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Adaptation of lentil (*Lens culinaris* Medik.) to Mediterranean-type environments: effect of time of sowing on growth, yield, and water use

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Abstract. This study examined the adaptation of lentil (*Lens culinaris* Medik. cv. Digger) to dryland Mediterranean-type environments of southern Australia and determined the effect of time of sowing on growth, yield, and water use. Phenology, canopy development, radiation absorption, dry matter production and partitioning, seed yield, and water use were measured from a range of sowing times at a number of field locations in south-western Australia in 1994, 1995, and 1996.

Contrary to previous results with poorly adapted cultivars, our study showed that lentil is well adapted to low to medium rainfall regions (300–500 mm/year) of south-western Australia and that seed yields greater than 1·0 t/ha and up to 2·5 t/ha can be achieved when sown early. Even in the dry season of 1994 when May–October rainfall was <200 mm, yields of approximately 1·0 t/ha were produced from early sowings. Seed yields were reduced with delayed sowing at rates of 4–29 kg/ha·day. Sowing in late April or early May allowed a longer period for vegetative and reproductive growth, rapid canopy development, greater absorption of photosynthetically active radiation, more water use, and, hence, greater dry matter production, seed yield, and water use efficiency than when sowing was delayed. Early-sown lentils began flowering and filling seeds earlier in the growing season, at a time when vapour pressure deficits and air temperatures were lower, and used more water in the post-flowering period when compared to those treatments where sowing was delayed. The values of water use efficiency for dry matter and grain production, and transpiration efficiency, for early-sown lentil (up to 30 kg/ha·mm, 11 kg/ha·mm, and 20 kg/ha·mm, respectively) were comparable to those reported for cereal and other grain legume crops in similar environments. The development of earlier flowering cultivars than Digger with greater dry matter production together with improved agronomic packages will increase and stabilise lentil yields in low rainfall environments of southern Australia.

Additional keywords: water use efficiency, early sowing.

Introduction

Grain legume (pulse) production in Australia is dominated by narrow-leafed lupin (*Lupinus angustifolius* L.) grown mostly in Western Australia (WA) (Siddique and Sykes 1997). Farmers in WA have benefited from growing narrow-leafed lupin on deep coarse-textured soils with a neutral to acidic pH for many years. However, this crop is poorly adapted to the neutral to alkaline calcareous red-brown earths, grey-brown clays, duplex soils, and shallow red earths that are widespread in regions throughout southern Australia which experience a Mediterranean-type climate. Farmers with these soil types are searching for pulses other than narrow-leafed lupin for inclusion in their cropping systems.

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Recent field studies conducted in the cropping regions of WA identified several pulses with good adaptation and a capacity to produce profitable yields. These include chickpea (*Cicer arietinum* L.), faba bean (*Vicia faba* L.), field pea (*Pisum sativum* L.), albus lupin (*Lupinus albus* L.), and several other promising species (Siddique *et al*. 1993, 1996*a* 1996*b*; Siddique and Loss 1996; Loss and Siddique 1997; Thomson *et al*. 1997). These studies have contributed to the emergence of commercial industries based on some of these crops in WA.

In the past, lentil (*Lens culinaris* Medik.) received little attention from both breeders and agronomists in Australia and attempts at commercial production by individual growers in the 1980s were largely unsuccessful due to a lack of adapted cultivars and basic crop management packages. In the early to mid 1990s, several improved red (*microsperma*) and green (*macrosperma*) lentil cultivars with earlier flowering than Laird or Callisto were selected from germplasm introduced from the International Center for Agricultural Research in Dry Areas (ICARDA), Syria, and released for commercial production in Victoria (J. B. Brouwer, unpublished data) and South Australia (M. Ali, unpublished data).

Previous studies in WA using ill-adapted lentil cultivars (e.g. Laird) and poor agronomic packages concluded that lentil has a narrow adaptation to this environment, and that its low yields would inhibit the wide scale development of a lentil industry in this State (Walton and Trent 1988). Similarly, lentil produced the lowest seed yield among the grain legume species studied by Siddique *et al*. (1993). Again, the cultivars used in this study (Laird and Callisto) were late flowering and suffered from difficulties with mechanical harvesting. Subsequent evaluation has shown that many of the cultivars released in Victoria and South Australia have much improved adaptation and seed yield in WA when compared with other old cultivars (Siddique *et al*. 1997).

At present, lentil is a fledgling export crop in Australia, largely based on the Victorian and South Australian varieties. The area has increased from less than 1000 ha in 1993 to about 15 000 ha in 1996 with substantial potential for further expansion (Siddique and Sykes 1997). Further expansion of lentil production requires the development of improved cultivars together with suitable agronomic packages. There is a large demand for lentil from the Indian sub-continent and other export markets (Siddique 1993), and given the high on-farm price of lentil at present ($A400), the yields required to generate profitable gross margins are not large when compared with other grain legumes.

In Mediterranean-type environments, seed yields can be optimised by matching crop development and growth with the timing and amount of rainfall received (Loss and Siddique 1994). This can be achieved by altering the time of sowing and by choosing a cultivar with an appropriate maturity pattern. The significance of time of sowing on seed yield in south-western Australia has been illustrated in cereals (Anderson and Smith 1990; Kerr*et al*. 1992), narrow-leafed lupin (Perry 1975), field pea (French 1990), chickpea (Siddique and Sedgley 1986), and faba bean (Loss and Siddique 1997). In general, these studies demonstrate high yield potentials when crops are sown soon after the first autumn rains compared with delayed planting. Early sowing enables the effective use of growing-season rainfall and stored soil moisture at sowing, greater dry matter production, earlier flowering and an improved harvest index. However, sowing early can also increase the risk of seedling mortality due to inadequate seed bed moisture, frost damage around flowering, and fungal diseases, while also minimising the opportunity for pre-sowing weed management. In overseas studies, lentil seed yields increased dramatically with early sowing in the Mediterranean environments of northern Syria (Silim *et al*. 1991). However, there is limited information on the adaptation and optimum time of sowing of lentil to maximise seed yields in southern Australia.

The aim of this study was to examine the adaptation of lentil to dryland Mediterranean-type environments by measuring the growth, phenology, canopy development, radiation absorption, biomass production, seed yield, and water-use efficiency of the best adapted cultivar (Digger) from a range of sowing times at a number of locations over 3 years in south-western Australia.

Materials and methods

Experimental design and management

Red lentil (*microsperma*) cv. Digger was sown at 4 dates ranging from early April to mid July at 3 sites in 1994, 6 sites in 1995, and 5 sites in 1996 (Table 1). Time of sowing was used as a treatment in these experiments to create a range of environmental conditions at each site and in each season. Field experiments were conducted at experimental stations or farmers' fields and represented a diverse range of environments within south-western Australia. As lentil is sensitive to waterlogging (Siddique *et al*. 1993; Erskine *et al*. 1994), the sites were selected to minimise the risk of waterlogging in susceptible regions by planting the experiments in the high parts of the landscape.

The field experiments were sown in a completely randomised block design and included 4 replicates. At all sites, the crop in the previous year was a cereal. Seeding rates were calculated using percentage germination and mean seed weight to achieve a density of 120 plants/m^2. The seed was inoculated with a commercial rhizobial inoculum (strain SU303) immediately prior to sowing. Plots were sown with a cone seeder and were

Table 1. Site, soil type, sowing dates and fertiliser, and seasonal rainfall (May-Oct.) at the sites in south-western Australia

Site	Soil type	Sowing date and fertiliser	May–Oct. rainfall (mm)	Long-term av.
		1994		
Merredin Agriculture WA Research Station (31°29′S, 118°12′E)	Reddish brown sandy clay loam (pH 6·0) over a yellowish red heavy clay (pH 7·8) at 30 cm	23 May, 6 June, 22 June, 4 July; 54 kg/ha of double superphosphate at sowing	168	212
Mullewa Agriculture WA Research Station (28°32′S, 115°30′E)	Well-structured deep silty clay loam with a surface pH of 8.0 and increasing to 9·0 at 30 cm; abundant lime segregations at 20 cm and deeper	25 May, 31 May, 10 June, 20 June; 70 kg/ha of double superphosphate at sowing	201	249
Northam Muresk Agricultural Research Institute (31°43′S, 116°41′E)	Red brown loam (pH 5·0), over reddish brown clayey sand (pH 6·1) at 90 cm; surface pH was increased to 6·0 with lime addition	12 May, 1 June, 15 June, 8 July; 113 kg/ha of superphosphate at sowing; 20 kg/ha of urea topdressed 16 August	256	368
		1995		
Gnowangerup Farmer's field site (33°57′S, 117°56′E)	Hypocalcic mesonatric brown sodosol; very shallow loam over brown sodic calcareous clay at 10 cm (hard setting grey clay)	24 May, 6 June, 19 June, 3 July; 100 kg/ha of diammonium phosphate at sowing	235	283
Merredin Agriculture WA Research Station	Reddish brown sandy clay loam (pH 6·0) ovet a yellowish red heavy clay pH 7·8) at 30 cm	13 May, 26 May, 13 June, 27 June; 80 kg/ha of diammonium phosphate at sowing	290	212
Mullewa Agriculture WA Research Station	Red sandy loam; pH 5·2 increasing to 5·8 at depth (30–40 cm)	12 May, 29 May, 12 June, 25 June; 100 kg/ha of diammonium phosphate at sowing	243	249
Northam Muresk Agricultural Research Institute	Red-brown loam (pH 50) over a reddish-brown, clayey sand (pH 5·5) at 40 cm	11 May, 24 May, 13 June, 6 July; 130 kg/ha of Agrich (14% N and 12% P) at sowing	407	368
Salmon Gums Agriculture WA Research Station (32°59′S, 121°37′E)	Kumarl sandy loam on salmon gum/mallee vegetation; pH 7·8 increasing to 8·4 (20–30 cm)	26 May, 9 June, 22 June, 6 July; 100 kg/ha of diammonium phosphate at sowing	188	204
Three Springs Farmer's field site (29°34′S, 115°45′E)	Reddish brown coarse sandy loam over sandy clay loam; pH 5·2 increasing to 6·6 (20–30 cm)	8 May, 19 May, 30 May, 20 June; 96 kg/ha of diammonium phosphate at sowing	271	293
		1996		
Cunderdin Agricutural College (31°39′S, 117°114′E)	Reddish brown sandy clay loam with a surface pH 6·0 increasing to 6·5 at 30 cm	16 May, 22 June, 5 July, 19 July; 107 kg/ha of Agrich at sowing	302	274
Merredin Agriculture WA Research Station	Reddish brown sandy clay loam (pH 6·0) over a yellowish red heavy clay (pH 7·8) at 30 cm	16 April, 15 May, 17 June, 5 July; 75 kg/ha of diammonium phosphate at sowing	255	212
Mullewa Agriculture WA Research Station	Red sandy loam with a surface pH 4·3 increasing slightly to 4·6 at 30 cm	23 April, 9 May, 31 May, 14 June; 75 kg/ha of diammonium phosphate at sowing	327	249
Nyabing Farmer's field site (33°33′S, 118°06′E)	Hard setting grey clay with a surface pH 6·0 increasing to 7·6 at 30 cm	21 May, 4 June, 23 June, 28 June; 75 kg/ha of diammonium phosphate	300	292
Salmon Gums Agriculture WA Research Station	Kumarl loam, solonised brown soil with a surface pH 7·9 increasing to 8·5 at 10–20 cm	13 June, 1 July, 11 July, 22 July; 81 kg/ha of Agras no. 1 at sowing	226	204

1·44 m wide (8 rows, 18 cm apart) and 20 m long at all sites except Merredin in 1995 and 1996, where they were sown as double plots (i.e. 2×1·44 m wide and 20 m long) to allow for intensive plant sampling and crop water use measurements.

Weeds were controlled before sowing with 1 L/ha of Sprayseed (paraquat/diquat 250 g a.i./L) or Roundup (glyphosate 450 g a.i./L), plus 2 L/ha of Bladex (500 g a.i./L of cyanazine). In some cases, 0·75 L/ha of diuron was also used to control weeds post-sowing, but before the crop had emerged. Grass weeds that emerged after crop emergence were controlled with 400 mL/ha of Fusilade (212 g a.i./L of fluiazifop-p-butyl) or 1·0 L/ha of Verdict (104 g/L of haloxyfop), while broadleafed weeds were minimal. Redlegged earth mite (*Halotydeus destructor*), lucerne flea (*Sminthurus viridis*), aphids (*Aphis craccivora*), and pod borer (*Helicoverpa* sp.) were controlled with insecticides when required.

Seed yields were determined from machine harvests for all sites, but more detailed measurements were carried out at the Merredin and Northam sites. The Northam site was replaced by Cunderdin in 1996 for intensive sampling.

Observations and sampling procedures

Climatic data

Daily rainfall was recorded at each site or obtained from nearby weather stations or farmer records. At Merredin minimum and maximum temperatures were recorded at the site by an automatic weather station.

Phenology

The times from sowing to the following phenological stages were estimated in each plot: (*i*) first flower, when 50% of the plants had at least 1 fully opened flower with the corolla visible; (*ii*) first pod, when 50% of the plants had their first pod visible; (*iii*) maturity, when the earliest (lowest) pods on 95% of plants were light brown. At this time, the later formed (highest) pods were well filled, but had a slight green colour.

Dry matter, green area index, and radiation absorption

At Merredin in 1994, 1995, and 1996, each plot was sampled for dry matter and leaf area every 2 weeks from about 4 weeks after sowing until maturity. Above-ground dry matter was measured by cutting off plant shoots at ground level in a 0·5-m^2 quadrat in 2 positions in each plot and weighing the sample after it was dried in a forced-draught oven at 70°C for 48 h. At the same time, 10 uniform plants were collected randomly from each plot and the number of nodes on the main stem was recorded. Each plant was then separated into stems, leaves, flowers, pods, and seeds. The area of green leaves and stems was measured by passing them through a Licor Inc. (Lincoln, Nebraska) LI-3100 area meter and all plant components were dried at 70°C for 48 h and weighed separately.

The partitioning of dry matter was calculated on a m^2 basis from the proportions of each component in the 10-plant sample and the quadrat dry matter measurement for each plot. Green area index (GAI) was calculated from the green area of the 10-plant sample multiplied by the ratio of the quadrat and 10 plant dry weights.

In 1995 and 1996 at Merredin, photosynthetically active radiation (PAR) was measured near midday every 2 weeks using a Sunfleck Ceptometer (Decagon; Pullman, Washington, USA) held perpendicular to the rows at 5–10 cm above the crop canopy and below the canopy at 2–3 cm above the soil surface. The percentage of absorbed radiation (PAR) by the crop was calculated using the following equation:

$$\mathrm{R\ absorbed} = [(\mathrm{R_1} - \mathrm{R_2} - \mathrm{R_3} + \mathrm{R_4})/\mathrm{R_1}] \times 100$$

Where R_1 is the incident flux about 1 m above the canopy; R_2 is the upward reflected flux above the canopy, obtained by inverting the ceptometer above the canopy; R_3 is the transmitted flux at the base of the canopy; and R_4 is the reflected flux from the soil below the canopy.

Water use

Evapotranspiration (E_t) or crop water use was determined at Merredin in 1995 and 1996 according to the equation:

$$\mathrm{E_t} = \Delta\theta + \mathrm{P}$$

where $\Delta\theta$ is the change in stored water in the profile between 0 and 170 cm in the period considered and P is the recorded rainfall. Surface runoff and drainage below 170 cm were not observed and were assumed to be negligible. For the period between sowing and the soil water measurement, E_t was assumed to be the same as bare soil evaporation (Es), and was estimated using the bare soil evaporation model of Ritchie (1972).

At sites other than Merredin, E_t was estimated using a modified French and Schultz (1984) approach. Soil evaporation over summer (1 November–31 March) was estimated using the model of Ritchie (1972) and the soil parameter values listed earlier. Stored soil water at the start of the growing season (1 April) was then estimated by difference between rainfall received over summer and bare soil evaporation over this period. The estimate of stored soil moisture was then added to rainfall received over the growing season (1 April–30 September, 31 October, or 30 November, depending on location) to provide an estimate of E_t. Similar procedures are widely used in southern Australia to estimate crop water use and potential seed yields (Tennant *et al*. 1991; French 1991; McDonald 1995).

Water use efficiency based on dry matter production (WUE_{dm}) was estimated as the ratio of the above-ground biomass at maturity to the total E_t throughout the growing period. Water use efficiency for grain production (WUE_{gr}) was based on the machine-harvested grain yield (GY).

Harvest components

At Merredin and Northam in 1994 and 1995, and Merredin and Cunderdin in 1996, the above-ground dry matter in a 1-m^2 area was measured at crop maturity and used to determine biological yield and harvest index. Plants were dried at 70°C for 48 h in a forced draught oven and weighed. Samples were then threshed, and grain redried and weighed. Ten uniform plants were selected from each plot and used to determine pod number per plant, seed number per pod, and mean seed weight. The inner 6 rows of all plots were machine-harvested at maturity and these seed yields are reported here.

Statistical analyses

All measurements were statistically analysed using analysis of variance. Each trial was analysed separately, because of differences in sowing time, soil type, season, and location. The relationships between seed yield and dry matter production, pre- and post-flowering Et, and yield components were investigated using a linear regression analysis across times of sowings, sites, and seasons.

Results

Weather

The 1994 year was one of the driest in WA for decades. The first autumn rains were received during the third week of May followed by below average rainfall in June and July. Mullewa received significant summer rainfall in February. Seasonal rainfall (May–October) was 44–112 mm less than the long-term averages across sites (Table 1). Merredin received only 168 mm rainfall during May–October, compared with the long-term average of 212 mm. The long term probability of Merredin receiving this amount of rainfall is <10%.

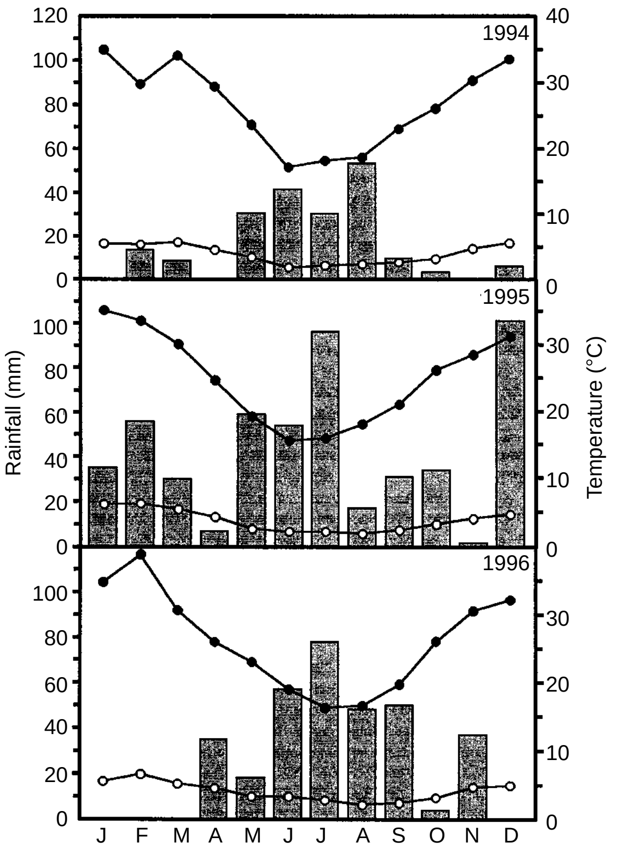

Fig. 1. Mean monthly rainfall (histogram), and mean maximum (●) and mean minimum (○) air temperatures at Merredin in 1994, 1995, and 1996.

All sites received significant summer rainfall in January and February 1995, with the exception of Northam and Mullewa. Most sites received the first autumn rains from late April through to mid May. Above average rainfall in July resulted in transient waterlogging at Merredin, Northam, and Mullewa. Gnowangerup, Nyabing, and Salmon Gums did not experience these heavy rainfalls in July, but received late unseasonal rains during October. Growing season rainfall varied from 78 mm above average at Merredin to 48 mm below average at Gnowangerup.

In 1996, all sites received opening rains in April and May, and Mullewa also received substantial summer rainfall providing good soil moisture at the beginning of the season. Seasonal rainfall was 8–78 mm greater than the long-term average across sites.

The mean monthly minimum and maximum temperatures, and rainfall over 3 seasons at Merredin, which is a low rainfall site typical of many areas in WA, are depicted in Fig. 1. There were no major differences in air temperatures during the growing season between years.

Crop establishment and days to first flower, 50% podding, and maturity

Crop establishment (average 95 plants/m^2) was less than the target density of 120 plants/m^2 at all sites in all years (data not presented). Sowing date had no consistent effect on crop establishment at all sites. No fungal diseases or effects of waterlogging were evident in any of the experiments even though commercial crops and other experiments were affected by waterlogging in susceptible areas in 1995 and 1996. Apart from the April sowing at Merredin in 1996, the duration from sowing to first flower, 50% podding, and maturity decreased with delayed sowing at Merredin and Northam in all 3 years (Table 2).

Number of nodes

At Merredin in 1994, 1995, and 1996 the mean number of nodes produced on the mainstem was generally greater for the first sowings throughout the growing season ($P < 0\cdot05$, Fig. 2). The reduction in the number of nodes per plant with delayed sowing was greater in 1996 where the first sowing was very early (April) than in 1994 and 1995. The rate of node appearance (mean = $0\cdot142$ nodes/day) in each season was similar across sowing times. The mean maximum number of nodes ranged from 17 in 1994 to 26 in 1996. At maturity, plant height was shorter for later sowings and ranged from 41 cm (mid April sowing at Merredin, 1996) to 20 cm (early June sowing at Merredin, 1994) (data not presented).

Green area index and absorbed radiation

At Merredin, the GAI was smallest in the dry 1994 season and greatest in 1996 (Fig. 3). GAI did not exceed $1\cdot6$ in 1994; however, it reached approximately $2\cdot5$ and $4\cdot5$ in 1995 and 1996, respectively. Peak GAI tended to be greater ($P < 0\cdot05$) and earlier in the season in early-sown treatments compared with later sowings. In all 3 years, the early-sown treatments had significantly greater ($P < 0\cdot05$) GAI through-

Table 2. Sowing dates of lentil, days after sowing (DAS) to first flower, dry matter (DM) at first flower, and DAS to first pod and maturity from time of sowing field trials in 1994, 1995, and 1996

Site and date sown	First flower (DAS)	DM at first flower (g/m^2)	First pod (DAS)	Maturity (DAS)
		1994		
Merredin				
23 May	93	116	109	150
6 June	92	101	100	142
22 June	80	94	88	131
4 July	75	72	80	120
l.s.d. ($P = 0\cdot05$)	2	17	4	3
Northam				
12 May	102	46	113	163
1 June	91	58	103	147
16 June	78	33	91	135
8 July	70	61	77	124
l.s.d. ($P = 0\cdot05$)	—	14	—	—
		1995		
Merredin				
13 May	100	183	111	167
26 May	94	132	105	154
13 June	88	97	94	150
27 June	83	138	90	136
l.s.d. ($P = 0\cdot05$)	—	32	—	—
Northam				
11 May	117	70	123	180
24 May	110	95	116	169
13 June	105	36	104	152
6 July	90	56	94	131
l.s.d. ($P = 0\cdot05$)	—	41	—	—
		1996		
Merredin				
16 April	80	55	121	189
15 May	112	87	119	174
17 June	92	104	100	154
5 July	77	199	88	136
l.s.d. ($P = 0\cdot05$)	—	67	—	—
Cunderdin				
16 May	120	150	—	—
22 June	97	288	—	—
5 July	84	203	—	—
19 July	84	200	—	—
l.s.d. ($P = 0\cdot05$)	—	42		

out June, July, and August than those sown later, after which GAI declined rapidly as the early-sown treatments began to mature. This was particularly pronounced in the long 1996 growing season.

The pattern of absorbed PAR (%) in 1994 and 1996 at Merredin tended to parallel the development of GAI (Fig. 4). Absorbed PAR in the first sowing was significantly greater ($P < 0\cdot05$) than the third and fourth sowings in 1994 and all other sowings in 1996 until mid to late September. In 1996, the PAR of the second sowing exceeded the first sowing in mid to late September when the GAI of the first sowing was declining rapidly. The peak absorption of PAR was 61% for the first sowing in 1994, and 92% and 88% for the first and second sowings in 1996, respectively.

Dry matter production and partitioning

Total above-ground dry matter production at Merredin was greater in 1996 than 1994 and 1995, and was generally greater ($P < 0\cdot05$) for the early sowings for most of the growing season (Fig. 5). In 1996 where the range in sowing dates was wider and growing conditions more favourable than the previous years, differences in dry matter production between sowing times was larger. For early sowings, peak dry matter production exceeded 600 g/m^2 in 1996 and 500 g/m^2 in 1995, but did not exceed 300 g/m^2 in the dry 1994 season. Dry matter production at first flower was greater with earlier sowing, except at Merredin in 1994 and 1996 (Table 2).

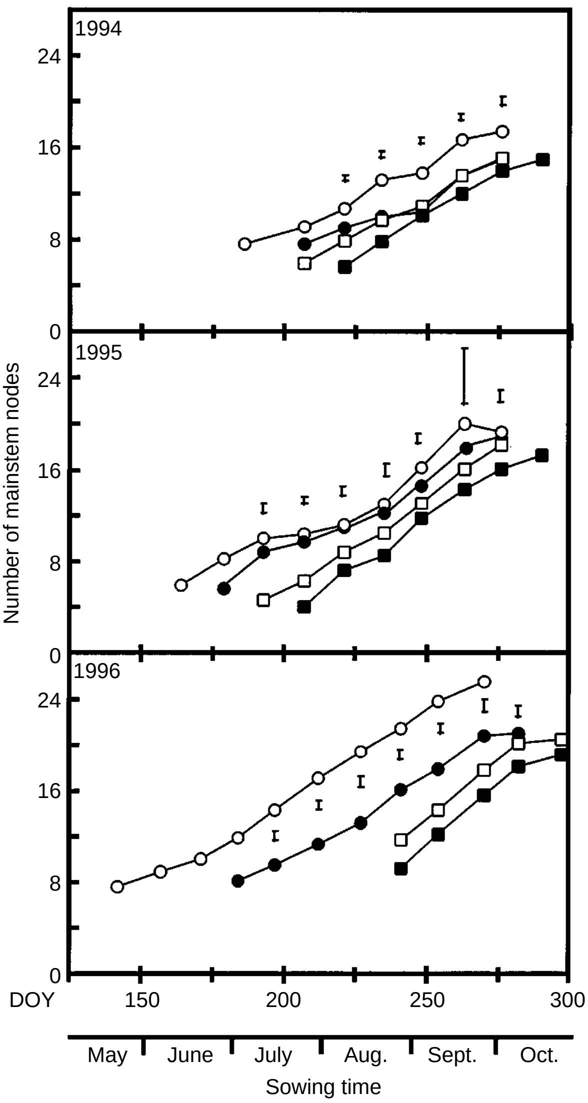

Fig. 2. Number of nodes per mainstem of lentil at various times of sowing (○ 1st, ● 2nd, □ 3rd, ■ 4th) in 3 years at Merredin. Bars indicate l.s.d. at $P = 0 \cdot 05$. DOY, day of year.

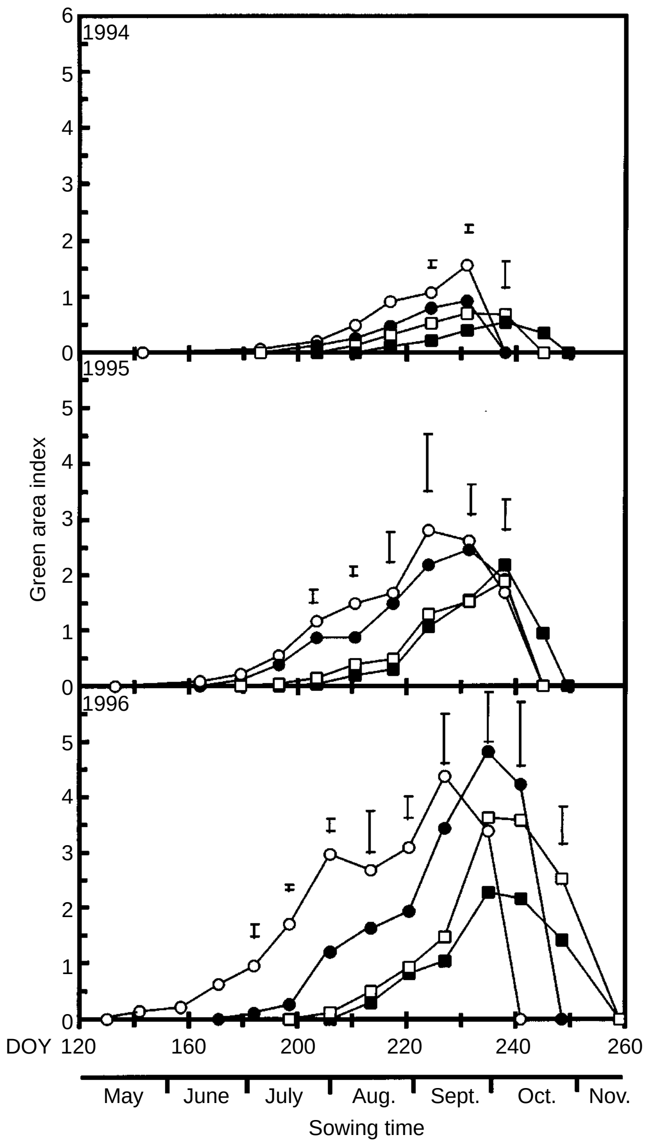

Fig. 3. Green area index of lentil sown at various times (○ 1st, ● 2nd, □ 3rd, ■ 4th) in 3 years at Merredin. Bars indicate l.s.d. at $P = 0 \cdot 05$. DOY, day of year.

The partitioning of dry matter in the 4 sowing time treatments at Merredin in 1996 is presented in Fig. 6. Most of the early dry matter production was partitioned into leaves. However, during the early flowering stages when internode length increased and stems elongated, more dry matter was partitioned into stems than leaves. There was some pod wall and seed growth prior to peak dry matter production, but most dry matter was partitioned into stems and leaves. In general, senescence of lower leaves began about 2 weeks before peak dry matter for the first time of sowing when GAI exceeded $4 \cdot 0$, and this increased to about 3 weeks for the later sowing times. Seed growth began approximately 2 weeks prior to peak dry matter production and reached 254 g/m^2 for the second sowing and 56 g/m^2 for the last time of sowing.

Seed yield

There was a general trend for reduced machine-harvested seed yields with delayed sowing across all years (Fig. 7). In general, low-yielding sites showed smaller responses to delayed sowing (e.g. Mullewa, Nyabing, and Salmon Gums).

Smallest seed yields were produced in the dry 1994 season, when yields were greatest (about $1 \cdot 0$ t/ha) from sowings in mid–late May. The average yield penalty for delayed seeding varied from 6 kg/ha·day at Mullewa to 20 kg/ha·day at Merredin.

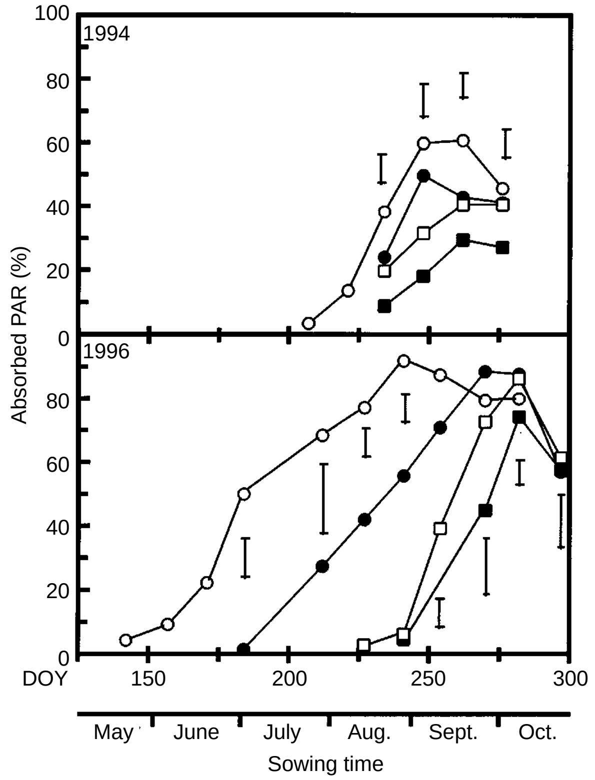

Fig. 4. Percentage of absorbed PAR of lentil at various times of sowing (○ 1st, ● 2nd, □ 3rd, ■ 4th) in 2 years at Merredin. Bars indicate l.s.d. at $P = 0{\cdot}05$. DOY, day of year.

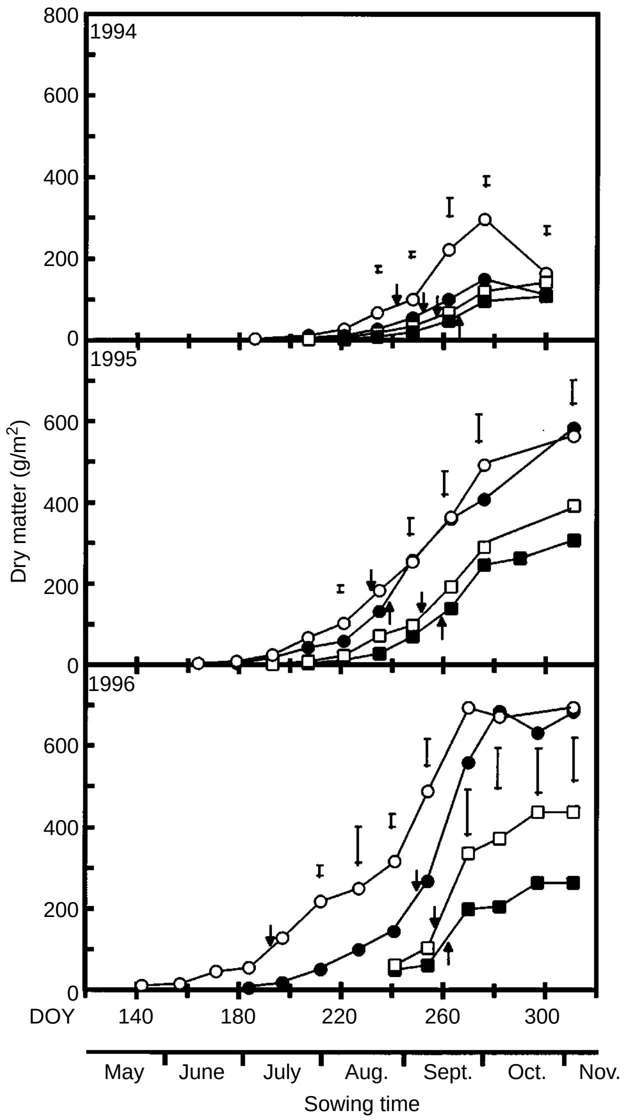

Fig. 5. Dry matter production of lentil at various times of sowing (○ 1st, ● 2nd, □ 3rd, ■ 4th) in 2 years at Merredin. Bars indicate l.s.d. at $P = 0{\cdot}05$. DOY, day of year.

In 1995, the mid May sowings produced the greatest seed yields at most locations, except Gnowangerup and Salmon Gums. Seed yields exceeded 1·8 t/ha at Three Springs and Merredin. The average yield penalty for delaying sowing varied from 8 kg/ha·day at Mullewa to 29 kg/ha·day at Three Springs.

In 1996, the mid May sowings produced the greatest seed yields at all locations, except at Merredin where a similar yield (about 2·5 t/ha) was produced from the mid April sowing, and Nyabing, where the late June sowings were greater. Seed yields were low at Mullewa, because of low pH at this site together with large harvesting losses, and at Salmon Gums, where dry conditions during the early part of the season and boron toxicity appeared to limit growth and yield. The average penalty for delayed sowing varied from 2 kg/ha·day at Salmon Gums to 22 kg/ha·day at Merredin.

Yield components

In general, biological yield and harvest index were reduced with delayed sowing. Biological yields ranged from 75 to 724 g/m^2 and, on average, were greatest with early sowings (Table 3). The largest HI (50%) was recorded at Northam with the first sowing in 1995 and lowest (32%) at Merredin with the latest sowing in 1996. In general, pod number per plant decreased with delayed sowings, except at Merredin in 1994 where there was no significant difference between sowing times ($P > 0{\cdot}05$). Pod number per plant was variable across sites and seasons, ranging from 20 pods/plant from the mid July sowing at Cunderdin in 1996, to 138 pods/plant from the mid-April sowing at Merredin in 1996.

The number of seeds per pod (1·1–1·5) was not significantly affected by delayed sowing across all sites and seasons ($P > 0{\cdot}05$). Apart from Merredin in 1994 and Cunderdin in 1996, 100-seed weight (3·0–4·4 g) was also not affected by delayed sowing ($P > 0{\cdot}05$).

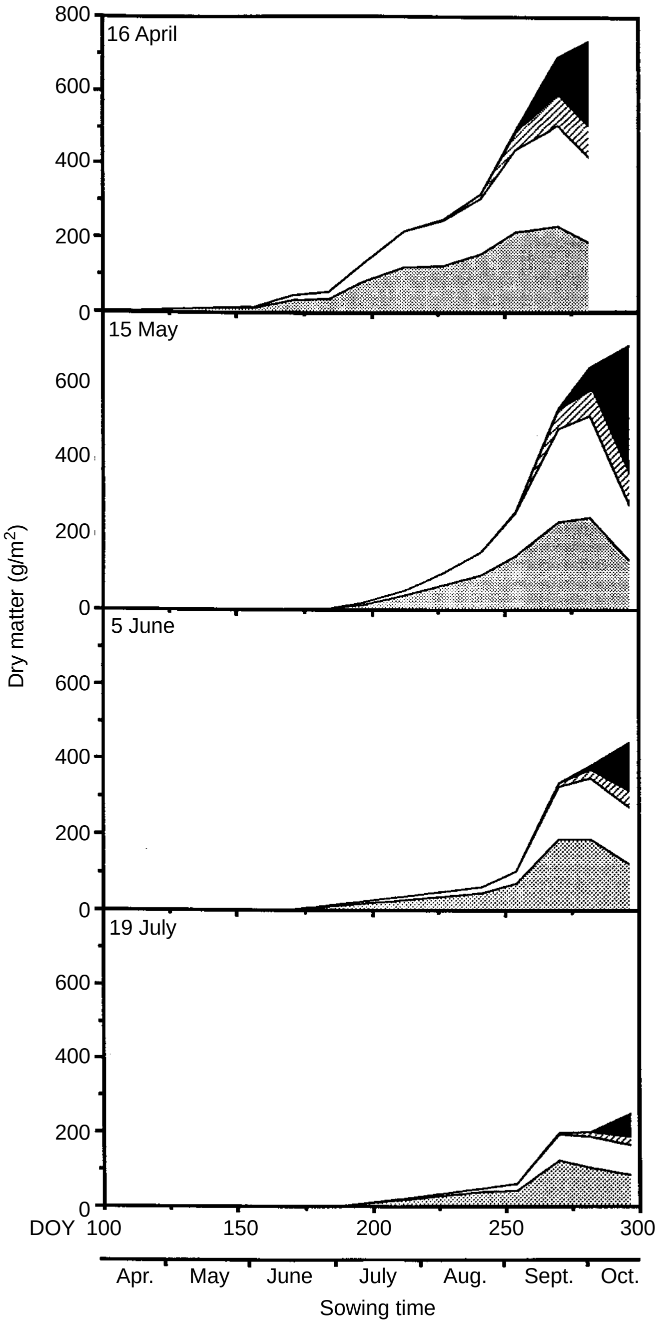

Fig. 6. Dry matter partitioning of lentil sown at 4 times at Merredin, 1996: seed (dark shading), flowers and pod wall (diagonal lines), stem (white areas), and leaf (grey shading). DOY, day of year.

Seed number per pod was slightly lower in the dry season of 1994, while the 100-seed weights were greatest at Northam in 1994 and lowest at Cunderdin in 1996.

Water use

At Merredin, total water use was greater in 1996 than 1995, and was generally greater for the earlier sowings (Table 4). The ratio of pre- to post-flowering water use was greatest for the fourth sowing in 1995 (4·3) and smallest for the first sowing in 1996 (0·4). WUE_{dm} and WUE_{gr} were greatest for the first 2 sowings in 1995 and 1996. WUE_{dm} ranged from 13·5 to 30·3 kg/ha·mm, and were similar in both years. However, the greatest WUE_{gr} was achieved with the early sowings at Merredin in 1996.

Actual measured E_t from time of sowing trials at Merredin in 1995 and 1996, and estimated E_t, was plotted against seed yield from variety and plant

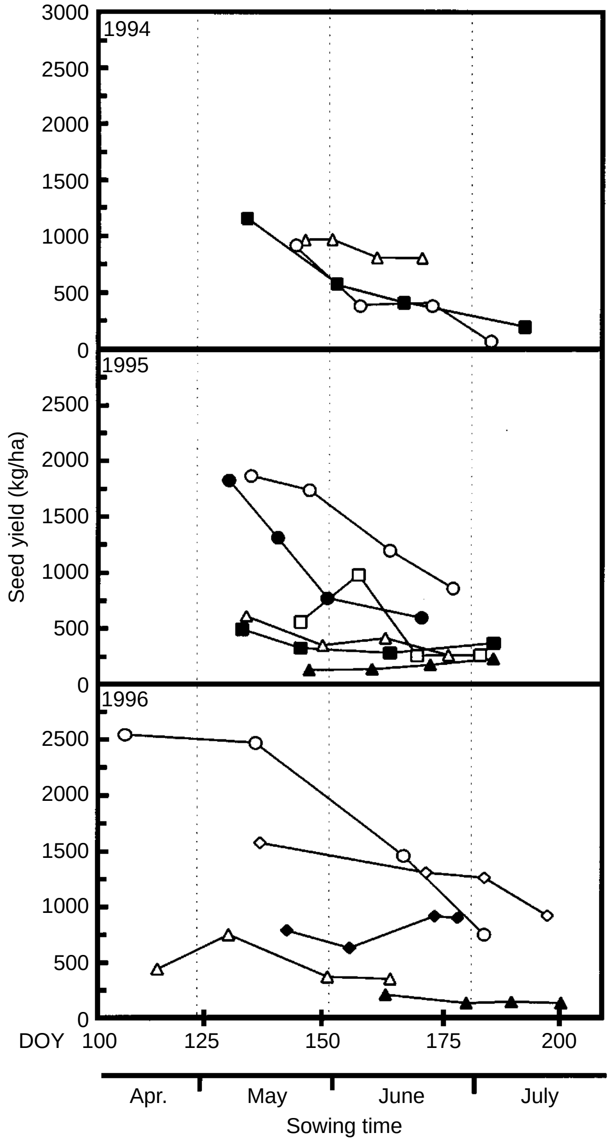

Fig. 7. Machine-harvested lentil seed yields from time of sowing experiments in south-western Australia in 1994, 1995, and 1996. Sites and l.s.d. ($P = 0·05$) for each year are: ◇ Cunderdin (—, —, 147), □ Gnowangerup (—, 358, —), ○ Merredin (112, 176, 400), △ Mullewa (561, 84, 277), ■ Northam (432, 84, —), ◆ Nyabing (—, —, 264), ▲ Salmon Gums (—, 58, 66), ● Three Springs (—, 325, —). DOY, day of year.

Table 3. Yield components from lentil time of sowing field experiments in 1994, 1995, and 1996

Site and date sown	Biological yield (g/m^2)	Harvest index (%)	No. of pods per plant	No. of seeds per pod	100-seed weight (g)
		1994			
Merredin					
23 May	164	42	27	1·3	3·6
6 June	112	39	28	1·2	3·9
22 June	142	41	29	1·2	4·1
4 July	109	40	27	1·3	4·2
l.s.d. ($P = 0{\cdot}05$)	21	3	14	0·1	0·2
Northam					
12 May	390	50	30	1·2	4·1
1 June	235	47	19	1·2	4·4
16 June	214	46	23	1·4	4·3
7 July	159	38	13	1·1	4·1
l.s.d. ($P = 0{\cdot}05$)	48	3	9	0·2	0·2
		1995			
Merredin					
13 May	564	39	53	1·6	3·9
26 May	583	37	53	1·7	3·3
13 June	391	34	45	1·6	3·8
27 June	306	33	35	1·6	3·6
l.s.d. ($P = 0{\cdot}05$)	70	2	13	0·5	0·5
Northam					
11 May	144	43	—	—	3·9
24 May	117	42	—	—	3·3
13 June	97	41	—	—	3·9
6 July	75	35	—	—	3·7
l.s.d. ($P = 0{\cdot}05$)	65	5			0·2
		1996			
Merredin					
16 April	693	35	138	1·5	3·9
15 May	684	37	124	1·4	3·3
17 June	437	34	64	1·1	3·8
5 July	263	32	40	1·3	3·6
l.s.d. ($P = 0{\cdot}05$)	107	3	39	0·1	0·5
Cunderdin					
16 May	724	41	87	1·4	3·1
22 June	648	38	55	1·4	3·0
5 July	582	41	30	1·4	3·3
19 July	412	39	20	1·4	3·6
l.s.d. ($P = 0{\cdot}05$)	127	8	40	0·6	0·2

Table 4. Total post-sowing water use (E_t, mm), pre-flowering water use (E_{ta}, mm), post-flowering water use (E_{tpa}, mm), ratio of pre- to post-flowering water use (E_{ta}/E_{tpa}), and water use efficiency for dry matter production (WUE_{dm}, kg/ha·mm) and grain yield (WUE_{gr}, kg/h·mm) for lentil time of sowing trials at Merredin in 1995 and 1996

Time of sowing	E_t	E_{ta}	E_{tpa}	E_{ta}/E_{tpa}	WUE_{dm}	WUE_{gr}
			1995			
13 May	240	151	89	1·8	23·6	7·8
26 May	209	137	72	1·9	28·1	8·4
13 June	181	117	64	1·8	21·6	6·6
27 June	179	144	35	4·3	17·3	4·8
l.s.d. ($P = 0{\cdot}05$)	26	20	16	0·8	4·1	1·4
			1996			
16 April	266	71	195	0·4	26·1	9·6
25 May	226	127	98	1·3	30·3	11·0
17 June	202	140	87	1·6	19·0	6·4
5 July	194	108	86	1·3	13·5	3·8
l.s.d. ($P = 0{\cdot}05$)	42	22	24	0·2	3·7	2·2

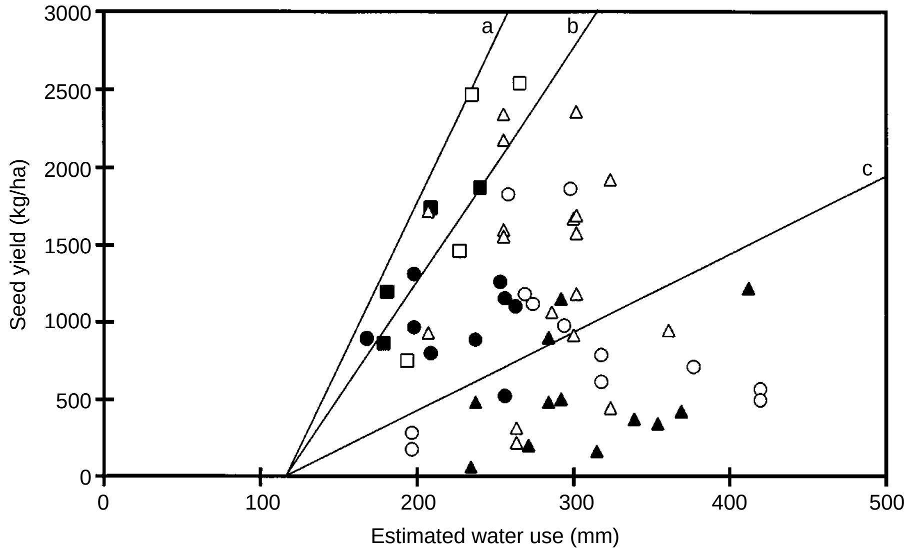

Fig. 8. Estimated water use (1 April to end of growing season) and seed yields of lentil grown in south western Australia. Lines are based on an intercept of 115 mm and slopes of (*a*) 20, (*b*) 15, and (*c*) 5 kg/ha·mm. Data plotted are from time of sowing experiments at Merredin in 1995 ■ and 1996 □ (actual measured water use); variety and plant density trials 1994 ■, 1995 ○, and 1996 △; and several sites from Siddique *et al.* (1993) ▲.

density trials in 1994, 1995, and 1996 (K. H. M. Siddique, unpublished data), and several sites from Siddique *et al.* (1993) (Fig. 8). The line representing an intercept of 115 mm (soil evaporation, Es) and slope of 15–20 kg/ha·mm (transpiration efficiency, TE) encompassed most of the high-yielding treatments across a range of environments. The TE for the time of sowing trials at Merredin in 1995 and 1996 were all close to the 15 and 20 kg/ha·mm benchmark. At several sites, particularly those from Siddique *et al.* (1993), TE for lentil was well below 5 kg/ha·mm.

Discussion

This study, together with recent evaluations of lentil germplasm (Sarker *et al.* 1995, Clements *et al.* 1996) and comparisons of grain legume species (Siddique *et al.* 1993; Thomson *et al.* 1997), demonstrate that lentil is well adapted to well-drained, neutral to alkaline loam and clay loam soil types in south-western Australia. Contrary to previous results with poorly adapted cultivars (Walton and Trent 1988; Siddique *et al.* 1993), our study shows that seed yields >1·0 t/ha and up to 2·5 t/ha can be achieved with the red lentil cultivar Digger when sown early. Even in the dry season of 1994, yields of approximately 1·0 t/ha were produced from early sowings. Seed yields were compromised where soil pH was <6·0 (measured in a $CaCl_2$ extract), for example, at Northam in 1995, and Mullewa in 1996.

Lentil is adapted to low rainfall areas in Mediterranean-type environments and is frequently grown in a similar agro-ecological zone to barley in West Asia and North Africa where other cool-season food legumes such as chickpea and faba bean produce low and variable yields unless irrigated (Erskine *et al.* 1994). The strategy of lentil in Mediterranean environments is typically one of drought escape, with vigorous growth in winter when conditions are favourable and rapid senescence induced by high temperatures and drought stress in late spring or early summer (Silim *et al.* 1993). However, recent studies indicate that lentil has considerable potential for drought resistance through osmotic adjustment (Turner *et al.* 1996). A recent evaluation of a wide range of lentil germplasm in northern Syria, Turkey, and Lebanon suggests that small-seeded (*microsperma*) red lentils are better adapted to environments with low rainfall and high spring temperatures than the large-seeded (*macrosperma*) green lentils (Erskine 1996). Hence, one would expect red lentil to be better adapted to much of southern Australia than green types.

This study showed how seed yields of lentil are generally reduced with delayed sowing. Sowing in late April or early May allowed a longer period for vegetative and reproductive growth, rapid canopy development, greater PAR absorption, more E_t, and, hence, greater dry matter production than when sowing was delayed.

Early-sown lentils began flowering and filling seeds earlier in the growing season, at a time when vapour pressure deficits and air temperatures were lower, when compared to those treatments where sowing was delayed. For instance, in 1996 at Merredin, the earliest sown plants began flowering in early July when the mean monthly maximum temperature was 16·3°C, 3·4°C lower than in September when the fourth time of sowing reached first flower. In many Mediterranean environments, seed yield has been directly related to the total above ground dry matter produced in a number of cool season grain legumes (Siddique *et al.* 1993; Silim *et al.* 1991, 1993; Thomson *et al.* 1997; Loss and Siddique 1997). Indeed, seed yield was highly correlated with total above ground dry matter in this study ($r = 0{\cdot}917$, $P < 0{\cdot}01$). Among the yield components, early sowing resulted in more pods per plant, and seed yield was also highly correlated with pod number ($r = 0{\cdot}872$, $P < 0{\cdot}01$). We did not observe any reduction in seed size or number of seeds per pod with delayed sowing and this may have been associated with the decrease in pod and seed number per plant.

The yield penalty associated with delayed sowing of lentil depends on the environment. Penalties ranged from 2 kg/ha·day at sites with low yield potential (Salmon Gums in 1996) to 29 kg/ha·day at high yielding sites (Three Springs in 1995). Greater penalties, up to 56 kg/ha·day, have been reported for faba bean in similar environments (Loss and Siddique 1997). In situations where seed yield is not increased with early sowing, increased dry matter production will improve the suppression of broad-leafed weeds, a serious problem for commercial producers. On the other hand, delayed sowing could enable improved weed management before sowing. Early-sown lentils with large dry matter production may not always produce more seed yield but will fix more nitrogen than late-sown crops, which will in turn increase the residual nitrogen effect for following crops. In this study, early sowing resulted in a tall canopy and hence, easier and more efficient mechanical harvesting. Ease of harvesting can also be improved by rolling the seed bed after planting and by the use of crop lifters at harvest (Riethmuller and Siddique, unpublished). In overseas studies, increased plant height has encouraged lodging (Ibrahim *et al.* 1993). However, this occurred where annual rainfall was >500 mm/year or when supplementary irrigation was provided, and where soil fertility is much higher than in south-western Australia.

Although early-sown crops have generally greater E_t than when sowing is delayed (Keatinge and Cooper 1983; Siddique and Sedgley 1987; Loss *et al.* 1997), there was little difference in the E_t of lentil between sowing times when E_s before emergence of the later sown treatments was taken into account. Early-sown crops with their rapid canopy development generally allow less E_s in this environment, which is often greater than 40% of the total E_t (Siddique and Sedgley 1987; Siddique *et al.* 1990). The pattern of crop water use is almost as important as the total water use in Mediterranean-type environments (Loss and Siddique 1994). As is the case in other crops (Siddique *et al.* 1990; Loss *et al.* 1997), lentil seed yield was highly correlated with post-flowering E_t in this study ($r = 0{\cdot}720$, $P < 0{\cdot}01$). The ratios of pre- to post-flowering E_t ranged from 1·8 to 4·3 in 1995 and 0·4 to 1·6 in 1996. These values are similar to that reported with time of sowing studies in faba bean (Loss *et al.* 1997) but less than reported for cereal crops in similar environments (French and Schultz 1984; Siddique *et al.* 1990).

The values of WUE_{gr} and WUE_{dm} for lentil from early sowings in this study (up to 30 kg/ha·mm and 11 kg/ha·mm, respectively) were comparable to those reported for cereals (Siddique *et al.* 1990; Tennant *et al.* 1991), chickpea (Siddique and Sedgley 1987), field pea (McDonald 1995), and lentil (Erskine and El Ashkar 1993) in similar environments. However, these values are lower than that reported for early-sown faba bean crops in this environment (Loss *et al.* 1997). Several points on Fig. 8 were above the line representing a TE of 15 kg/ha·mm for lentil, indicating the likelihood of even higher potential TE than 15 kg/ha·mm through use of improved cultivars and production packages. Those points below the line were from sites where seed yields were reduced due to poor weed management, waterlogging, low pH, harvesting losses, and poorly adapted cultivars (Siddique *et al.* 1993). The TE values of 15 kg/ha·mm together with Es values of 115 mm found in this study can be used as a bench mark to assess yield potential of dryland lentil crops in the Mediterranean-type environments of southern Australia.

Early-sown crops can experience damaging sub-zero temperatures around flowering and podding in this environment. However, lentil is regarded as one of the most cold-tolerant pulse crops and has the ability to flower and set pods under relatively cool conditions when compared to species such as chickpea and lupin. Lentil has poor tolerance to high temperatures, especially at flowering and pod set (Erskine *et al.* 1994) and late-sown crops are more likely to be exposed to these conditions. In general, early-sown crops are more prone to foliar diseases such as ascochyta blight (*Ascochyta lentis*). However, we observed little incidence of ascochyta, because lentil is a relatively new crop in WA, and hence, low levels of disease inocula are currently present in this environment. Ascochyta in lentil can be managed by planting disease-resistant cultivars (e.g. Northfield), applying suitable seed dressings and foliar fungicides, and selecting appropriate crop rotation practices.

The cultivar used in this study (Digger) was initially selected in the favourable environments of the Victorian Wimmera region. The development of early-maturing lines with greater dry matter production together with improved agronomic packages will increase and stabilise lentil yields in low rainfall environments of southern Australia. Two such lines with earlier flowering and greater yields than Digger have recently been identified and are being considered for commercial release (K. H. M. Siddique, unpublished data).

In summary, the lentil cultivar Digger is well adapted to dryland Mediterranean-type environments of south-western Australia, escaping drought through rapid seedling growth, early flowering and pod filling in winter, and rapid senescence in late spring. Seed yields decline with delayed sowing, especially in environments with a high yield potential. Sowing in late April or early May is recommended for high seed yields in low rainfall regions (300–400 mm/year) of Western Australia, while sowing in early to mid May is likely to be optimum in medium rainfall areas (400–600 mm) to allow for good weed management before sowing and reducing the risk of fungal diseases.

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