change in EMC likely to be experienced in the more populated areas of Australia may be estimated from the fact that most of the regions experience monthly average relative humidities within the range 50 to 70 per cent, and they only occasionally fall to as low as 40 per cent, or rise to as high as 80 per cent (Anon. 1967). For the temperatures normally associated with these relative humidities, the equivalent seasonal EMCs for timber under sheltered outdoor sites usually range from about 9 per cent to 14 or 15 per cent, with only periodic departures to as low as 7 per cent or as high as 16 per cent. At the same time, it should be recognized that in some of the less populated inland parts of Australia the mean seasonal EMC may drop to as low as 5 per cent (e.g. central Australia), and may rise to as high as 20 per cent in others (e.g. North Queensland).

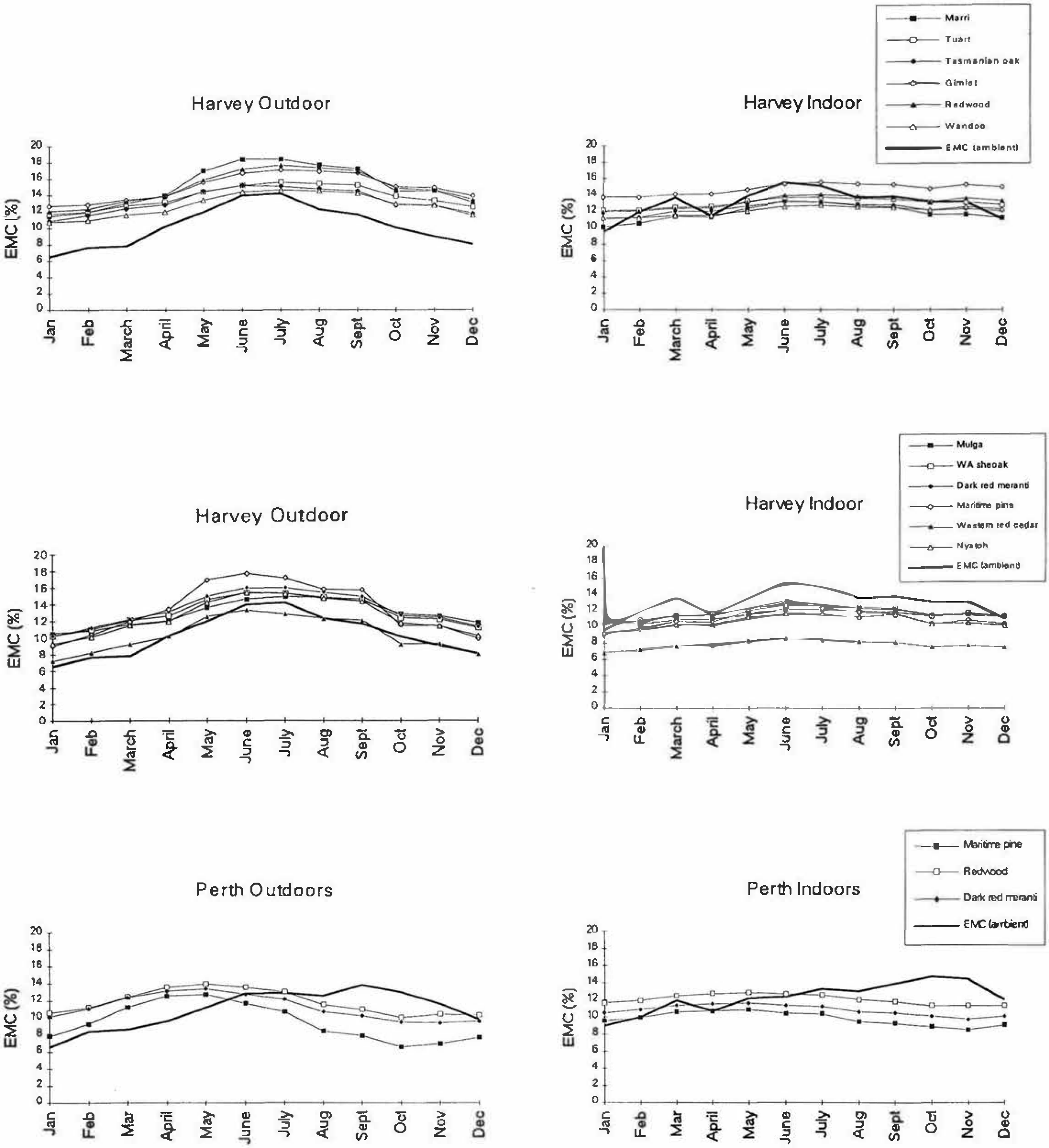

Figure 2. EMCs of additional species assessed at Harvey and Como (outdoors and indoors) over a two-year period.

Indoor EMC

Indoor conditions are not as predictable as outside conditions because of varying forms of heating and circulation that are encountered in houses and offices (Orman 1955). However, in many situations ambient conditions can be constant owing to modern air-conditioning and central heating as found in large office buildings. Generally the EMCs of indoor specimens show less seasonal fluctuations than the outdoor specimens, although Walpole, Narrogin and Harvey show marked seasonal changes. These fluctuations would be owing to samples being in sites without constant heating or air-conditioning and therefore under the influence of changing ambient conditions as occur in the outdoors. For example, the Harvey specimens were stored in a large enclosed wood-processing shed, which although partly insulated, had no air-conditioning or heating.

Mean indoor EMCs varied from Kalgoorlie (5.6 per cent) and Karratha (6.1 per cent) to Narrogin (10.9 per cent) and Walpole (11.8 per cent). Specimens at Kalgoorlie and Karratha were stored in air-conditioned environments, whereas Narrogin and Walpole indoor sites had no air-conditioning and were influenced by outside ambient conditions. The Perth indoor samples were subjected to reasonably constant indoor conditions, with a mean EMC of 10.3 per cent, but a range of 7.4 to 13.3 per cent still occurred. The Kalgoorlie indoor samples had the lowest range in EMCs between species (1.6 per cent) and Walpole the highest (3.7 per cent).

Comparing the mean EMCs of the five species exposed to indoor and outdoor under cover situations showed indoor specimens with lower EMCs, except for Karratha where the indoor EMC was 0.3 per cent higher. The indoor specimens at Karratha were stored in an air-conditioned environment and maintained a constant EMC, but the extremely dry outdoor conditions resulted in EMCs being lower than the indoor specimens. Kalgoorlie also had very low indoor and outdoor EMCs. Finighan (1966) showed that there is a distinct tendency for indoor values (non-centrally heated houses) to be 1 to 4 per cent lower than the outdoor values, depending on the microclimatic conditions. In all locations the wood EMCs were below the EMCs based on ambient conditions, with Karratha 3 to 4 per cent, Esperance 5 to 6 per cent and Kalgoorlie 2 to 4 per cent below the ambient EMCs.

Lamond and Hartley (1991) reported that in air-conditioned buildings timber should be seasoned to about 10 per cent. Timber dried for the higher outdoor EMCs is not appropriate for use in indoor air-conditioned environments, and should be strip stacked within the air-conditioned environment prior to fixing. In general, moisture contents for indoor unheated conditions range from 1 to 4 per cent lower than outdoor values depending on locality and site factors and a correction factor of 2 per cent lower, would seem acceptable, for practical purposes in most temperate areas of Australia (Finighan 1965). In areas close to the sea, the correction could be smaller while in houses that tend to have high indoor temperatures (e.g. large glassed-in areas) the correction may tend to be larger. Smith *et al.* (1991) recommended the applicable target moisture content for timber products used in air-conditioned buildings in Queensland as 9 per cent, unless otherwise required and specified. If the timber is not at the recommended EMC it should be allowed to dry to the required EMC by strip stacking or loose laying the timber under shelter for two to four weeks prior to fixing. This is particularly important with flooring and joinery timbers. AFRDI (1993) also recommended a mean indoor EMC of 9 per cent, with a range between 6 and 12 per cent, and timber used in dry centrally heated offices or in permanently air conditioned buildings can have EMCs as low as 6 or 7 per cent.

Variation between Species

Although the EMC of certain species for any specific set of psychrometric conditions is often found to be approximately the same, the rates of moisture movement for these species often differ very markedly. This phenomenon of varying rates of absorption cannot be owing solely to climatic differences, but other factors include the degree of heating, ventilation and sheltering, and the density of the timber. Because of the greater response of some timbers than others, the maximum and minimum figures vary considerably for fluctuating conditions. The mean EMCs for jarrah, karri and radiata pine were higher than those for Douglas fir and Tasmanian blue gum, and radiata pine EMC was slightly less than those for jarrah and karri, in both outdoor and indoor situations. This survey indicates that species EMCs may vary by more than 2 per cent, both indoors and outdoors, for a given location and time.

The high standard deviations of the lower density softwood timbers (radiata pine and Douglas fir) and Tasmanian blue gum, indicate large variations in moisture content at all sites compared with jarrah and karri, particularly in outdoor locations that experience large seasonal fluctuations (Table 3). For example, the outdoor EMCs for Harvey gave a standard deviation of 3.6 per cent for radiata pine, 3.3 per cent for Douglas fir and 3.9 per cent for Tasmanian blue gum, with jarrah 2.5 per cent and karri 2.1 per cent. Similar examples for other locations can be seen in Table 3. The additional species assessed at Harvey and Como indicated similar trends with the lower density species indicating greater fluctuations than the higher density species. For example, the standard deviations of maritime pine, western red cedar and nyatoh were 3.7, 3.0 and 2.8 per cent respectively, whereas the higher density species had smaller variations, e.g. the standard deviations for mulga, tuart and wandoo were 1.6, 1.5 and 1.5 per cent respectively. Tasmanian oak and western red cedar assessed indoors indicated a small fluctuation in EMC despite having a lower density than mulga, tuart and wandoo. Other factors, e.g extractive contents, previous drying history and hysteresis, may be influencing the EMC of the Tasmanian oak specimens. Similarly, at Como maritime pine had a higher standard deviation (2.3 per cent) than dark red meranti (1.6 per cent) and redwood (1.6 per cent).

The specimens assessed indoors at all sites showed less fluctuations than the outdoor specimens, owing to the constant indoor ambient conditions (Figs 1 and 2). The standard deviations of the indoor EMCs assessed at Narrogin are similar to the outdoor EMCs and generally higher than the standard deviations assessed at other locations. Like the outdoor specimens the indoor specimens of radiata pine and Douglas fir showed greater fluctuations than the higher density hardwoods, e.g. radiata pine and Douglas fir assessed at Harvey were 1.5 and 3.3 per cent respectively and jarrah and karri were 0.9 and 0.7 per cent respectively. Maritime pine assessed at Harvey also showed a large variation with a standard deviation of 1.8 per cent.

Figure 2 gives the EMC curves for the additional species assessed at Harvey and Como. For both indoor and outdoor specimens assessed at Harvey, EMCs for western red cedar were 2 to 3 per cent lower, and gimlet was approximately 2 per cent higher than the other species. All the other species were within 1 per cent of each other and followed the trend of changes in EMC with changes in the environmental conditions. For the three additional species assessed at Como (indoors and outdoors), redwood had the highest EMC, then dark red meranti and maritime pine. Where there is a considerable variation between species and winter and summer conditions, timber should be protected as far as possible by using moisture resistant coatings.

Because of the greater response of some timbers than others, the maximum and minimum figures vary considerably for fluctuating conditions. Hardwoods usually possess a lower mean EMC than softwoods, though various exceptions do occur (Orman 1955). Hartwig (1959) found the EMCs of eucalypts were significantly higher than those of the pines when the minimum values only were compared. However, when the mean values were examined, no significant differences in EMCs were found between the eucalypt and pine specimens. Ellwood and Leslie (1949) found that the EMC of various species for any specific set of psychrometric conditions can have a difference of up to 4.5 per cent moisture content, although for practical purposes they are assumed to be the same. Howland and Matabwa (1971) found that species EMCs can vary as much as 5 per cent within sites. Measuring weather conditions in close proximity to wood specimens, Tsoumis (1964) found the difference between average actual and EMCs from meteorological data ranged from 0 to 2.8 per cent. This is a good agreement for practical purposes, and EMC values may serve as estimates of expected wood moisture content variations.

Temperatures and RH Comparisons

Regression analysis was used to compare the 12.00 noon temperature and RH readings taken over the two-year study period with the 9.00 a.m. and 3.00 p.m. meteorological readings for Manjimup, Narrogin, Esperance, Perth (Como) and Kalgoorlie. These equations were developed to allow any missing 12.00 noon data to be determined. Very good relationships were found between the temperature readings at 12.00 noon and the 9.00 a.m. and 3.00 p.m. temperatures recorded by the meteorological bureau over the two-year study period, with correlation coefficients greater than 0.90. Comparing the RH at 12.00 noon with the RH at 9.00 a.m. and 3.00 p.m. indicated good correlations for Manjimup, Narrogin and Kalgoorlie with coefficients between 0.70 and 0.80. Poor correlations for Esperance and Perth could be owing to the coastal influence, where humidity can change very quickly with the onset of coastal sea breezes. Regressions based on 9.00 a.m. temperature and RH data were used to determine any missing 12.00 noon data.

Regression Analysis of Density and EMC

No correlation was found between basic and air-dry density when compared with actual EMCs (based on oven-drying the whole specimen) for the five species assessed at all locations, owing to the small sample size of three basic and five air-dry densities for each location. When the EMC and density data of all the species assessed at Harvey (indoors and outdoors) were included in the analysis the sample size was increased and the following were found:

- outdoor EMC was not related to air-dry density ($r^2 = 0.43$);

- indoor EMC was directly related to air-dry density, i.e.

$$EMC_{indoors} = 0.005ADD + 6.5 \quad (r^2 = 0.57)$$

- the best relationship between EMC and basic density was found for the indoor samples (r^2 0.47).

When EMCs of all the species assessed at Harvey by season, i.e. summer (December, January and February) and winter (June, July and August) or by eucalypt and softwood were compared with density the following were found:

- the EMCs of the summer outdoor and indoor specimens were directly related to air-dry and basic density, i.e.

Air -dry density

$$EMC_{indoors} = 0.005\,ADD + 6.33 \quad (r^2 = 0.60)$$

$$EMC_{outdoors} = 0.0047\,ADD + 6.7 \quad (r^2 = 0.51)$$

Basic density

$$EMC_{indoors} = 0.005\,BD + 7.4 \quad (r^2 = 0.59)$$

$$EMC_{outdoors} = 0.004\,BD + 8.542 \quad (r^2 = 0.50)$$

Although the correlation coefficients are between 0.50 and 0.60 the large sample size would indicate significant relationships.

Owing to the small number of basic densities, these data were excluded and only air-dried density was used to relate the EMCs assessed in summer or winter and EMCs of the eucalypt or softwood. For example, the relationships for the summer outdoor and indoor specimens are:

$$EMC_{outdoors} = 0.005\,ADD + 6.938 \quad (r^2 = 0.58)$$

$$EMC_{indoors} = 0.008\,ADD + 3.595 \quad (r^2 = 0.72)$$

Softwood Regressions

EMC was directly related to air-dry density for the softwoods, but no relationships were found for the eucalypts assessed in summer or winter.
The regressions for the softwood specimens over the two-year period were:

$$EMC_{indoors} = 0.017\,ADD + 1.024 \quad (r^2 = 0.74)$$

$$EMC_{outdoors} = 0.16\,ADD + 3.504 \quad (r^2 = 0.92)$$

The softwood EMC was also directly related to air-dry density for summer outdoors and winter indoors and outdoors. The relationships are:

Softwoods - summer

$$EMC_{outdoors} = 0.014\,ADD + 1.977 \quad (r^2 = 0.85)$$

Softwoods - winter

$$EMC_{outdoor} = 0.18\,ADD + 6.534 \quad (r^2 = 0.94)$$

$$EMC_{indoors} = 0.03\,ADD - 4.218 \quad (r^2 = 0.90)$$

Hardwood Regressions

Owing to the large variation in densities for the eucalypts, the lower density species of Tasmanian blue gum, Tasmanian oak and marri were excluded from the regression analysis. The following relationship was found between EMC and air-dry density for the higher density eucalypts assessed indoors over the two-year study period and outdoors during summer:

Indoors - over the two-year study period

$$EMC_{indoors} = 0.007\,ADD + 4.88 \quad (r^2 = 0.62)$$

Outdoors - during summer

$$EMC_{outdoors} = 0.005ADD + 6.94 \quad (r^2 = 0.58)$$

Chafe (1991) found that wood blocks (25 mm square and 20 mm long) and thin sections (1 mm thick) of mountain ash (*Eucalyptus regnans* F. Muell.) equilibrated to 17 per cent, 12 per cent or 5 per cent were positively related to density. Christensen and Kelsey (1959) had estimated for mountain ash that the relative contributions to the total sorption of the wood by cellulose, hemicellulose and lignin were 47 per cent, 37 per cent and 16 per cent respectively. This suggested that wood of higher density may have proportionally more cellulose and/or hemicellulose and less lignin than wood of lower density, hence higher moisture absorption properties. However, in this trial the lower density softwoods, particularly radiata pine, had higher maximum EMCs compared with the hardwoods. Bragg (1986) found that EMC was directly related to air-dry density, when he assessed a number of timber species throughout Queensland. Hartwig (1959) found that the lower density pine samples absorb moisture at a faster rate than eucalypts and the ultimate EMCs of the pine samples are higher than those of the eucalypt samples. This is discussed in more detail under 'Absorption rates' below.

Outdoor EMC Compared with Indoor EMC

Regression analysis was used to relate outdoor and indoor EMCs, based on oven-drying the whole specimen at the end of the trial. The overall equation for all species at 10 sites (excluding Broome and Kununurra) based on mean monthly readings is:

$$EMC_{indoors} = 0.83\,EMC_{outdoors} + 0.49 \quad (r^2 = 0.70)$$

Relationships for individual locations are given in Table 5. Significant relationships were found for Harvey, Esperance, Karratha, Narrogin and Perth as indicated by the high coefficient of determination. Outdoor and indoor EMCs for jarrah, karri, radiata pine, Douglas fir and Tasmanian blue gum assessed at Harvey were compared by regression analysis and indicated significant relationships for all species (Table 6).

TABLE 5

Regression analysis of outdoor EMCs and indoor EMCs for ten locations (all regressions are significant at $P < 0.001$).

LOCATION	REGRESSION EQUATION	R^2	N
Karratha	$EMC_{indoor} = 0.97\,EMC_{outdoor} + 0.45$	0.57	107
Geraldton	$EMC_{indoor} = 1.95\,EMC_{outdoor} - 12.8$	0.24	85
Perth	$EMC_{indoor} = 0.65\,EMC_{outdoor} + 3.15$	0.55	120
Harvey	$EMC_{indoor} = 0.56\,EMC_{outdoor} + 3.48$	0.70	135
Busselton	$EMC_{indoor} = 2.00\,EMC_{outdoor} - 9.97$	0.21	129
Manjimup	$EMC_{indoor} = 1.30\,EMC_{outdoor} - 8.44$	0.18	100
Walpole	$EMC_{indoor} = 2.35\,EMC_{outdoor} - 21.61$	0.20	119
Narrogin	$EMC_{indoor} = 0.96\,EMC_{outdoor} - 0.28$	0.96	107
Esperance	$EMC_{indoor} = 0.90\,EMC_{outdoor} - 0.47$	0.76	120
Kalgoorlie	$EMC_{indoor} = 0.59\,EMC_{outdoor} + 2.15$	0.38	130

TABLE 6

Regression analysis of outdoor EMCs and indoor EMCs of five wood species assessed at Harvey (all regressions are significant at $P < 0.001$).

SPECIES	REGRESSION EQUATION	R^2	N
Jarrah	$EMC_{indoors} = 0.40\,EMC_{outdoors} + 6.56$	0.86	27
Karri	$EMC_{indoors} = 0.44\,EMC_{outdoors} + 5.70$	0.74	27
Radiata pine	$EMC_{indoors} = 0.37\,EMC_{outdoors} + 6.22$	0.83	27
Douglas fir	$EMC_{indoors} = 0.38\,EMC_{outdoors} + 5.30$	0.85	27
Tasmanian blue gum	$EMC_{indoors} = 0.35\,EMC_{outdoors} + 5.78$	0.80	27

In the absence of indoor EMC data, EMC values appropriate to the inside of non-heated or non air-conditioned buildings can be computed from outdoor EMCs using the above overall equation or for a specific location where there is a significant relationship (Table 5). If indoor RH and temperature data are available, the equation given by Simpson (1971) can be used to determine EMC of the room, which is the EMC a timber specimen should eventually attain.

Bragg (1986) found:

$$EMC_{indoors} = 0.83\ EMC_{outdoors}$$

which gives a 0.5 per cent difference to the indoor EMC calculated from the above equation, developed from data collected in this trial. In comparison, Finighan (1966) found that indoor EMCs of non centrally heated houses were between 1 and 4 per cent less than in outdoor sheltered positions, but that the effect was variable and dependent on the microclimate specific to each building.

Comparison of Actual EMC and Theoretical EMC

Figure 3 shows the relationship between actual EMC (based on oven-drying the whole sample) and theoretical EMC (based on 12.00 noon RH and temperature data) for five species assessed and overall for outdoors sites at Harvey, Kalgoorlie and Manjimup. These locations were selected because they occur in different EMC zones and complete sets of data were available. Regression analysis showed the outdoor specimens had strong correlations for the individual species and the overall EMC. The overall relationships for Harvey, Kalgoorlie and Manjimup were :

Harvey: $EMC = 0.902EMC_{form} + 3.71 \quad (r^2 = 0.68)$

Kalgoorlie: $EMC = 0.88EMC_{form} - 0.95 \quad (r^2 = 0.61)$

Manjimup: $EMC = 0.38EMC_{form} + 9.26 \quad (r^2 = 0.56)$

EMC_{form} is the theoretical EMC.

The indoor specimens showed poor correlations owing to the small variation in data, as shown with the small standard deviations given in Table 3. Using the 12.00 noon RHs and temperatures, the actual EMCs for Harvey, Kalgoorlie and Manjimup can be determined from the regression equation or the graphs in Figure 3. Similar relationships can be developed for other locations.

Howland and Matabwa (1971) found strong correlations between actual EMC and the theoretical EMC based on mean weekly RHs and temperatures. Ellwood and Leslie (1949) found that when EMCs calculated from directly weighing specimens (estimated EMC) and theoretical EMC calculated from monthly RH and temperature were compared, the EMCs were very irregular and did not correspond at all well with the moisture contents estimated from weighing specimens.

Finighan (1966) related the EMC of wood specimens exposed to outdoor conditions by an empirical equation using mean monthly temperatures and RHs. The predicted moisture contents determined by the equation for the sites assessed differ from the observed moisture contents by more than 2 per cent, but when Alice Springs and Broken Hill data were excluded, approximately 95 per cent of predictions differed from observed values by only 1 per cent or less.

Models for Predicting EMC from Meteorological Data

The meteorological data used in regression analysis presented in Table 7 were compared with the combined species EMCs (based on oven-drying the whole sample) for each location given in Table 3. Evaporation data were unavailable for Busselton, Narrogin and Walpole, therefore when evaporation was included in the regression analysis these locations were excluded.

In Table 7 temperature and RH data recorded at 12.00 noon were used, whereas long term data are recorded at 9.00 a.m. and 3.00 p.m., therefore 12.00 noon readings should be used to predict EMC. A stepwise regression determined which meteorological readings were best at predicting EMC. The correlation coefficients and probabilities derived using all the available data from ten locations (excluding Broome and Kununurra) are listed in Table 8.

All four variables were strongly correlated with EMC, as indicated by the correlation coefficients and the probabilities. RH is highly significant at predicting EMC ($P < 0.001$) and, as expected, evaporation and temperature were strongly inversely related to EMC. The regression analysis (with evaporation included) showed that RH was the strongest predicter of EMC with the following relationship:

$$EMC = 0.26\ RH_{12pm} - 4.393 \quad (r^2 = 0.80)$$

When the evaporation figures were excluded from the analysis, the sample size was increased to ten locations and the relationship derived was:

$$EMC = 0.19\ RH_{12pm} + 0.003\ RAIN - 2.559 \quad (r^2 = 0.87)$$

Rainfall has been included in the equation, although it does not have the same effect as RH. Temperature and evaporation have minor effects in determining EMC. When the other variables are used either singly or in combination, they are not as strong at predicting EMC as RH with correlation coefficients between 0.60 and 0.75. When RH and temperature were used to determine EMC the following equation was derived:

$$EMC = 0.248\ R.H._{12pm} - 0.038\ TEMP_{12pm} - 2.863 \ (r^2 = 0.80)$$

This equation shows the small effect temperature has in determining EMC.

These three regression equations, combined with long term meteorological data (12.00 noon readings) allow the prediction of EMC for 20 mm thick timber in sheltered outdoor situations throughout WA. RH is the most significant variable in predicting EMC, however, where rainfall and temperature data are available they can be used to improve the prediction.

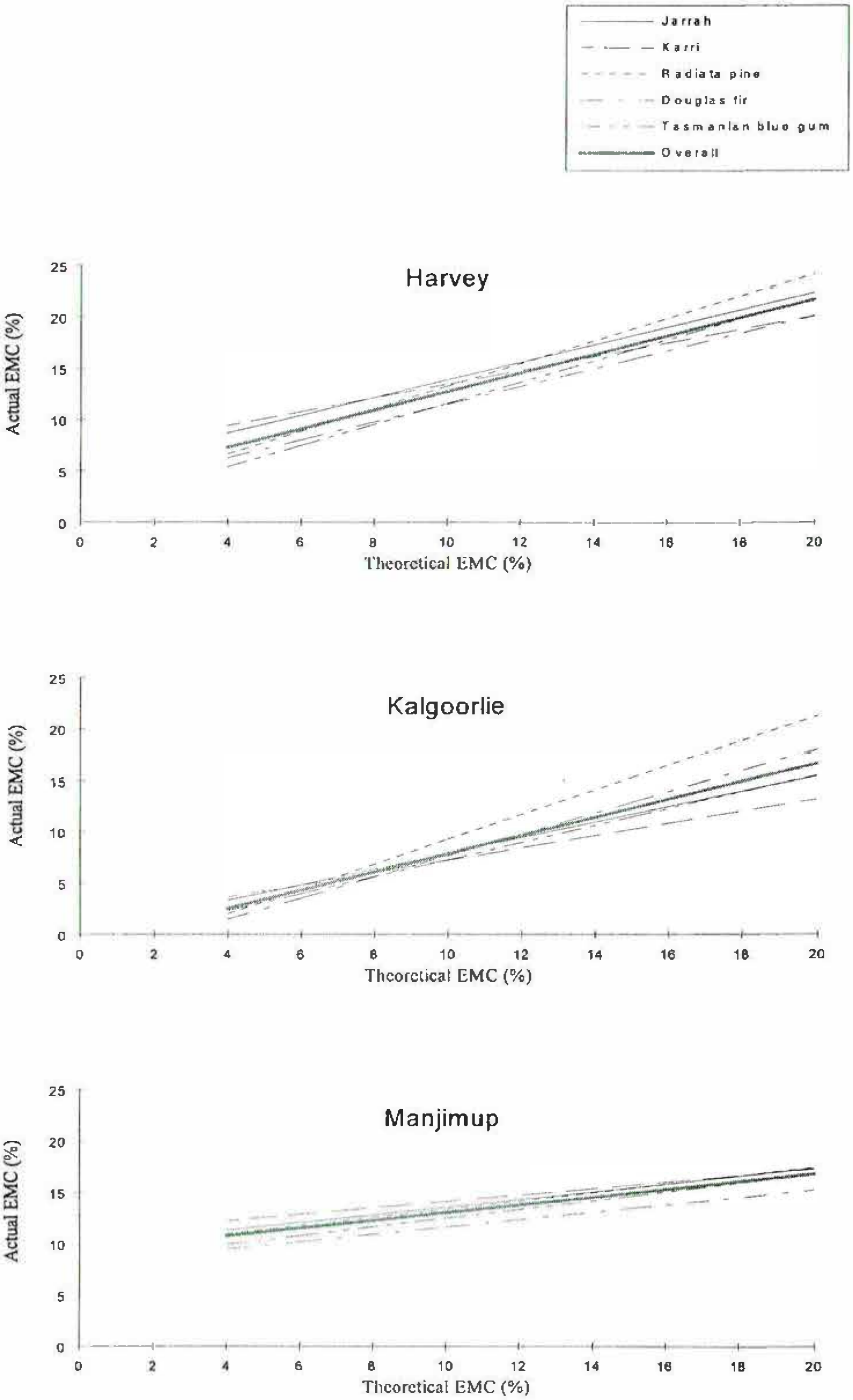

Figure 3. The relationship between theoretical EMC (based on 12.00 pm RH and temperature data) and actual EMC (based on oven-drying the whole sample) values for five species assessed outdoors at Harvey, Kalgoorlie and Manjimup.

TABLE 7

Meteorological data[a] used in the regression analysis.

LOCATION	RAINFALL (mm)	EVAP (mm)	TEMP 12.00 noon(°C)	RH (%)
Karratha	209.7	3146.8	31.2	37.8
Geraldton	469.3	2301.7	21.8	63.6
Perth (Como)	931.9	2007.4	24.0	60.2
Harvey	1025.3	1652.1	21.1	55.7
Busselton	860.3	N.A.	18.6	65.0
Manjimup	1005.0	1043.6	18.2	67.3
Walpole	1252.3	N.A.	18.9	65.5
Narrogin	545.3	N.A.	21.0	63.8
Esperance	645.1	1610.0	19.8	57.1
Kalgoorlie	347.3	2442.9	24.1	42.4

[a] Meteorological data are based on annual means for the study period of two calendar years, which may vary from the long term values.

Data from Broome and Kununurra are excluded.

N.A. - Not available.

TABLE 8

Correlation coefficient (r) and probability matrix for meteorological variables using the mean of the annual readings from ten locations.

	EMC	EVAP	RAIN	RH 12.00 noon	TEMP 12.00 noon
EMC	1.00 (0.000)				
Evap	-0.85 (0.016)	1.00 (0.000)			
Rain	0.83 (0.022)	-0.86 (0.014)	1.00 (0.000)		
RH_{12pm}	0.95 (0.001)	-0.80 (0.032)	0.73 (0.061)	1.00 (0.000)	
$Temp_{12pm}$	-0.81 (0.028)	0.93 (0.003)	-0.69 (0.086)	-0.82 (0.024)	1.00 (0.000)

Notes:

Probabilities are given in parentheses.

EMC = EMC (%) based on oven-drying the whole wood sample.

Evap = evaporation mm/annum.

Rain = rainfall in mm/annum for 1991 and 1992.

RH_{12pm} = relative humidity 12.00 noon (%), yearly mean for 1991 and 1992.

$Temp_{12pm}$ = Temperature 12.00 noon (°C), yearly mean 1991 and 1992.

Bragg (1986) developed models for predicting EMC in Queensland and found that RH (9.00 a.m. and 3.00 p.m.) and the natural logarithm of rainfall were highly significant, and when 3.00 p.m. RH was used the prediction was better than using 9.00 a.m RH. Ellwood and Leslie (1949) examined the effect of EMC using monthly mean 9.00 a.m. humidities and temperatures, for the current month, the previous month and the previous two months, because current EMC of exposed timber depends on both the actual and past RH and temperature conditions. They found the current mean monthly humidity and mean humidity for the past two months were highly significant, but mean humidity for the previous month generally had no significant effect. The effect of temperature for the previous two months was non-significant, but the current monthly temperature in general had a significant effect (Ellwood and Leslie 1949).

Comparison of Estimated and Actual EMC

Initially EMCs were estimated from monthly specimen weighings and the moisture content calculated from these readings. At the completion of the trial the whole specimen was oven-dried and moisture content determined from the initial and oven-dry weights. Table 9 lists the regressions comparing the EMCs based on weight change (estimated EMC) and EMCs based on oven-drying the whole (actual EMC) specimen, for all locations (outdoors and indoors). The regressions for the outdoor equations indicated good correlations for the five species assessed at all locations and the overall equation for the combined species. For the indoor specimens, all species except karri had direct correlations between EMCs based on weight change and EMC determined by oven drying the whole specimen (Table 9). When the EMCs for the additional species assessed at Harvey and Como were included in the regression analysis they also produced good correlations for outdoor and indoor sites.

EMC Map

A map dividing WA into three EMC zones for outdoor conditions is given in Figure 4. The map was developed by using the long term climatic averages for 160 different meteorological stations in WA and the combined timber species mean EMC for each site assessed. A regression based on the mean wood EMCs measured at 12.00 noon and long term mean 9.00 a.m. RH and temperatures were used to arrive at the EMC for each meteorological station.

The three EMC zones for WA give seasoning targets for timber used in outdoor sheltered conditions.

Zone 1 is for EMCs greater than 12 per cent and covers the high rainfall areas of the south-west and from the edge of the Darling Scarp, east of a line extending from Northam to the South Coast, midway between Bremer Bay and Albany.

Zone 2 is for EMC between 10 and 12 per cent and includes the Swan coastal plain, north of Bunbury to south of Jurien Bay (175 km north of Perth), then extending from Jurien Bay to between Northam and Merredin, and between Norseman and Esperance to the South Coast approximately 200 km east of Esperance. This zone encompasses the Perth metropolitan area and the major coastal towns of Mandurah and Bunbury, where the majority of WA's population live and a high proportion of the State's timber would be used.

Zone 3 is for EMC less than 10 per cent, and covers the majority of WA that is relatively low in population, but includes the major towns of Geraldton and Kalgoorlie.

Owing to the lower EMC required for Zone 3, difficulty may be experienced in supplying seasoned timber at the correct moisture content, from coastal centres, to the drier inland areas.

Bragg (1986) developed an EMC map for sheltered outdoor sites in Queensland based on predicted EMC for 148 sites and divided the State into three EMC zones. The target moisture contents for these zones are:

Zone 1 - 12 per cent (range 10 - 12 per cent)
Zone 2 - 9 per cent (range 7 - 12 per cent) and
Zone 3 - 7 per cent (range 5 - 10 per cent)

Smith *et al.* (1991) further reduced the Queensland map to two zones. Zone 1 covers the area where the 10 to 15 per cent EMC range is appropriate. This includes most of the major centres of population in Queensland, particularly around the coast. Zone 2 is for the far west where a lower EMC of 7 to 12 per cent is required.

AFRDI (1993) gave outdoor and indoor EMC for Victoria, Tasmania, New South Wales, South Australia, WA, tropical Australia and southern Queensland. For WA AFRDI recommended a mean outdoor EMC of 10 per cent (range 7 to 13 per cent). Tropical Australia presumably includes the Kimberley region of WA and AFRDI recommended a mean outdoor EMC of 14 per cent (range 12 to 17 per cent). The outdoor mean for WA of 10 per cent given by AFRDI would be appropriate for timber supplied into Zones 1 and 2, but Zone 3 would require a miosture content less than 10 per cent. Specimens assessed in the tropical areas of WA (Broome and Kununurra) had EMC for the combined species of 10. 4 per cent for Broome and 5.2 per for Kununurra, and the Kununurra specimens were assessed in hot and humid spring/summer months. EMC based on long term meteorological data for these two centres also indicate mean EMC less than 14 per cent and the EMC given by AFRDI for tropical areas of WA are not appropriate. The sources of the AFRDI (1993) data or boundaries of tropical Australia are not given.

In practice, the ideal would be to season wood to a moisture content equal to the average EMC for the particular area where it is to be used. Difficulty may be experienced in supplying seasoned timber from the coastal regions to areas of lower EMC. In such cases Smith *et al.* (1991) recommended that the seasoned timber should be allowed to come to EMC on site. This procedure is advisable throughout Zone 3, where EMC can be as low as 6 or 7 per cent, and should be done by strip stacking or loose laying the timber under shelter for two to four weeks prior to fixing. This is particularly important with flooring and joinery timbers. It is important that seasoned timber and wood-based products are protected from the weather and other dampness until fixed under the specified conditions of use. Similarly, for air-conditioned buildings in Zones 1 and 2, the 10 to 15 per cent EMC range is not appropriate, and the timber should be strip stacked within the air-conditioned environment or seasoned to the required moisture content prior to fixing. Smith *et al.* (1991) recommended the applicable target moisture content for timber products in air-conditioned buildings as 9 per cent unless otherwise required and specified. Similar practices need to be applied in WA when timber is taken from zones of high EMC to lower EMC.

In the United States, the Department of Agriculture recommended, that if it is unknown in what locality a product will be used, before drying, the wood should be dried to a moisture content of about 8 per cent, which is close to the average of the values preferred for arid and damp regions (United States Department of Agriculture 1973).

TABLE 9
Regression analysis of EMCs based on weight change (EMC_{ast}) and EMCs based on oven-drying the whole specimen ($EMC_{oven\ dry}$).

SPECIES	REGRESSION EQUATIONS					
	Outdoors	(r^2)	N	Indoors	(r^2)	N
Jarrah	$EMC_{ast} = 0.722\ EMC_{oven\ dry} + 5.23$	0.85	249	$EMC_{ast} = 0.585\ EMC_{oven\ dry} + 6.29$	0.76	248
Karri	$EMC_{ast} = 0.591\ EMC_{oven\ dry} + 6.31$	0.75	246	$EMC_{ast} = 0.388\ EMC_{oven\ dry} + 8.13$	0.40	245
Radiata pine	$EMC_{ast} = 0.774\ EMC_{oven\ dry} + 5.15$	0.85	248	$EMC_{ast} = 0.773\ EMC_{oven\ dry} + 4.865$	0.78	247
Douglas fir	$EMC_{ast} = 0.8\ EMC_{oven\ dry} + 4.058$	0.98	248	$EMC_{ast} = 0.667\ EMC_{oven\ dry} + 4.82$	0.77	247
Tasmanian blue gum	$EMC_{ast} = 0.762\ EMC_{oven\ dry} + 3.75$	0.89	249	$EMC_{ast} = 0.588\ EMC_{oven\ dry} + 4.946$	0.72	247
Overall	$EMC_{ast} = 0.749\ EMC_{oven\ dry} + 4.67$	0.83	1233	$EMC_{ast} = 0.641\ EMC_{oven\ dry} + 5.344$	0.68	1235

Notes: All regressions are significant at $P < 0.001$.
Data for all locations have been included in the analysis

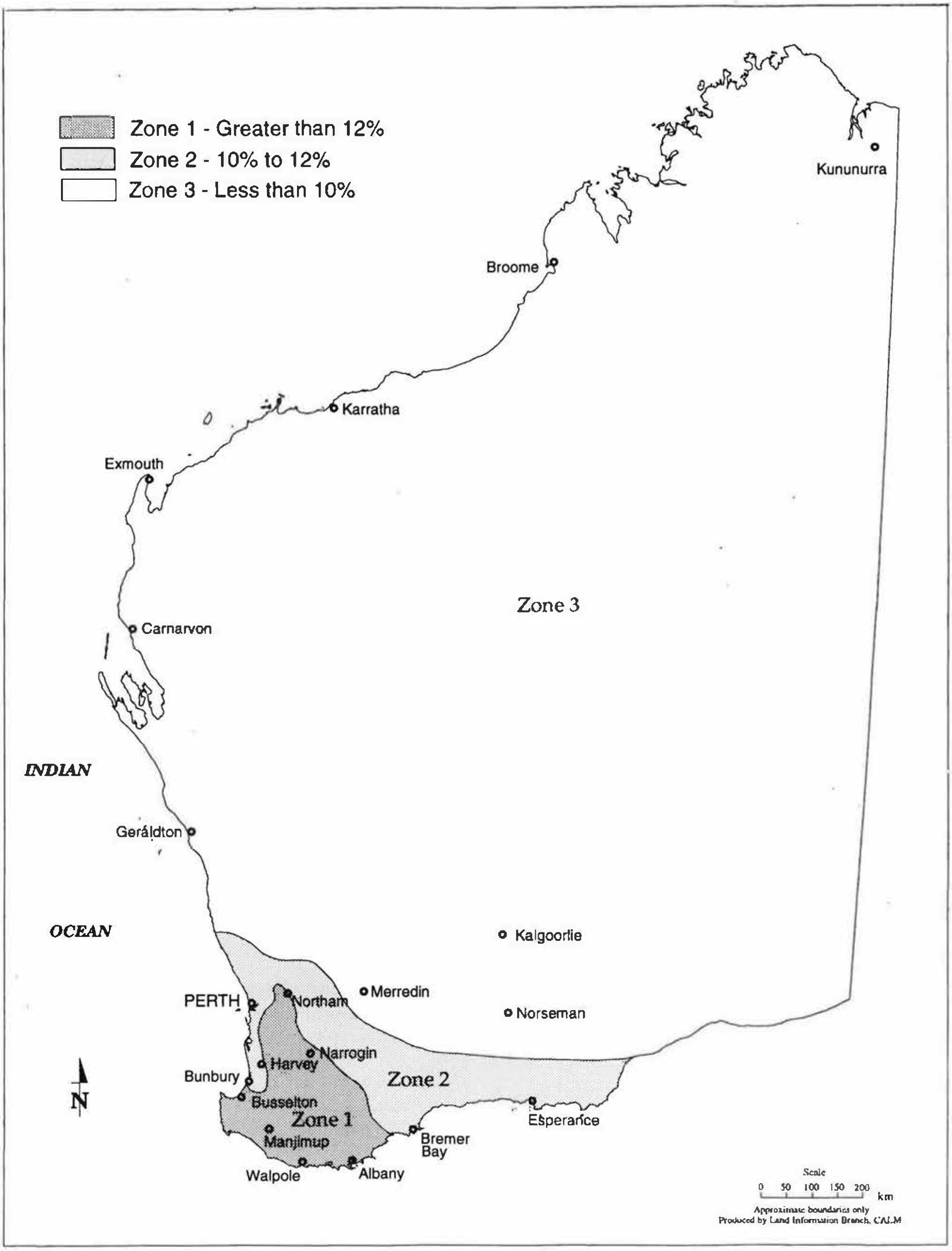

Figure 4. Equilibrium Moisture Content Zones of Western Australia.

McNaught (1988) stated that it is important to appreciate that EMC zones do not bear the same significance to framing timber as they do to appearance quality products. The effect on appearance timber, flooring and panelling can result in checking and large shrinkage or swelling when timber is supplied at the incorrect moisture content. Hardwood framing must be seasoned to moisture contents less than 15 per cent and pine framing less than 10 per cent to achieve the required stability and strength rating.

Problem with Predicting EMC

The choice of RH and temperature data to give meaningful results can have quite a bearing on the EMC values given in charts, equations or maps. It is recognized that the average meteorological conditions do not coincide with the average EMC values but there appears to be no general agreement as to which data should be used (Gough 1977). Finighan (1966) recommended the use of the mean of the daily maximum and minimum temperatures for each month and average of the 6.00 a.m. and 3.00 p.m. RH readings to be closer to the actual conditions. Ellwood and Leslie (1949) found that the current mean monthly humidity and mean RH of the past two months are highly significant in predicting EMC and generally the current mean monthly temperature has a significant effect. The mean RH and temperature for the past month generally has no significant effect on EMC.

Orman (1955) found that the monthly averages (taken from weekly readings of moisture content) showed little effect from the previous month's humidity and temperature conditions. In other words, the mean moisture content of a species could be directly related to the mean humidity and temperature conditions for a particular month, the sensitivity of the species being sufficient to overcome any residual effect of the previous month's climatic conditions.

Owing to the great number of factors influencing EMC, including such secondary factors as effects of previous drying history, air velocity, time or ageing effects, whether quartersawn or backsawn, and thickness of timber, it is not always possible to obtain perfect agreement between the empirical and theoretical determinations. Another factor of some importance is the case where meteorological data are obtained from sites not typical of the environment to which the samples are exposed. Orman (1955) found that the effect of this microclimate variation owing to local phenomena is often marked over comparatively short distances. For example, two stations less than 5 km apart show up to 0.5 per cent moisture content differences under identical exposure conditions.

In actual practice, when wood is in use, constant RH and temperature conditions are rarely attained, consequently, the moisture content of wood is seldom in equilibrium with the psychrometic conditions of the environment owing to the varying nature of the environmental conditions (Ellwood and Leslie 1949). Except in the case of extremely thin sections, wood exhibits a considerable lag in reaching the moisture content determined by the psychrometic conditions of the environment. The rate of moisture diffusion through the wood is the limiting factor. Generally, diurnal variations would only influence the percentage moisture content of thin veneer, e.g. 3 to 4 mm thick. Joinery or building timber, which is considerably thicker, is chiefly affected by seasonal and yearly changes. The effect of short term environmental fluctuations will be superimposed, to a certain extent, upon the major or long term variations of wood moisture content. Therefore, at any one time, the moisture content of wood depends not only on the EMC corresponding to the environment at that time, but also upon the rate and method of moisture exchange when subjected to the varying atmospheric conditions (Ellwood and Leslie 1949).

Tsoumis (1964) stated that when EMC values given in a chart or determined by Simpson's equation are computed on the basis of curves constructed from data obtained from Sitka pine (*Picea sitchensis* Carr.), the generalization of such data is limited to this effect. Although most temperate species show good agreement, large deviations may be expected at high relative humidities, especially in woods containing high amounts of extractives.

Absorption Rates

Figure 5 shows the comparative rates of moisture absorption and Tables 10 and 11 list the actual moisture contents and the rate of absorption for 1, 2, 4, 6 or 8 weeks after oven-drying, for the specimens assessed outdoors and indoors at Harvey. The two pine species (maritime and radiata) clearly have greater moisture absorption rates than the other species, and the lower density Tasmanian blue gum had a faster rate than the other eucalypts. The higher density species, e.g. mulga, wandoo, redwood, gimlet and tuart had the slowest moisture absorption rates. For example, radiata pine absorbtion decreased from 9.5 per cent in the first week to 0.9 per cent in the ninth week, and the higher density mulga specimens had absorbed 1.5 per cent in the first week and 0.34 per cent in the ninth week (Table 10). The absorption rates decreased after the first week and if the exposure time had been extended the specimens would have reached EMC. Owing to the 'hysteresis' effect, when timber takes up moisture it assumes an appreciably lower EMC than when it loses moisture to the air, and oven-drying specimens can cause the extractives to be redistributed within the timber, blocking cells and restricting moisture uptake. Oven-drying would restrict the uptake of moisture, but a substantial uptake would still occur (Chafe[1] personal communication). Koponen (1985) claimed that EMC in absorption may be approximately 80 per cent of the value in desorption. Further assessments are required to determine the time it takes to reach EMC and compare this with EMC of specimens that have been equilibrated to a constant EMC, e.g. 10 per cent instead of initially oven-drying. Samples were weighed weekly generally between 9.00 and 10.00 a.m., whereas temperature and RH were

[1] Dr Sam Chafe, CSIRO Division of Forest Products, Clayton, Victoria.

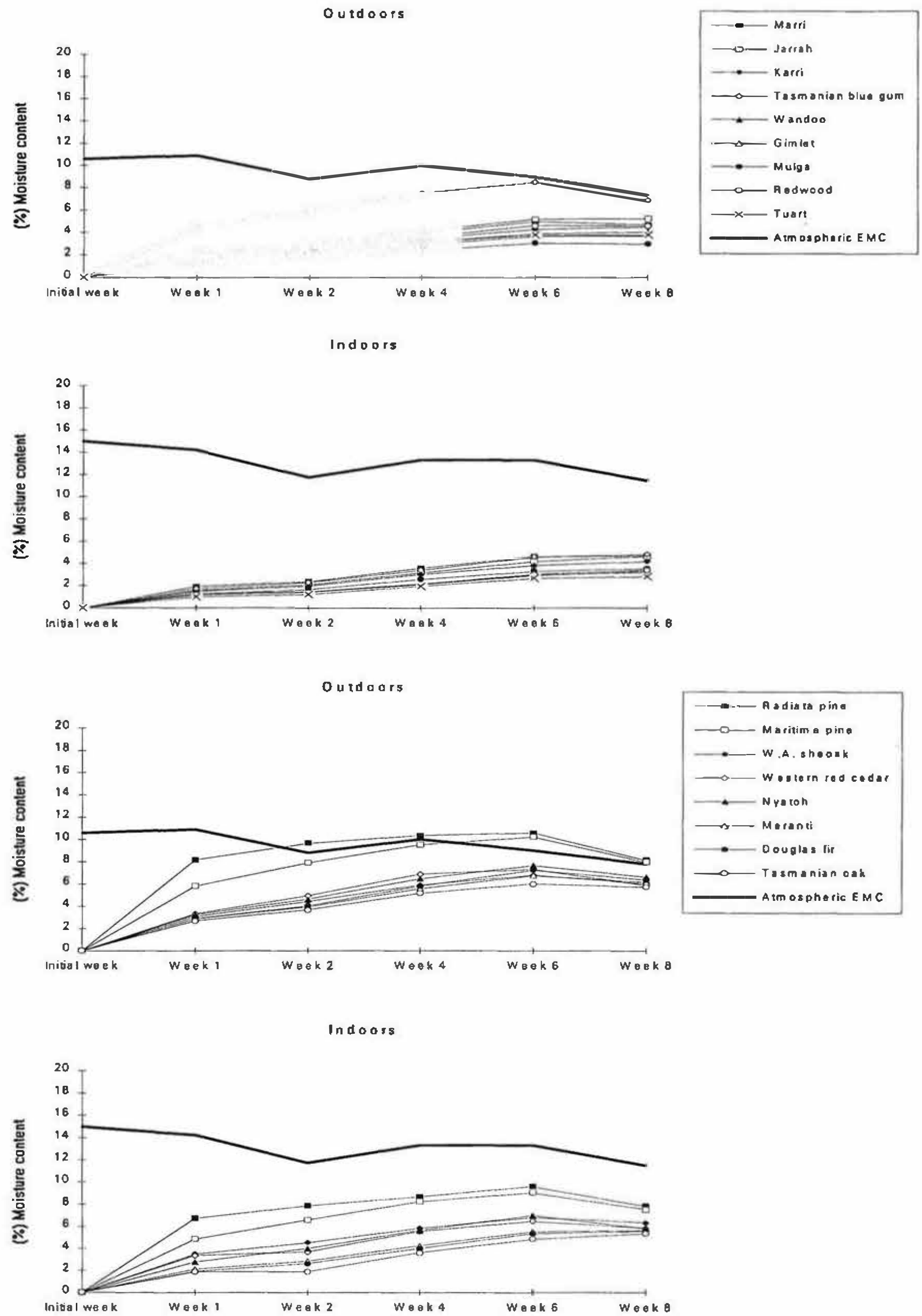

Figure 5. Rate of moisture absorption of specimens assessesd at Harvey (outdoors and indoors).

TABLE 10

Actual moisture contents and rates of absorption after oven drying and exposing to outdoor conditions at Harvey.

SPECIES	WEEK 1		WEEK 2		WEEK 4		WEEK 6		WEEK 8	
	Moisture content (%)	Absorption rate (%/week)	Moisture content (%)	Absorption rate (%/week)	Moisture content (%)	Absorption rate (%/week)	Moisture content (%)	Absorption rate (%/week)	Moisture content (%)	Absorption rate (%/week)
Jarrah	2.55	2.55	2.94	1.58	4.10	1.11	5.21	0.91	5.24	0.60
Karri	2.23	2.23	2.48	1.33	3.44	0.93	4.29	0.75	4.50	0.52
Radiata pine	9.49	9.49	9.65	5.19	10.36	2.80	10.60	1.86	8.12	0.93
Douglas fir	3.38	3.38	4.03	2.17	5.80	1.57	7.23	1.27	6.37	0.73
Tasmanian blue gum	5.10	5.10	5.90	3.17	7.53	2.04	8.51	1.49	6.92	0.80
Marri	2.31	2.31	2.86	1.54	3.91	1.06	4.99	0.88	4.70	0.54
Tuart	1.91	1.91	2.26	1.22	3.14	0.85	3.79	0.66	3.79	0.44
Tasmanian oak	3.14	3.14	3.69	1.98	5.16	1.39	6.01	1.05	5.71	0.66
Gimlet	2.04	2.04	2.19	1.18	2.91	0.79	3.66	0.64	3.71	0.43
Redwood	2.09	2.09	2.47	1.33	3.54	0.96	4.63	0.81	4.59	0.53
Wandoo	2.00	2.00	2.23	1.20	3.12	0.84	3.89	0.68	4.05	0.47
Mulga	1.46	1.46	1.62	0.87	2.39	0.65	3.05	0.53	2.99	0.34
WA sheoak	3.58	3.58	4.42	2.38	5.89	1.59	6.79	1.19	6.03	0.69
Meranti	3.38	3.38	3.93	2.11	5.58	1.51	6.75	1.18	6.15	0.71
Maritime pine	6.75	6.75	7.87	4.23	9.52	2.57	10.22	1.79	7.96	0.92
Western red cedar	3.87	3.87	4.95	2.66	6.87	1.86	7.31	1.28	5.87	0.67
Nyatoh	3.77	3.77	4.65	2.50	6.47	1.75	7.66	1.34	6.64	0.76
Atmospheric EMC	10.9		8.8		10.0		9.0		7.4	

TABLE 11

Actual moisture contents and rates of absorption after oven drying and exposing to indoor conditions at Harvey.

SPECIES	WEEK 1		WEEK 2		WEEK 4		WEEK 6		WEEK 8	
	Moisture content (%)	Absorption rate (%/week)	Moisture content (%)	Absorption rate (%/week)	Moisture content (%)	Absorption rate (%/week)	Moisture content (%)	Absorption rate (%/week)	Moisture content (%)	Absorption rate (%/week)
Jarrah	1.78	1.78	2.07	1.11	3.14	0.85	4.18	0.73	4.65	0.53
Karri	1.70	1.70	1.95	1.05	3.00	0.81	3.82	0.67	4.17	0.48
Radiata pine	7.77	7.77	7.82	4.20	8.64	2.33	9.57	1.68	7.82	0.90
Douglas fir	2.23	2.23	2.62	1.41	3.99	1.08	5.33	0.94	5.58	0.64
Tasmanian blue gum	1.97	1.97	2.28	1.22	3.38	0.91	4.58	0.80	4.83	0.56
Marri	2.21	2.21	2.35	1.26	3.56	0.96	4.62	0.81	4.68	0.54
Tuart	1.13	1.13	1.21	0.65	1.95	0.53	2.65	0.46	2.81	0.32
Tasmanian oak	2.21	2.21	1.88	1.01	3.61	0.97	4.84	0.85	5.33	0.61
Gimlet	1.39	1.39	1.43	0.77	2.09	0.56	2.91	0.51	3.33	0.38
Redwood	1.35	1.35	1.41	0.76	2.13	0.58	3.04	0.53	3.42	0.39
Wandoo	1.52	1.52	1.44	0.77	2.16	0.58	2.98	0.52	3.22	0.37
Mulga	1.36	1.36	1.65	0.88	2.58	0.70	3.30	0.58	3.54	0.41
WA sheoak	4.03	4.03	4.50	2.42	5.80	1.57	6.78	1.19	6.34	0.73
Meranti	2.46	2.46	2.85	1.53	4.24	1.15	5.50	0.96	5.62	0.65
Maritime pine	5.61	5.61	6.54	3.52	8.20	2.22	9.00	1.58	7.53	0.87
Western red cedar	3.90	3.90	3.68	1.98	5.52	1.49	6.45	1.13	5.86	0.67
Nyatoh	3.23	3.23	3.98	2.14	5.61	1.52	6.98	1.23	5.81	0.67
Atmospheric EMC	10.9		11.7		13.3		13.3		11.5	

recorded daily at 12.00 noon, and this may have affected the results. In future trials the samples should be weighed at the same time temperature and RH are recorded.

The absorption rates of the indoor specimens are similar to those of the outdoor specimens, with the two pine species showing greater absorption rates than the higher density species, particularly the eucalypts. Tasmanian blue gum indoor specimens had similar absorption rates to the other eucalypts, whereas the outdoor specimens had higher rates. Radiata pine absorbed 7.8 per cent moisture in the first week which is slightly less than the outdoor specimens, but over the eight-week assessment period the rates were similar. It was expected that the indoor specimens would absorb moisture faster than the outdoor specimens, owing to the high ambient EMC conditions.

Hartwig (1959) found, after oven-drying pine and eucalypt specimens and subsequently stacking them indoors, that after 25 days the pine specimens had reached a moisture content which varied from 6.1 to 9.0 per cent and averaged 7.75 per cent. The eucalypts after 28 days had much lower moisture contents, between 2.83 and 5.36 per cent, with an average of 3.65 per cent. After 12 months the moisture contents of the pine and eucalypt specimens were similar, but the ultimate EMC of the pine specimens was higher than that of the eucalypt specimens. The current pilot study needs to be extended to 12 to 24 months to determine the ultimate EMC of different species after oven drying.

Practical Aspects of the Results

EMC and seasonal changes in moisture that have so far been discussed and the results illustrated by curves are of no practical importance because of the shrinkage and swelling that accompanies them. Seasonal variation must be expected to occur in the moisture content of timber in normal use as furniture and panelling, and this will be accompanied by an approximately proportional change in dimension. The shrinkage or expansion of wood in common use can be minimized by choosing, as the moisture content at manufacture, the mean of the extreme values of the range of seasonal variation. Furniture should also be designed to allow some freedom for shrinkage and expansion of timber components.

In certain types of products, shrinkage may be a more serious matter than expansion, or alternatively, the most appropriate moisture content for the timber at manufacture should tend towards the lower or higher extremity rather than to the mean value. In these cases it is necessary to leave the actual choice of moisture content to the manufacturer, to be decided according to the requirements of the product.

Perth, the south-west locations, and the coastal towns of Geraldton and Esperance have higher outdoor EMCs than Karratha and Kalgoorlie. Difficulty may be experienced in supplying seasoned timber from Perth and the south-west to these areas of lower EMC. In such cases it is recommended that the seasoned timber should be allowed to come to the specified EMC for its in-service location. This could be done by strip stacking the timber under shelter for two to four weeks prior to fixing. This is particularly important with flooring and joinery timber. In the case of timber going from areas of lower EMC to those of higher EMC, e.g. from Perth to Manjimup, Walpole or Albany, allowance must be made for swelling.

Timber dried to the average moisture content that will be encountered in service, may then change during storage, delivery or installation, particularly in buildings where the wet trades such as bricklaying and plastering result in very high humidities during construction (Richardson 1993). Floors are sometimes laid in new buildings very promptly after kiln-drying and the high humidity then causes them to expand so that sometimes the entire floor lifts or the expansion causes serious damage to the surrounding walls. Stacking the wood for a period inside the building before laying will avoid this particular problem as the wood will thus reach equilibrium with the high humidity in a damp new building. When the building is ultimately occupied, the relative humidity will fall and shrinkage defects will develop (Richardson 1993). For example, quartersawn floorboards will simply shrink in width leaving gaps at the joints, but backsawn boards will cup. Backsawn boards should be laid with the heart surface upwards so that the cupping causes each board to be raised in its centre rather than at its edges where it can cause tripping. Shrinkage gaps can be reduced by using tongue and groove boards, where the tongue can span these shrinkage gaps.

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REFERENCES

AFRDI (1993). The moisture content of furniture timber. *Australian Furniture Research and Development Institute, Technical Note* No.1.

Anon. (1929). The moisture content of wood with special reference to furniture manufacture. *Department of Scientific and Industrial Research, Forest Products Research Bulletin* No. 5. Princes Risborough, Bucks.

Anon. (1967). Equilibrium moisture content and the moisture content of wood in use. In : *Timber Manual*, Vol. 1: *Victorian Timbers*. Victorian Sawmillers Association, Melbourne, Victoria.

Bois, P.J. (1959). Wood moisture content in homes - seasonal variations in the south-east. *Forest Products Journal* 9(11), 427-431.

Bootle, K.R. (1983). *Wood in Australia- Types, properties and uses.* McGraw-Hill Book Company, Sydney.

Bragg, C. (1986). An equilibrium moisture content survey of timber in Queensland. *Queensland Department of Forestry, Technical Paper* No. 40.

Bureau of Meteorology (1988). *Climatic averages - Australia.* Australian Government Publishing Service, Canberra.

Canada Department of Resource and Development (1952). Moisture content changes in seasoned lumber in storage and in transit. Forest Products Laboratories Division, *Bulletin* No. 102, Vancouver, Canada.

Cassens, D.L. and Feist, W.C. (1991). Exterior wood in the south - Selection, application and finishes. Forest Products Laboratory, Forest Service U.S. Department of Agriculture, *General Technical Report* FPL - GTR- 69.

Chafe, S.C. (1991). A relationship between equilibrium moisture content and specific gravity in wood. *Journal of the Institute of Wood Science* **12** (3), 119-122.

Christensen, G. N. and Kelsey, K.E. (1959). Die sorption von Wasserdampf durch diechemischen Bestandteile des Holzes. *Holz Roh. Werkst.* 17, 178-188. Cited by Chafe (1991).

Ellwood, E.L. and Leslie, R.T. (1949). Determination of the moisture content of seasoned wood from meteorological data. CSIRO Division of Forest Products, *Experimental Report* S17/6.

Finighan, R. (1965). Australia - New Guinea EMC survey. Paper presented at the 12th Forest Products Research Conference, CSIRO Melbourne, Victoria, November 1965.

Finighan, R. (1966). Moisture content predictions for eight seasoned timbers under sheltered outdoor conditions in Australia and New Guinea. CSIRO Division of Forest Products, *Technological Paper* No. 44.

Gough, D.K. (1977). The assessment of equilibrium moisture content with particular reference to Fiji. Paper presented at the 18th Forest Products Research Conference, CSIRO Highett, Victoria May 30 - June 3, 1977.

Hartwig, G.L.F. (1959). The equilibrium moisture content of wood - part 1 and 2. *Timber Technology* **67**, 284-286, 323-327.

Haygreen, J.G. and Bowyer, J.L. (1982). *Forest Products and Wood Science - An Introduction.* The Iowa State University Press.

Higgins, N.C. (1957). The equilibrium moisture content - relative humidity relationships of selected native and foreign woods. *Forest Products Journal* 7(10), 371 - 377.

Howland, P. and Matabwa, C.J. (1971). Equilibrium moisture content of seasoned wood in Malawi - Part 2: Specific EMC values for important species. *Malawi Forest Research Institute, Research Record* No. 52.

Kingston, R.S.T. and Risdon, C. June E. (1961). Shrinkage and density of Australian and other south-west Pacific woods. *CSIRO Australia, Division of Forest Products, Technological Paper* No. 13.

Koponen, H. (1985). Sorption isotherms of Finnish birch, pine and spruce. *Paperi-ja-Puu* **67**(2), 70-72, 74-77.

Lamond, A. and Hartley, J. (1991). Seasoning of timber. *Forest Commission of New South Wales, Wood Technology and Forest Research Division, Technical Publication* No.9.

McNaught, A. (1988). Equilibrium moisture content of timber. Queensland Department of Forestry, *Timber Note* No. 23.

Orman, H.R. (1955). The response of New Zealand timbers to fluctuations in atmospheric moisture conditions. *Forest Research Institute, New Zealand Forest Service, Technical Paper* No. 8.

Richardson, B.A. (1993). *Wood Preservation.* 2nd edn. Published by E. and F.N. Spon, an imprint of Chapman and Hall, London.

Simpson, W.T. (1971). Equilibrium moisture prediction for wood. *Forest Products Journal* **21**(5), 48-49.

Smith, W.J., Kynaston, W.T., Cause, M.L. and Grimmett, J.G. (1991). Seasoning of timber. In: Building timbers - properties and recommendations for their use in Queensland. *Queensland Forest Service, Department of Primary Industry,Technical Pamphlet* No.1.

Stamm, A.J. (1967). *Wood and Cellulose Science.* The Ronald Press Company, New York.

Tsoumis, G. (1964). Estimated moisture content of air-dry wood exposed to the atmosphere under shelter, especially in Europe. *Holzforschung* **18**(3), 76-81.

United States Department of Agriculture (1973). Moisture content of wood in use. Forest Products Laboratory, Forest Service U.S. Department of Agriculture, *Research Note* FPL - 226.

Van Wyk, J.H. (1957). Variation throughout the year in the moisture content of wood manufactured into furniture and joinery. *The South African Forestry Association* **30**, 40-43.

Van Wyk, J.H. (1963). The importance of the moisture content of wood. *Forestry in South Africa* **2**, 1 - 6.

Welsh, M.B. (1936). The moisture equilibrium of timber in different parts of New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* **67**, 364-385.

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

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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 discolorous 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

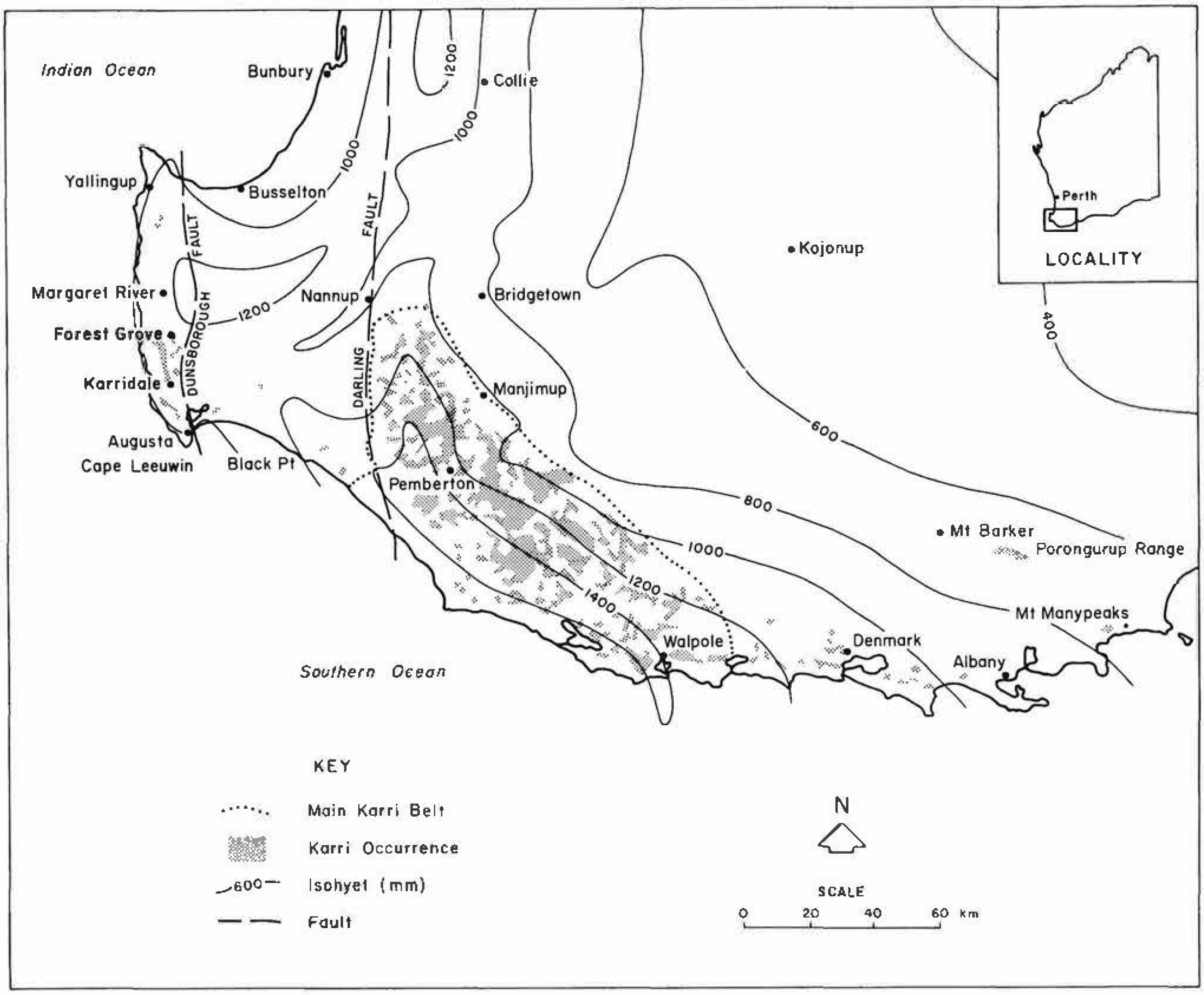

Figure 1. Karri occurrence in south-west Western Australia.

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 m^2 (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 CAGES WITHOUT BEES	BEE POLLINATION CAGES WITH BEES	BEE POLLINATION OPEN CROWNS	ARTIFICIAL POLLINATION SELF	ARTIFICIAL POLLINATION 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 (Loneragan[1] 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.

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

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.

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 m^2 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:

Seeds per capsule x capsules per twig x twigs per unit crown area (21) x 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 m^2 and this decreases to 1 twig per m^2 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 (McCaw[2], 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 (dieldren) 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.

	SPRING			AUTUMN		
TREATMENT	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 x 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 FRESH ASHBED	CLEAN SURFACE	POOR SEEDBED	TOTAL
Summer 1957 seeding and Winter 1957 germination	Seedbed area sampled (m^2)	8.8	24.1	14.0	46.9
	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 Winter 1957 establishment	Seedbed area sampled (m^2)	10.4	6.9	12.8	30.1
	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 annnotated 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)* 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 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)

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 Rotheram (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. (Underwood[3], 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 8.5	16 000 (90%)	1 900 (39%)	30 (2%)	17 900 (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 Annels[4] (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 terbumeton (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), oxyflurofen (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. Oxyflurofen 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.

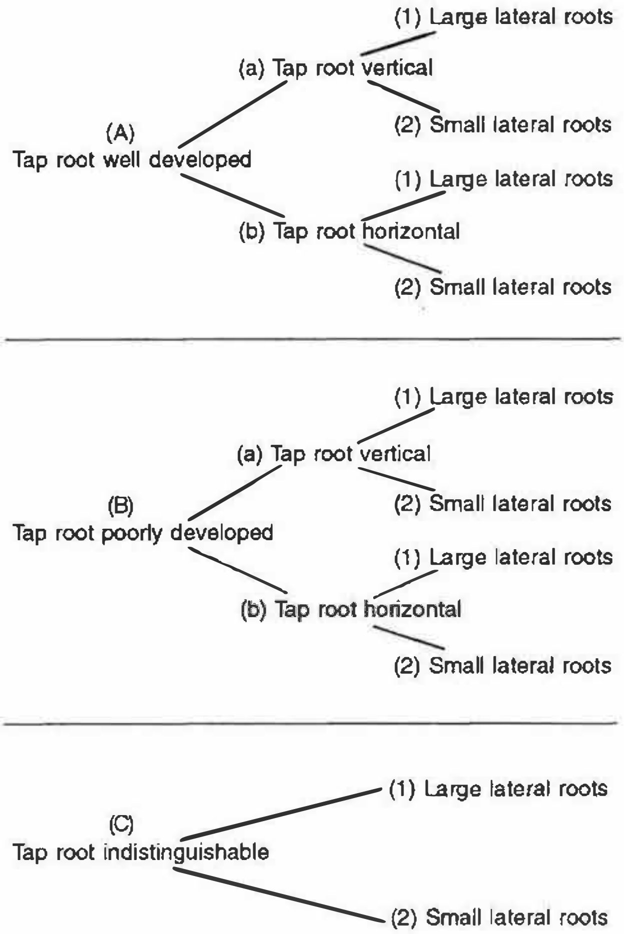

Figure 2. Karri root system key.

TABLE 10

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

ROOT TYPE (from Fig. 2)	SOIL TYPE LOAM N	LOAM H/P	SAND N	SAND H/P	PODZOL N	PODZOL H/P	CLAY[a] N	CLAY[a] 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 ($g \times 10^{-1}$ 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 ($g \times 10^{-1}$ 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/Agran, 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	10g 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 sterate (<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	K	S	FERT. COSTS ($/ha)	TOTAL COSTS ($/ha)[a]	MEAN HT GROWTH (cm)	COST EFFECTIVENESS[b]
	g/PLANT							
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 : Breidahl (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 (Breidahl 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).

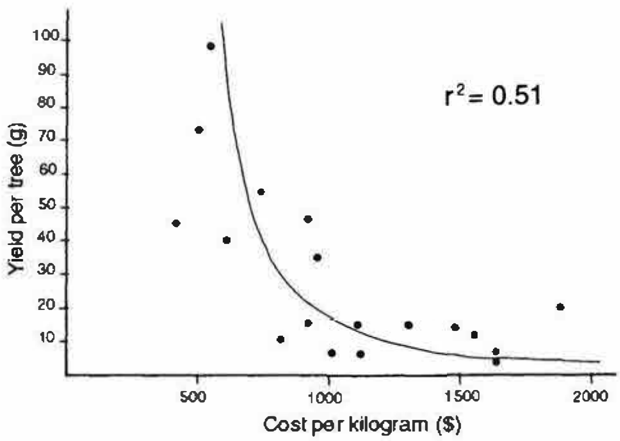

Figure 3. Effect of seed yield per tree on the cost/kg of seed collected at Hayles seed orchard.

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 (Hodges[5], 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 Jnr., 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).

Wronksi (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 m^3 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 (McGrath[6], personal communication).

[6] J. McGrath, Department of Conservation and Land Management, Busselton.

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 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.

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).

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) Thinned	Unthinned	DIFFERENCE (cm)	RESPONSE (%)
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.

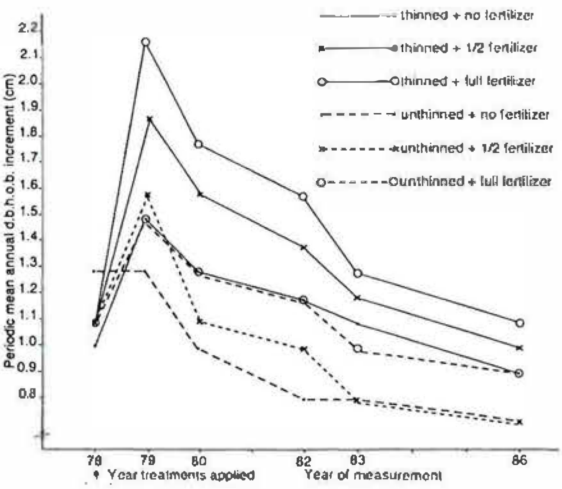

Figure 4 Periodic mean annual diameter increment. Quartz road experiment.

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 thinnings. 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 m^2ha^{-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 $m^2 ha^{-1}$ 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 $m^2 ha^{-1}$). 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 $m^2 ha^{-1}$, 20 $m^2 ha^{-1}$, 15 $m^2 ha^{-1}$ and 10 $m^2 ha^{-1}$) and unthinned controls (43$m^2 ha^{-1}$) 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 $m^2 ha^{-1}$ 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.

	MEAN d.b.h.u.b. INCREMENT (cm yr^{-1})			
	LARGEST 100 s.p.ha		LARGEST 200 s.p.ha	
Thinning and Fertilizing Combined	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.

	MEAN d.b.h.u.b. INCREMENT (cm yr^{-1})			
	LARGEST 100 s.p.ha		LARGEST 200 s.p.ha	
Thinning intensity	+ 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.

	MEAN DIAMETER OVER BARK INCREMENT (1985-1988) cm yr^{-1}		
Residual Basal area	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).

	BOLE DAMAGE CLASSES				
OPERATION	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 (Voutier[7], 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.

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

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.

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 foresake 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.

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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, Tacomma, 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.

Breidahl, 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. Tickskrift 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 Malacjzuk, 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 Malacjzuk, 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 Zeitschrirft 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.

Rotheram, 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 periodicty 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.

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Review of WURC stockpiling and sawmilling studies

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SUMMARY

The stockpiling and sawmilling research trials carried out since 1986 at the Wood Utilisation Research Centre of the Western Australian Department of Conservation and Land Management are reviewed in this report. The major species assessed were jarrah (*Eucalyptus marginata* Donn. ex Sm.) and karri (*E. diversicolor* F. Muell.). Other species assessed were marri (*E. calophylla* R. Br. ex Lindl.), and six species growing in the eastern Goldfields area: Dundas blackbutt (*E. dundasii* Maiden), York gum (*E. loxophleba* Benth.), gimlet (*E. salubris* F. Muell.), redwood (*E. transcontinentalis* Maiden), mulga (*Acacia aneura* F. Muell. ex Benth.), and northern cypress pine (*Callitris columellaris* F. Muell. sens. lat.). Western Australian-grown Tasmanian blue gum (*E. globulus* Labill. ssp. *globulus*), and rose gum (*E. grandis* W. Hill ex Maiden) were also assessed, as well as karri, red mahogany (*E. resinifera* Sm.), spotted gum (*E. maculata* Hook.) and tallowwood (*E. microcorys* F. Muell.) grown on rehabilitated bauxite minesites.

The stockpiling trials indicated that storing logs under a water spray schedule of 15 min in every 3 hours gave acceptable log quality with a 93 per cent saving in power and water. The sawmilling trials indicated the potential for processing small regrowth eucalypts into structural or appearance grade timber products, and the results confirmed the close correlation between log size and sawn recoveries.

The comparatively high incidence of defects, e.g. knots, borer damage, rot, bow and spring reduced graded recoveries in all species.

INTRODUCTION

The Department of Conservation and Land Management's (CALM) Wood Utilisation Research Centre (WURC) at Harvey was originally established in 1984 to carry out both applied and basic research to assist the Western Australian (WA) timber industry. The 1993 WURC Mission Statement reads: 'to provide scientifically sound information to improve the efficiency and timber utilisation in Western Australia'.

The major research program carried out by the WURC was the Small Eucalypt Processing Study from 1986 to 1990 to develop techniques for value-adding of small regrowth eucalypt thinnings. The program was funded by the Commonwealth through a Public Interest Project on a $1 for $2 basis. The program carried out applied research in stockpiling logs, sawmilling, timber drying and assessment of wood properties, before developing VALWOOD® (an edge- and face-glued panel) and the CALM Solar-assisted kilns, and commencing a computer model of the timber industry. The individual trials were previously reported in WURC Reports or WURC Technical Reports, as part of a Commonwealth requirement for quick dissemination of research results.

This review discusses the research trials on stockpiling and sawmilling of regrowth and plantation-grown eucalypts carried out at the WURC since 1986. The major species assessed were jarrah (*Eucalyptus marginata* Donn. ex Sm.) and karri (*E. diversicolor* F. Muell.). Other species assessed were marri (*E. calophylla* R. Br. ex Lindl.), and six species growing in the eastern Goldfields area: Dundas blackbutt (*E. dundasii* Maiden), York gum (*E. loxophleba* Benth.), gimlet (*E. salubris* F. Muell.), redwood (*E. transcontinentalis* Maiden), mulga (*Acacia aneura* F. Muell. ex Benth.), and northern cypress pine (*Callitris columellaris* F. Muell. *sens. lat.*). Western Australian-grown Tasmanian blue gum (*E. globulus* Labill. ssp. *globulus*), and rose gum (*E. grandis* W. Hill ex Maiden), were also assessed, as well as karri, red mahogany (*E. resinifera* Sm.) spotted gum (*E. maculata* Hook.) and tallowwood (*E. microcorys* F. Muell.) grown on rehabilitated bauxite minesites.

STOCKPILING

A major factor in the WA timber industry is the need for sawmillers to stockpile logs for processing during the winter months. The logging season is restricted in order to minimize the spread of dieback, caused when *Phytophthora cinnamomi* Rands fungal spores are carried in wet soil on machinery or transport. Industry experience had confirmed that dry stockpiling of logs results in unacceptable degradation, particularly end splitting and insect attack. Stockpiling under water sprays is essential to reduce end-splitting and surface checking of logs, and to reduce the incidence of insect attack, particularly by the bardi borer (*Phoracantha semipunctata*). There is evidence from the eastern States that stockpiling under water sprays can also reduce the level of growth stresses in ash-type eucalypts, which will consequently reduce the amount of bow and spring in the sawn product (Waugh 1980).

White (1990) compared the efficiencies of a high pressure spraying system, with its high volume knocker-type sprinklers, and a low pressure/low volume black polypipe 'Soaket' system. Twenty cubic metres of bark-on and debarked regrowth jarrah sawlogs, including a mixture of butt and crown logs, were assessed under each system. The components and costs of each system are given. Each log was assessed for sapstain, insect damage, surface checking and decay before sawing. The results indicated that both systems were capable of maintaining regrowth jarrah logs in good condition through the severe summer conditions. The daily consumption of water using continuous watering was 26.6 kL and 6.9 kL for high pressure and low pressure systems respectively for 20 m^3 of logs. White (1990) recommended the low pressure system where capital and water are limiting factors and where stockpiles are small.

Although Brennan (1988) reported a stockpiling trial of WA sheoak (*Allocasuarina fraseriana* (Miq.) L. Johnson), the major trial on regrowth eucalypts was that by Brennan *et al.* (1990) on stockpiling regrowth jarrah and karri using the high pressure watering system. The trial was conducted in two parts: the first part, using jarrah logs, compared the effects of water spray schedules ranging from continuous (during daylight hours) to 1 h on : 3 h off, by assessing log degradation and borer infestation in the stockpiling, and the amount of bow and spring in flitches, wings and sawn boards after sawmilling. The results indicated that the most extreme watering schedule assessed (1 h on : 3 h off) did not adversely affect the quality of logs or sawn timber.

The results of the first part were the basis for the second part of the study, in which regrowth karri logs were included with the regrowth jarrah. More radical watering schedules were used, although karri is known to be more susceptible to splitting than is jarrah. The results indicated that a 15 min on :165 min off schedule (i.e. 15 min in each 3 h) gave satisfactory results, and this would result in a 92 per cent savings in water and electricity compared with continuous water spraying. The technical details of the high pressure system are given by Brennan *et al.* (1990). Logs that were dry stockpiled developed major splitting, which made many of them unsuitable for milling, and those milled produced very low recoveries.

SAWMILLING

Jarrah

The first major trial was an assessment of the effects of sawmilling and stockpiling of 50-year-old regrowth jarrah (White 1989b). By measuring bow and spring in flitches and boards, White compared the sawn graded recoveries from logs, either freshly sawn or stockpiled under water sprays before milling (and sawn using one of three different sawmilling patterns), in reducing the effects of growth stresses in these regrowth logs. The sawmilling patterns assessed were based on those described by Waugh (1980) and Machin (1981) and are shown in Figure 1. Data were collected for four log length classes and five log diameter classes. The results indicated that, in both freshly sawn and stockpiled treatments, log length had no effect on sawn graded recoveries, but as expected, increasing log

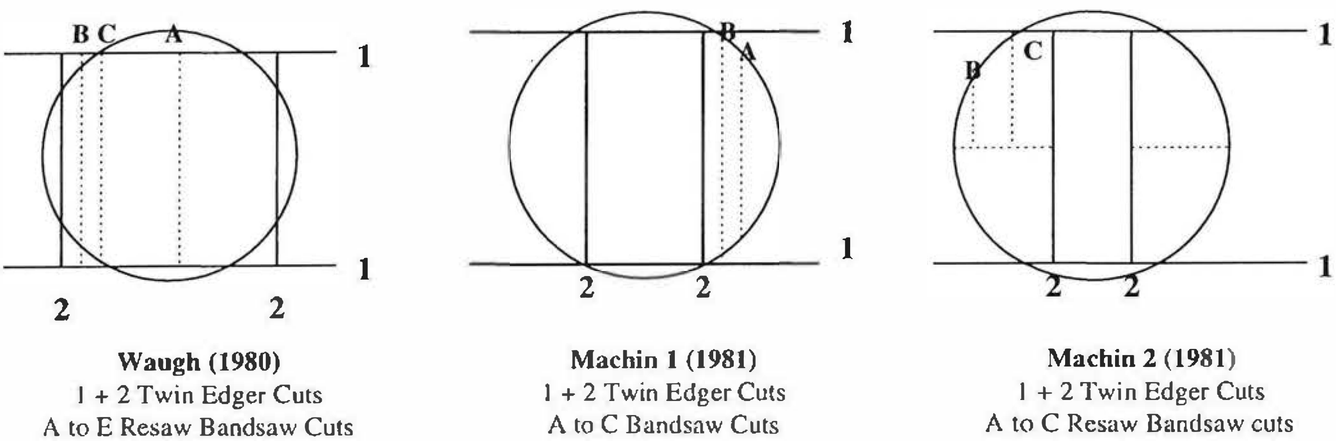

Figure 1. Sawing patterns tested in jarrah sawmill trial.

diameter resulted in increasing recoveries. The recoveries from each sawing pattern were similar, ranging from 20.2 per cent to 22.2 per cent. Log diameter differences in each treatment would explain the small variation. The three different sawing patterns resulted in similar levels of bow and spring in flitches, but bow in boards was slightly larger in the stockpiled material. All were within Australian Standard AS 2082-1979 specifications (Standards Association of Australia 1979).

Brennan and Ward (1990) summarized studies on the green sawn recoveries of 28 mm thick regrowth jarrah boards milled from the following areas in the northern jarrah forest :

Banksiadale Road, Dwellingup District;
Inglehope Plots, Dwellingup District;
Kent Block, Harvey District;
Ross Block, Harvey District.

The Inglehope Plots logs were either fresh-sawn or stockpiled for three to four months before milling, and the standard log specification for small regrowth eucalypt logs used in the study is given in Appendix 1 of the present review.

The sawing pattern based on Waugh (1980) was followed, using a twin-edged saw with overhead beam feed for initial breakdown, and a vertical bandsaw for resawing. The appearance grade timber produced was graded to WURC Grading Rules (Appendix 2), which are similar to the specifications of the 'Industry Standard for Seasoned, Sawn and Skip-dressed WA Hardwoods', subsequently published (FIF (WA) 1992). The latter is now the standard reference.

The dimensions and green sawn recoveries from the logs from the different areas are given in Table 1.

The combined data showed that sawn graded recovery was not affected by log length, but increased significantly with increasing log diameter. Apart from the constraints of milling small diameter logs, brittle heart was the major factor reducing recovery, followed by knots, rot, kino, wane and insect damage.

Brennan and Pitcher (1992) also assessed green sawn recoveries from regrowth jarrah grown under different stand densities in the Inglehope Plots, Dwellingup District. The nominal stand basal areas under bark of five different treatments ranged from 7.0 to 22.0 m^2 ha^{-1}, but only the lowest three basal area treatments (7.0, 11.0 and 15.4 m^2 ha^{-1}) were used for this study. Before thinning again the actual basal areas were 12.8, 17.7 and 21.8 m^2 ha^{-1} respectively. Both sawlogs and poles were extracted. The sawlog specification is given in Appendix 1.

The logs were broken down by two passes through a twin-edged saw with overhead beam feed to produce a centre baulk, and the baulk and wings were resawn on a vertical bandsaw or circular saw. Logs were either sawn fresh or milled after stockpiling under water sprays for three months. Log degradation was assessed, and bow and spring of flitches and boards measured to compare the two treatments, using combined data from the three stand basal areas.

Stockpiled logs had less end splitting than logs sawn fresh, which were stored in a dry stockpile until actually milled. The results indicated that in thinning the same basal area from different stands, the lowest stand basal area (thinned from 12.8 to 4.8 m^2 ha^{-1}) produced twice the number and 2.5 times the volume of sawlogs produced from the medium stand basal area (thinned from 21.8 to 15.8 m^2 ha^{-1}). The effects of log diameter class and log length were assessed for the combined data, and while the green sawn recovery increased with increasing log diameter, there was a trend to decreasing recoveries with increasing log length (which could be attributed to variations in stem straightness). The sawn recoveries from the fresh-sawn and stockpiled logs were 24.7 and 20.4 per cent respectively, but the mean s.e.d.u.b. (small end diameter under bark) figures were 22.6 and 20.2 cm, which would explain most of the variation. The graded recoveries for the combined material, using the WURC Grading Rules (Appendix 2), were as follows: Clear (12.1 per cent), Feature (32.2 per cent), Processing (16.6 per cent), Merchantable (37.7 per cent), and Reject (1.5 per cent). The major defects in Feature grade material were

TABLE 1
Mean small end diameter (s.e.d.u.b.), log length and green sawn recovery percentage of timber milled from four different log sources.

LOG SOURCE	S.E.D.U.B. (cm) MEAN	S.D.	LOG LENGTH (m) MEAN	S.D.	RECOVERY (%) MEAN	S.D.
Banksiadale Road	21.2	4.3	3.6	1.2	21.6	8.3
Inglehope Plots						
(fresh-sawn)	22.8	5.4	3.4	1.1	25.6	10.2
(stockpiled)	20.4	3.4	3.6	1.1	21.4	8.7
Kent Block	19.3	3.9	3.3	0.8	21.2	8.4
Ross Block	20.9	3.6	5.0	1.0	26.4	8.2
Mean	20.9	5.3	3.8	1.2	23.2	9.2

epicormics, in Processing grade skip, knots and epicormics, and in Merchantable grade surface checks, knot holes, knots, gum veins and skip.

A study of sawn recoveries of regrowth jarrah, which actually included some karri logs, assessed two grades of regrowth jarrah logs and a single grade of regrowth karri logs that were substantially smaller than the mature logs currently supplied to industry (White and Siemon 1992). Four log size classes were assessed, with combinations of 15-19.9 cm or 20-30 cm s.e.d.u.b. and 2.4 m or 3.6 m length. The log specifications were: (1) Regrowth 1st Grade logs had minimum 50 per cent millable wood at the worst end, with maximum sweep of 30 mm in any 2 m length in one direction only. (2) Regrowth 2nd Grade logs had minimum 30 per cent millable wood at the worst end, with similar sweep provision. In both grades minimum acceptable log length was 1.2 m, and minimum s.e.d.u.b. was 150 mm. The sawing strategies used were designed to produce structural timber, boards, or a combination of both products. Any defects that required docking to upgrade the boards were assessed.

Analysis of the data indicated significant differences in sawn graded recovery between species and grade ($p < .001$) which was the result of 2nd Grade jarrah logs producing lower grade timber. As expected, log size class and the species *x* size class interaction were significantly different at the same probability level. The mean log diameter and graded recoveries in each log size class are given in Table 2.

The mean s.e.d.u.b. figures for 1st Grade jarrah logs indicate some bias in sampling with three treatments around 20 cm in the 15-19.9 cm s.e.d. class (Table 2). However, the average 5 cm difference between the two log diameter classes provides adequate variation. The ungraded sawn recoveries were closely associated with log size classes, and long slender logs (3.6 m, 15-19.9 cm) gave lowest recoveries. The 1st Grade logs in the largest diameter class (20-30 cm) produced a mean 35.8 per cent ungraded recovery, similar to that reported from industry milling of mature logs. The mean graded recovery over the three treatments in this diameter class was 23.8 per cent (Table 2).

The timber was graded into structural or appearance grades, as discussed below.

The mean graded recoveries in the smallest size class (2.4 m, 15-19.9 cm s.e.d.) showed major differences between 1st Grade jarrah and the other two log sources. As expected, the 2nd Grade jarrah logs produced low recoveries, but log quality was obviously a problem in 1st Grade karri logs with defects that could not be predicted by inspection of log ends.

The major defects docked from structural timber to comply with Structural Grade 3 of AS2082-1979 (Standards Association of Australia 1979) or from boards to comply with Appearance Grades 1 and 2 of AS 2796-1985 (Standards Association of Australia 1985), in decreasing order of occurrence, were as follows :

1st Grade jarrah	wane, knots, end splits
2nd Grade jarrah	rot, gum veins, knots
1st Grade karri	knots, insect attack

A detailed description of defect occurrence is given in White and Siemon (1992).

TABLE 2

Mean graded recovery from different sawing strategies for graded regrowth logs in different length and diameter classes.

			1ST GRADE JARRAH		2ND GRADE JARRAH		1ST GRADE KARRI	
Sawing Strategy	Log length (m)	s.e.d. Class (cm)	Mean s.e.d.u.b. (cm)	Mean graded recovery (%)	Mean s.e.d.u.b. (cm)	Mean graded recovery (%)	Mean s.e.d.u.b. (cm)	Mean graded recovery (%)
S	2.4	15-19.9	20.0	25.1	18.7	0.0	17.4	1.5
B	"	"	19.7	28.4	17.7	4.5	17.8	16.2
B & S	"	"	19.7	24.6	18.7	8.9	18.6	5.6
S	2.4	20-30	25.4	30.4	26.0	6.5	25.4	23.2
B	"	"	25.5	35.7	26.6	10.7	27.5	51.9
B & S	"	"	23.0	27.2	23.0	12.6	26.1	29.3
S	3.6	15-19.9	20.0	14.3	18.4	0.0	18.1	13.4
B	"	"	19.9	13.9	18.8	0.6	18.2	10.8
B & S	"	"	18.3	10.1	19.1	1.6	18.8	13.7
S	3.6	20-30	25.6	26.7	25.4	5.5	26.3	24.0
B	"	"	24.8	22.1	24.5	2.1	27.5	14.6
B & S	"	"	26.9	22.5	26.5	5.1	27.0	26.1

S = structural timber
B = boards

Karri

White (1989c) reported the results of a regrowth karri sawmilling trial after two years stockpiling logs under water sprays. While stockpiling under water sprays is essential, as explained previously, the trial was designed to assess whether long term stockpiling produced any adverse effects on log quality. The logs were sawn on a twin-edged saw with overhead beam feed for initial breakdown and a circular resaw, using a sawing pattern based on Machin (1981). Logs exceeding 40 cm s.e.d.u.b. were broken down on an old sizing carriage. The green structural grade products were graded to AS 2082-1979 (Standards Association of Australia 1979), and appearance products to TAS-G4 (1985) (FPA (WA) 1985) and AS 2796-1985 (Standards Association of Australia 1985) after drying in a progressive tunnel kiln, and dressing. The green timber was stored under water spray and regraded after three months to assess possible reduction in growth stresses and therefore reduced bow and spring.

The mean log size was 32 cm s.e.d.u.b. The recoveries are given in Table 3.

Kino and brownwood associated with rot were the major factors for downgrading structural grades, but in the small volume of appearance grade material milled, insect damage was the major factor. Bow was considerably reduced in the green structural timber after three months storage under water sprays.

The major karri sawmilling study assessed structural and appearance grade timber milled from six different sites in the Southern Forest Region, representing a range of age classes (49-70 years) and dominance classes (dominant to suppressed stems) (Brennan *et al.* 1991). Basic details of the plots, which represent the range of site productivity in older regrowth stands, are given in Table 4.

The logs were sawn into structural timber (40 or 50 mm thick), and appearance grade boards (30 mm thick) that were air-dried for nine months before final drying to 8 per cent moisture content in a kiln. Structural timber was graded to AS 2082-1979 (Standards Association of Australia 1979); appearance grade timber was graded using WURC Grading Rules (Appendix 2).

Brennan *et al.* (1991) gave detailed results on log size distribution, and structural and appearance grade recoveries for each plot, showing the effect of site quality and dominance class.

The mean recoveries of timber milled from these regrowth karri logs are compared using site quality, log position and dominance class (Table 5). The overall relationship between log diameter class and green-sawn recoveries is shown in Figure 2.

The occurrence of defects in timber from each site type was assessed by Brennan *et al.* (1991). The major variation was in the incidence of borer damage, where the percentage of pieces of timber affected ranged from 34 per cent in Plot 4 to 87 per cent in Plot 2. While there was some rot associated with this borer damage, the overall occurrence of rot and brownwood varied in each plot. Incidence of knots, gum veins, sapwood, etc. was uniform.

The combined regrowth jarrah and karri study by White and Siemon (1992) was reported previously.

Twelve-year-old karri logs grown on a rehabilitated bauxite minesite were one of four species assessed by milling 18 mm thick appearance grade boards suitable for panel production (Brennan 1992). Although logs were comparatively large (mean s.e.d.u.b. and 21.9 cm), the dried dressed recovery of 10.8 per cent was low because of defects attributed mainly to borer damage.

TABLE 3

Green sawn structural and appearance grade recoveries from milling regrowth karri logs.

Structural Grade	Recovery (%) (based on log volume)
1	10.5
2	31
3	11.1
4	1.3
Reject	4.2
Appearance Grade	
Furniture	0.02
Standard	0.33
Utility	0.03
Commons	0.54

TABLE 4

Stand description of regrowth karri trees from six sites in the Southern Forest Region.

Plot No.	Location	Stand Age (years)	Site	Basal Area (m^2ha^{-1})	Stocking (stems ha^{-1})
1	Murtin Block	70	Very low	30.4	304
2	Sutton	58	Low	39.0	288
3	Channybearup	55	Med	30.3	460
4	Channybearup	49	Med	43.7	631
5	Court	53	High	23.8	364
6	Yanmah	51	Med	36.8	519

TABLE 5

Mean recoveries of timber by site quality, log position and dominance class.

Site Quality	Recovery (%)	Log Position	Recovery (%)	Dominance Class	Recovery (%)
High	36.6 (11.9)[a]	Butt	30.7 (12.8)	Dominant/ co-dominant	32.8 (11.4)
Medium	27.4 (13.7)	Mid	28.8 (10.6)	Sub-dominant/ suppressed	19.6 (12.4)
Low	20.4 (13.1)	Crown	16.4 (12.5)		

[a]S.D. is given in parentheses below the mean value.

Marri

While marri is a major species in the forests of south-west WA, its use for sawn timber has been restricted because of extensive occurrence of kino veins. It has been used for structural purposes, weatherboards and case material, but has potential for furniture manufacturing when the timber is comparatively free of kino veins.

White (1989a) described a sawmilling trial of regrowth marri from Pimelia Plantation in Pemberton District, which produced structural and some appearance grade products. The logs had been stockpiled under water spray, and milling was done using a twin-edged saw and two-operator resaw bench. The green recovery was 35.1 per cent, which reduced after docking to remove large knots and kino veins.

The timber was dipped in borax solution to prevent the powder post borer (*Lyctus* spp.) attacking the sapwood, and then block-stacked. The small quantity of appearance grade material produced was kiln-dried, dressed, and graded to AS 2796-1985 (Standards Association of Australia 1985), and the green structural material was graded to AS 2082-1979 (Standards Association of Australia 1979). The final recovery was 23.0 per cent structural grade and 3.0 per cent appearance grade, a total of 26 per cent.

Goldfields species

Assessment of response to sawmilling was part of an overall study of the utilization potential of six species growing in the eastern Goldfields of WA, *viz*. Dundas blackbutt, York gum, gimlet, redwood, mulga and northern cypress pine (Brennan and Newby 1992).

Logs were sawn on a 'Forester 150' horizontal bandsaw, mainly into 14 mm thick boards, with some flitch material cut for demonstration purposes. There were problems with milling because of the high wood density of the species (except for the cypress pine). Feed speeds through the saws had to be reduced, and saw life before sharpening was required was reduced. Drying rates were about one-third of those achievable for jarrah and karri boards of the same thickness, because of the high density of the eucalypt and mulga timbers.

Tasmanian blue gum

Tasmanian blue gum is the major species grown specifically for pulp and paper production in south-west plantations, but it has the potential to be a major source of sawlogs for structural and appearance grade timber.

Thomson and Hanks (1990) milled forty-one 24-year-old Tasmanian blue gum logs from Willow Springs Arboretum in Nannup District, to produce either 40 or 50 mm thick structural timber or 30 mm thick appearance grade boards. A twin-edged saw with overhead beam feed was used for initial breakdown, and a vertical bandsaw for resawing. Sweep was the most common defect found in the logs, but large branches and angular swellings were also found. End splitting caused losses in recovery, even when freshly docked during preparation before milling.

The operators considered Tasmanian blue gum more difficult to mill than regrowth jarrah and karri, and a slower feed speed was required through the saws. Sixty-four per cent of the sawn recovery met the requirements of Structural Grade 3 (SG3) or better (Standards Association of Australia 1979), and 39 per cent of this was Structural Grade 1. Docking of merchantable material to remove defects near the ends of the pieces would increase recoveries of SG3 or better to 79 per cent.

The major defect in the structural timber was excessive bow (which indicated high levels of growth stresses),

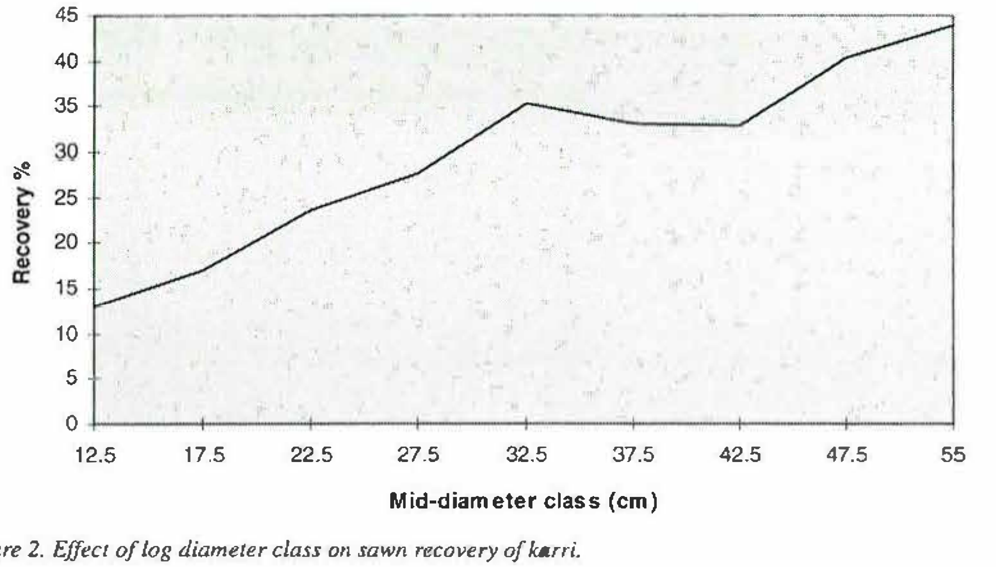

Figure 2. Effect of log diameter class on sawn recovery of karri.

followed by knots, kino veins, borer holes, spring and shakes. In the appearance grade timber, grading was carried out using the principle of 'phantom docking' (i.e. the position for docking is marked and lengths of different grades estimated, without the actual docking being done). Only 20.1 per cent of the 1.2 m^3 milled made Clear or Feature Grades, with 10.5 per cent Processing, 68.7 per cent Merchantable, and 0.7 per cent Reject material. The incidence of kino veins was the major reason for the low recovery of Clear or Feature grades, averaging more than one per board. Knots were the major defect on 32.2 per cent of the boards, followed by surface checking, cup, and skip. In general, the results indicated that appearance grade timber for furniture or joinery use would be a small percentage of the sawn timber, but structural timber recoveries were satisfactory.

Brennan *et al.* (1992) carried out a sawmilling study of very young Tasmanian blue gum, using 8-year-old trees from a former pastured site and 10-year-old trees from a former bush site. The initial breakdown was done using a 'Forestor 150' horizontal bandsaw, and boards were resawn to 18 mm thickness using a vertical bandsaw. Details of the drying schedules used are given, as well as basic data on shrinkage and density of this young plantation-grown material (Brennan *et al.* 1992).

The green sawn recovery of 18 mm thick boards was 52.7 per cent, with ex-pasture and ex-bush material producing 55.2 per cent and 49.9 per cent respectively. Dried dressed recovery of 10 mm thick boards (allowing for shrinkage and dressing) was 28.3 per cent based on log volume.

The data are broken down further into log s.e.d.u.b. class and log length class. The shrinkage in width of the mainly backsawn boards was 9.5 per cent, and in thickness 6.9 per cent. The mean basic density was 470 kg m^{-3}. The boards were subsequently used for VALWOOD® panel manufacture, but that aspect is outside the scope of this report.

Rose gum

The rose gum logs used in Hanks' (1990) sawmilling trial were first thinnings from a 1964 planting in the Willow Springs Arboretum in Nannup District. Two sawing methods were assessed : (1) 'Forestor 150' horizontal bandsaw for initial breakdown of logs, and resawing on a vertical bandsaw; (2) twin-edged saw for initial breakdown, and resawing on a vertical bandsaw. Boards were milled to 30 mm thickness, and then initially air-dried to below fibre saturation point and kiln-dried to final moisture content at temperatures increasing from 30° C to 80° C for over 2 h, then 80° C for 6 h.

The logs milled using the 'Forestor 150' for initial breakdown had green sawn recovery of 39.4 per cent, compared with the twin-edged saw breakdown and recovery of 32.1 per cent. With the former, logs were slightly larger, the saw has a smaller kerf (i.e. width of cut) and taper sawing can be done, which produces better recovery.

The dried dressed recoveries were 24.5 per cent and 20.0 per cent respectively. However, only 22.4 per cent of the boards produced were Clear or Feature grade, with 23.3 per cent Processing, 52.0 per cent Merchantable, and 2.3 per cent Reject. The major defects were knots in 50.3 per cent of boards, kino in 24.0 per cent, and borer damage in 20.2 per cent. Many boards were downgraded from Clear to Feature because of epicormics.

Red mahogany

The logs milled in this trial by Raper (1990) came from 23-year-old trees grown on a rehabilitated bauxite minesite in Turner Block, Dwellingup District. The mean s.e.d.u.b was only 190 mm (S.D. 2.4 mm), and mean length 2.7 m (S.D. 0.8 m). Two passes through a twin-edged saw with overhead beam feed produced a central baulk which was resawn on a vertical bandsaw to produce 115 x 34 mm pieces. Defects were docked, and a phantom grading done at the docker. After two weeks curing at high humidity, the timber was air-dried to below fibre saturation point, and then kiln-dried at 90°C to final moisture content. The boards were then pre-dressed to 100 x 25 mm and graded to Structural Grade 3 of AS 2082-1979 (Standards Association of Australia 1979).

The results confirmed the overall low quality of the logs, with a high incidence of defects. Some logs were actually rejected. The occurrence of decayed wood around branch stubs was of particular concern, and wandering heart was a problem. Grading at the docker before drying indicated the following defects: knots - 97.4 per cent of boards affected; sapwood - 94.9 per cent; borer damage - 76.9 per cent; gum pockets - 76.9 per cent; and rot - 28.2 per cent, i.e. combination of defects occurred in most boards. The WURC Grading Rules (Appendix 2) were used in the phantom docking exercise. There was no Clear grade material, 5.3 per cent Furniture grade, 16.1 per cent Processing, 68.5 per cent Merchantable, and 10.1 per cent Reject. Large knots, gum pockets, borer damage and rot were the major defects, resulting in the high percentage of Merchantable grade. The SG3 recovery after drying and dressing was only 12 per cent of log volume.

Twelve-year-old red mahogany logs grown on a rehabilitated minesite were milled into 18 mm thick boards, together with karri, spotted gum and tallowwood (Brennan 1992). The red mahogany boards were not kiln dried because the high incidence of defect, largely attributable to borer damage, prevented them satisfying the requirements for appearance grade products.

Spotted gum

The 13.5 per cent dried dressed recovery (based on log volume) of spotted gum timber from 12-year-old trees grown on a rehabilitated minesite was mainly attributable to the small log size (mean s.e.d.u.b. of 14.4 mm). There were few problems with defects in the timber (Brennan 1992).

Tallowwood

This material was 19-year-old timber, also milled from logs from a rehabilitated minesite. It was supplied to the WURC as 25 mm thick boards, which were dressed green to 18 mm before drying. Recovery data based on log volume were not available, but there were no particular problems with defects (Brennan 1992).

GENERAL DISCUSSION

The series of stockpiling and sawmilling trials carried out at the WURC since 1986 has provided useful information on the potential of small regrowth eucalypts for processing into either structural or appearance grade timber products. The effects of silvicultural treatment on jarrah log production were discussed by Brennan and Pitcher (1992), and the effects of site quality and dominance class on karri log production by Brennan *et al.* (1991).

General experience has confirmed the importance of minimizing the time between felling trees and either stockpiling or processing the logs. Stockpiling under water sprays is essential during the summer months to prevent end splitting, minimize insect attack, and possibly to reduce growth stresses. White (1990) found both high pressure and low pressure spray systems were effective. The former was more expensive but had advantages where water availability was not a problem. The supplementary research by Brennan *et al.* (1990) found that a watering schedule of 15 min on in each 3 h did not adversely affect log quality. Extended storage under water sprays was shown by White (1989c) to have no adverse effects on karri logs, just an economic disadvantage.

Sawmilling small regrowth eucalypt logs has one major disadvantage, *viz.* the occurrences of growth stresses, and *Eucalyptus* is the most susceptible of all genera (Kubler 1987). The problem decreases with increasing stem diameter, but the major effect in small logs is decreased sawn recoveries and increased bow and spring in the sawn timber. The production of backsawn boards (with growth rings parallel to the width) is recommended because bow can be reduced in drying, but the spring in quarter sawn boards cannot .

The trials confirmed that sawn recovery is closely related to log diameter, but the economies of milling logs smaller than 20 cm s.e.d.u.b. would be very doubtful because of low recoveries. The productivity rates were not assessed in any of the studies, but would obviously be substantially reduced using a small-log resource. Log length generally had no effect on sawn recoveries provided that stem straightness was acceptable; the exceptions were the Brennan and Pitcher (1992) trial where sawn recoveries decreased in long slender logs, and the White and Siemon (1992) trial where the 2.4 m, 15-19.9 cm class logs had higher recoveries than the 3.6 m, 15-19.9 cm class.

The milling equipment used for processing small regrowth logs has a significant effect on sawn recoveries, with 7-8 mm kerf of twin-edged circular saws compared with 3 mm kerf of bandsaws. The twin-edged saw has the advantage of reducing the effect of growth stresses by producing a stable central flitch, although the wings are bowed. The alternative method of using a linebar carriage and taper sawing to process regrowth eucalypt logs has been used for ash-type eucalypts. Accuracy of sawing has a major effect on the subsequent graded dried dressed recoveries, because undersized boards can twist between the stickers (i.e. strip sticks) during drying and cause problems when dressing the timber. The results of the WURC trials consequently provide a conservative guide to the ungraded sawn recoveries from regrowth and plantation-grown eucalypt logs.

Apart from the smaller log dimensions, the other major factor encountered in the sawmilling trials was the high incidence of defects, *viz.* knots, borer damage, rot, bow and spring were the major defects encountered. Consequently, there were major differences between the ungraded and graded recoveries in different species. The 2nd Grade jarrah and 1st Grade karri milling study reported by White and Siemon (1992) and the red mahogany study (Raper 1990) provided good examples.

Regrowth jarrah generally provides satisfactory sawn timber, although it is susceptible to borer (mainly bardi) and fungal attack. Branch size, and hence knot size, tend to be less significant. The karri logs assessed had a higher incidence of borer larvae attack, either the bullseye borer (*Tryphocaria* sp.) or cossid moth (*Xyleutes* sp.), as well as brownwood, which has been confirmed as incipient rot. Growth stress levels are comparatively high, and bow and spring reduce the graded recoveries.

Marri, like most bloodwoods, is susceptible to kino formation as a result of wounding, whether by insects, fire or mechanical damage. The kino veins produced are the major reason for the species' limited use as timber, as well as regular occurrence of damage by bardi or bullseye borers. The size of the resource means that it is essential to find an economic use, and it would be a definite advantage when value-added timber conforming to FIF (WA)(1992) specifications can be milled.

The sawmilling studies of Tasmanian blue gum (Thomson and Hanks 1990; Brennan *et al.* 1992) provided useful data on a rapidly expanding resource. Although the major planned use of the species is pulp and paper production, there is definite potential for structural and appearance grades. Although Thomson and Hanks (1990) produced low recoveries of appearance grade timber, there is a need for light coloured timber for furniture and flooring. Brennan *et al.* (1992) milled thin boards, which included reasonable proportions of face grade timber. The fast growth rates of the species could justify pruning of potential sawlogs to produce value-added products.

The rose gum sawmilling study (Hanks 1990) produced satisfactory results, but the red mahogany study (Raper 1990) indicated that wood quality was a major problem with trees grown on a rehabilitated minesite, owing to borer damage and rot associated with large knots.

Spotted gum and tallowwood grown on similar sites have potential for the production of appearance-grade timber.

Overall, the trials produced useful data on the sawn recoveries of structural and appearance grade timber milled from small regrowth logs of several eucalypt species. They also indicated the need for an integrated approach to carry out basic research on susceptibility to borer and fungal attack, and applied research on the interaction between borer, rot, silvicultural treatment and wood quality. A karri research strategy has been prepared and an integrated research project initiated.

REFERENCES

Brennan, G.K. (1988). Splitting of WA sheoak (*Allocasuarina fraseriana*) logs stored under water spray or dry stockpiled. Department of Conservation and Land Management, WURC Report No. 5.

Brennan, G.K. (1992). Processing eucalypts grown on a rehabilitated bauxite minesite. Alcoa of Australia Ltd, Unpublished Report.

Brennan, G.K. and Newby, P. (1992). Potential of Western Australian Eastern Goldfields timbers for high quality wood products. *Australian Forestry* **55**, 74-79.

Brennan, G.K and Pitcher, J.A. (1992). Sawing regrowth jarrah grown under different silvicultural prescriptions. Department of Conservation and Land Management, WURC Technical Report No. 32.

Brennan, G.K. and Ward, S.L. (1990). Recovery from regrowth jarrah sawlogs. Department of Conservation and Land Management, WURC Technical Report No. 20.

Brennan, G.K., Glossop, B.R. and Mathews, L.R. (1990). Stockpiling of regrowth jarrah and karri logs using different watering schedules. Department of Conservation and Land Management, WURC Report No. 16.

Brennan, G.K., Glossop, B.R. and Rayner M.E. (1991). Sawmilling regrowth karri of differing age and dominance class from a range of site types. Department of Conservation and Land Management, WURC Technical Report No. 29.

Brennan, G.K, Hanks, W.R. and Ward, S.L (1992). Processing plantation grown Tasmanian blue gum. Department of Conservation and Land Management, WURC Technical Report No. 41.

FIF (WA) (1992). Industry standard for seasoned, sawn and skip-dressed WA hardwoods. Forest Industries Federation (WA), Perth.

FPA (WA) (1985). Appearance graded Western Australian hardwoods for furniture use: TAS - G4 (1985). Forest Products Association (WA), Perth.

Hanks, W.R.(1990). Sawmilling trial of rose gum. Department of Conservation and Land Management. WURC Technical Report No. 17.

Kubler, H. (1987). Growth stresses in trees and related wood properties. C.A.B. International, *Forest Products Abstracts* **10** (3): 61 - 119.

Machin, J. (1981). The challenge of small diameter regrowth eucalypts. *Australian Forest Industries Journal* **47** (1), 48-50.

Raper, S.C. (1990). Sawmilling of red mahogany grown on a rehabilitated minesite. Department of Conservation and Land Management, WURC Technical Report No. 19.

Standards Association of Australia (1979). Visually stress-graded hardwood for structural purposes: AS 2082 - 1979. Standards Association of Australia, Sydney.

Standards Association of Australia (1985). Timber - seasoned hardwood -milled products: AS 2796 -1985. Standards Association of Australia, Sydney.

Thomson, A.B. and Hanks, W.R. (1990). Sawmilling study of Tasmanian blue gum grown in Western Australia. Department of Conservation and Land Management, WURC Technical Report No. 13.

Waugh, G. (1980). The potential of plantation eucalypts for sawlog production. CSIRO Division of Building Research, Reprint 1001.

White, K.J (1989a). Sawmilling trial of regrowth marri. Department of Conservation and Land Management, WURC Technical Report No. 6.

White, K.J (1989b). Regrowth jarrah stockpile and sawmilling trial. Department of Conservation and Land Management, WURC Technical Report No. 7.

White, K.J (1989c). Sawmilling of regrowth karri logs. Department of Conservation and Land Management, WURC Technical Report No. 8.

White, K.J. (1990). Comparisons of low and high pressure watering systems for stockpiling regrowth jarrah logs. Department of Conservation and Land Management, WURC Technical Report No. 14.

White, K.J and Siemon, G.R. (1992). Sawn recoveries from regrowth jarrah and karri graded logs. Department of Conservation and Land Management, WURC Technical Report No. 39.

APPENDIX 1

Specification for regrowth sawlogs.

1. Small end diameter under bark (s.e.d.u.b.)

   Minimum 150 mm
   Maximum 350 mm

2. Large end diameter under bark (l.e.d.u.b.)

   Minimum 175 mm
   Maximum 400 mm

3. Length

   Any of the following, aiming for long lengths:

   2.4, 3.6, 4.8, or 6.0 m

4. Quality

   Straightness - maximum 30 mm sweep in any 2.1 m length.
   Log ends at least 50 per cent solid wood.
   Both log ends cut square.
   No deformities such as dry sides, bumps or protrusions.

Note : Logs may be docked to shorter length if sweep is excessive or short lengths are required.

APPENDIX 2

WURC Specification for grading regrowth eucalypt timber (1990).

These grade rules are intended for use with regrowth eucalypts, particularly jarrah. However, material from mature trees may also be graded to these rules.

The rules are intended for use in the sorting of dry, pre-dressed boards into one of four grades. The sizes are based on the optimum metric size, taking account of increased shrinkage, section and length requirements of the appearance grade markets, as well as the capacity of the log resource to provide these sizes.

The grades are:

CLEAR GRADE
FEATURE GRADE
PROCESSING GRADE
MERCHANTABLE GRADE.

These grades will apply to sections dressed to 2 mm over the finished size of 10, 30, 40, 60, 80, 100, 150, or 180 mm.

Lengths will range from 0.6 m, in increments of 0.3 m, to a maximum of 3.6 m. Timber must be seasoned to 10 per cent moisture content or below.

Each piece will be free of :

- Compression failures and other fractures including brittle heart and shake
- Decay and included bark
- End splits.

CLEAR GRADE

Clear grade, as the name implies, will be clear of all imperfections excepting sapwood, which may occur on the back faces and up to three-quarters of the width of each edge. Sapwood within these limits will be accepted for the full length of the piece.

FEATURE GRADE

Will carry features to the following limits.

- **Sapwood** - No limit on one face or two edges; other face must be clear of sapwood.
- **Branch occlusions** or **Birds eye** : Sound, intergrown with seasoning splits up to 1 mm wide confined within the area of the feature.
- **Surface checks** : Length of individual checks not exceeding 200 mm. Width less than 1 mm. Only one check in any 50 mm width board face.
- **Knots** : Intergrown and sound not exceeding half the width of the face or 50 mm (measured at right angles to arrises). Separated in length by twice the width of the face.
- **Knot occlusions or holes** : Free from bark and decay. Associated voids not to exceed more than 25 mm^2, frequency as for knots.
- **Tight gum veins** : As for surface checks.
- **Pin holes** : Clean edge less than 1 mm diameter. Not more than 10 holes in 10 000 mm^2.
- **Grub holes** : Clean edge up to 100 mm^2. Can occur on one face or one edge. Not more than one per linear metre.
- **Bow and spring** : Maximum of 2 mm in any length up to 1.8 m.
- **Skip and machine marks** : Less than 1 mm deep on either face of edge.

PROCESSING GRADE

Acceptable features.

- **Sapwood** : Unlimited.
- **Birds eye** : Unlimited.
- **Surface checks** : Up to 300 mm long and 1 mm wide. One check in any 50 mm width of face. Can occur on both faces.
- **Knots** : Intergrown from bark and decay. May contain fractures or voids up to 200 mm^2. Frequency unlimited.
- **Knot occlusions or holes** : Free from bark and decay, not exceeding 200 mm^2.
- **Gum veins** : 3 mm in width, maximum of 500 mm in length intergrown.
- **Gum pockets or streaks** : As for knots and holes.
- **Bow and spring** : 5 mm in any length up to 1.8 m.
- **Skip or machine damage** : On one face only, not to exceed 2 mm. On two faces not to exceed 1 mm.
- **Pine holes** : Up to 2 mm in diameter, not more than 20 in any 10 000 mm^2.
- **Grub holes** : Clean edge up to 100 mm^2.

MERCHANTABLE GRADE

May contain features in excess of the above grades but must maintain structural integrity.

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