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Adaptation of lentil (*Lens culinaris* Medik) to short season Mediterranean-type environments: response to sowing rates

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Abstract. The growth and seed yield response of lentil (cv. Digger) to sowing rate (20–120 kg/ha) was studied at 13 sites over 3 seasons in the cropping regions of south-western Australia. The economic optimum plant density was estimated by fitting an asymptotic model to the data and calculating the sowing rate above which the cost for additional seed was equivalent to the revenue that could be achieved from the extra seed yield produced, assuming a 10% opportunity cost.

On average across all sites and seasons, only 51% of sown seeds emerged. Increasing sowing rate resulted in greater dry matter production at flowering and maturity, and fewer pods per plant. Harvest index (0·31–0·36), number of seeds per pod (1·13–1·84), and mean seed weight (2·9–3·6 g/100 seeds) remained relatively stable with changes in sowing rate. The asymptotic models fitted to seed yields accounted for 1–73% of the total variance in the data, except at one site where a model could not be found to provide an adequate fit to the data. In addition to this site, another 5 sites were excluded from further consideration where the percentage of variance accounted for was <25% or the predicted optimum densities and seed yield potentials were well beyond the range of the data. The economic optimum of the remaining 7 sites ranged from 96 to 228 plants/m^2, with a mean of 146 plants/m^2. These results suggest that lentil yields may be improved by increasing sowing rates beyond those currently targeted in southern Australia (100–125 plants/m^2). On the basis of these results, targeting a density of about 150 plants/m^2 by using a sowing rate of approximately 90–110 kg/ha is recommended, depending on mean seed weight and germination percentage of the seed. Even higher sowing rates may be optimum where the growing conditions are unfavourable and individual plant growth is limited.

Additional keywords: seeding rate, plant density, plant population, economic optimum, pulse.

Introduction

Over the past 20 years, narrow-leafed lupin (*Lupinus angustifolius*) has become the most popular grain legume in Australia and is mostly produced on coarse-textured acidic soils in the Mediterranean-type environments of south-western Australia (Siddique and Sykes 1997). Other grain legumes (pulses) that are more suited to neutral–alkaline, fine-textured and shallow duplex soils than narrow-leafed lupin, such as chickpea (*Cicer arietinum*), faba bean (*Vicia faba*), field pea (*Pisum sativum*), albus lupin (*Lupinus albus*), and lentil (*Lens culinaris*), are now also being included in farming systems of south-western Australia (Siddique *et al.* 1993; Thomson *et al.* 1997). In experiments conducted in the early 1990s, lentil produced the lowest seed yields of these pulse species (Siddique *et al.* 1993), but subsequent studies with better adapted cultivars and appropriate agronomy have demonstrated the potential of lentil on well-drained soils with pH >6·0 ($CaCl_2$), producing seed yields of 1–2 t/ha (Siddique *et al.* 1998*a*).

Along with further improvements in cultivar adaptation and yield, agronomic packages are currently being developed for lentil production in Western Australia including aspects such as time of sowing (Siddique *et*

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al. 1998*b*), sowing depth (Siddique and Loss 1998), the management of pests, diseases, and weeds, and sowing rate. There are few published studies of sowing rate responses in lentil in Australia. Sowing rate can affect crop establishment, canopy development, radiation absorption, dry matter production, weed competition, disease infection, crop height, lodging at maturity, and ease of mechanical harvest. In general, lentil has a short stature and small biomass, is a poor competitor with weeds, and is prone to lodging at maturity. Hence, sowing rate is likely to be a critical factor in its commercial production. In addition, the cost of lentil seed is high relative to cereal and oilseed crops, and the choice of sowing rate may have a large impact on crop profitability.

An optimum plant density of 100–125 plants/m^2 is suggested (Anon. 1992) for southern Australia, which equates to sowing rates of 50–75 kg/ha, depending on the seed size and establishment rate. In the Mediterranean environments of northern Syria, farmers traditionally broadcast lentil seed by hand at around 140 kg/ha, although studies have indicated that sowing rates of 95–115 kg/ha will produce maximum seed yields in crops sown mechanically (Silim *et al*. 1990). Optimum sowing rates as low as 35–40 kg/ha have been suggested in Canada (Wall 1994), 40–60 kg/ha in India (Ali *et al*. 1993; Sharma 1996), 35–40 kg/ha in Bangladesh (Miah and Rahman 1993), and 20–40 kg/ha in Nepal (Neupane and Bharati 1993). Soil fertility, moisture, and climatic conditions in these countries are quite different from Mediterranean-type environments and it is likely that these results are not applicable to southern Australia.

In the past, recommended sowing rates for many crops have been based on the rate required to produce maximum yields. However, the most profitable yields may not be achieved at these rates. In most crops, seed yield responds positively to increasing sowing rate or plant density, until a plateau is reached, and eventually, further increases in density may result in a yield decline (Holliday 1960). Therefore, there is a sowing rate above which the cost for the additional seed will be greater than the revenue that can be obtained from the extra seed yield produced. An alternative approach to determining optimum sowing rates was used by French *et al*. (1994) for narrow-leafed lupin. They determined the point on the response curve where the cost of the additional seed was equal to the return from the extra grain produced, allowing a 10% opportunity cost for the additional seed.

The work described in this paper forms part of a larger study to evaluate the adaptation of lentil to short season Mediterranean-type environments of south-western Australia (Siddique *et al*. 1998*b*). The aim of this study was to assess the effect of sowing rate on lentil growth and seed yield at a total of 13 sites over 3 seasons in the cropping regions of south-western Australia, and to determine the economic optimum sowing rate for lentil in these environments.

Materials and methods

Experimental design and management

The field experiments were a completely randomised block design of 6 sowing rate treatments and 4 replicates, and were conducted at 2 sites in 1994, 7 sites in 1995, and 4 sites in 1996 (Table 1). The sites were on either Agriculture Western Australia research stations or farmers' fields, and represented a diverse range of environments within the cropping region of south-western Australia.

At all sites, the crop in the previous year was a cereal. The red lentil cultivar Digger, which was the best adapted lentil cultivar available, was chosen for the study and was sown at 20, 40, 60, 80, 100, and 120 kg/ha, targeting plant densities of 46, 91, 137, 183, 228, and 274 plants/m^2 based on the mean seed weight (3·5 g/100 seeds) and the germination percentage (80%). The seed was inoculated with a commercial rhizobial inoculum (Group E, strain SU303) immediately before sowing. Plots were sown with a cone seeder and were 1·44 m wide (8 rows, 18 cm apart) and 20 m long.

Weeds were controlled before sowing with 2 L/ha of Bladex (500 g/L of cyanazine) plus of 1 L/ha of Sprayseed (paraquat/diquat 250 g/L) or Roundup (glyphosate 450 g/L). After sowing but before the crop had emerged, 0·75 L/ha of diuron was also applied. Grass weeds that emerged after sowing were controlled with 400 mL/ha of Fusilade (212 g/L of fluiazifop-*p*-butyl) or 1·0 L/ha of Verdict (104 g/L of haloxyfop) and broad-leafed 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.

Observations and sampling procedures

Weather data

Daily rainfall was recorded at each site or obtained from nearby weather stations or farmer records.

Plant density and phenology

Plant establishment was assessed 4 weeks after emergence using 0·5-m^2 quadrats placed at 5 positions in each plot. The following phenological stages were estimated in each plot at Merredin and Northam in 1994, and Merredin in 1996: (*i*) first flower, 50% of

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

Site	Soil characteristics[A]	Fertiliser[B] and sowing dates	May–Oct. rainfall (mm) Current year	Long-term average
		1994		
Merredin Agriculture WA Research Station (31°29′ S, 118°12′ E)	Reddish brown sandy clay loam (6·0) over a yellowish red heavy clay (7·8) at 30 cm.	54 kg/ha of DSP at sowing (24 May)	168	212
Northam Muresk Agricultural Research Institute (31°43′ S, 116°41′ E)	Red–brown loam (5·0) over reddish brown clayey sand (6·1) at 90 cm. Surface pH was increased to 6·0 with lime addition	113 kg/ha of SSP at sowing; 20 kg/ha urea topdressed 75 days after sowing (2 June)	256	368
		1995		
Merredin Agriculture WA Research Station (31°29′ S, 118°12′ E)	Reddish brown sandy clay loam (6·0) over a yellowish red heavy clay (7·8) at 30 cm	80 kg/ha of DAP at sowing (20 May)	290	212
Northam Muresk Agricultural Research Institute (31°43′ S, 116°41′ E)	Red–brown loam (5·0) over a reddish brown, clayey sand (6·0) at 40 cm	130 kg/ha of SSP+AS at sowing (16 May)	407	368
Bencubbin Farmer's field site (30°49′ S, 117°52′ E)	Reddish sandy clay loam. Surface pH 6·4 increasing to 7·8 at 30 cm	100 kg/ha of DAP at sowing (25 May)	369	212
Three Springs Farmer's field site (29°34′ S, 115°45′ E)	Reddish brown coarse sandy loam (5·2) over sandy clay loam (6·6) at 20–30 cm	96 kg/ha of DAP at sowing (16 May)	271	293
Dongara Farmer's field site (29°15′ S, 114°56′ E)	Grey brown alkaline (8·0) crumbly clay loam, cracks in summer 80–200 cm	108 kg/ha of DAP at sowing (22 May)	390	402
Mullewa Agriculture WA Research Station (28°32′ S, 115°30′ E)	Red sandy loam; pH 5·2 increasing to 7·1 at depth (30–40 cm)	100 kg/ha of DAP at sowing (20 May)	243	249
Pingaring Farmer's field site (33°06′ S, 118° 28′ E)	Dark greyish brown sandy loam (5·6) over yellowish red medium clay (7·7) at 40 cm	100 kg/ha of DAP at sowing (25 May)	265	244
		1996		
Cunderdin Agricultural College (31°39′ S, 117° 14′ E)	Reddish brown sandy clay loam with a surface pH of 6·0 increasing to 6·5 at 30 cm	107 kg/ha of SSP+AS at sowing (23 June)	302	274
Merredin WA Agriculture Research Station (31°29′ S, 118°12′ E)	Reddish brown sandy clay loam (6·0) over a yellowish red heavy clay (7·8) at 30 cm	75 kg/ha of DAP at sowing (11 June)	255	212
Bencubbin Farmer's field site (30°49′ S, 117°52′ E)	Reddish sandy clay loam. Surface pH 6·4 increasing to 7·8 at 30 cm	75 kg/ha of DAP at sowing (30 May)	207	212
Three Springs Farmer's field site (29°34′ S, 115°45′ E)	Reddish brown coarse sandy loam over sandy clay loam. Surface pH 5·9 increasing to 7·1 at 30 cm	81 kg/ha of Agras No. 1 at sowing (17 June)	369	293

[A] pH in $CaCl_2$ in parentheses.
[B] SSP, single superphosphate; DSP, double superphosphate; DAP, diammonium phosphate; AS, ammonium sulfate.

the plants with at least 1 fully opened flower visible; (*ii*) first pod, 50% of the plants with their first pod visible; (*iii*) end of flowering, 95% of the plants with no new flowers visible; and (*iv*) maturity, 95% of plants with the earliest (lowest) pods light brown, and the later (highest) pods well filled, but slightly green.

Dry matter production at flowering

Above-ground dry matter production was determined within a week of first flower at Merredin in 1994; Three Springs, Dongara, and Mullewa in 1995; and Bencubbin, Cunderdin, and Merredin in 1996. Shoots were cut off at ground level in a $0 \cdot 5$-m^2 quadrat in 2 positions in each plot, dried in a forced-draught oven at 70°C for 48 h, and then weighed immediately.

Seed yield and yield components

Seed yields were determined by harvesting the inner 6 rows of all plots at each site with a mechanical plot harvester. Yield components were measured at Merredin in 1994; and at Bencubbin, Cunderdin, and Merredin in 1996. Total dry matter production at maturity and seed yield components were determined from a 2-m^2 area and used to calculate 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 also selected from each plot and used to determine pod number per plant, seed number per pod, and mean seed weight.

Economic optimum plant density

The economic optimum plant density for each field experiment was calculated using a similar method to that of French *et al.* (1994). The following model, which describes an asymptotic increase in machine-harvested seed yield (y, t/ha) as plant density (x, plants/m^2) is increased, was fitted to each data set at each site (see Fig. 2):

$$y = ax/(1 + bx)$$

At all sites, this asymptotic model was found to be more suitable than the 3-parameter quadratic model, which describes a response curve where y rises to a maximum, but declines with further increases in x.

Economic optimum densities for each experiment were chosen as the density where the cost of additional seed was equivalent to the revenue that could be achieved from the additional seed yield allowing a 10% opportunity cost for the money invested for the additional seed. The slope of the yield response curve at this point was determined using the method described by French *et al.* (1994) assuming a lentil seed cost of \$A600/t, a return from harvested grain of \$A400/t, a mean seed weight of $3 \cdot 5$ g/100 seeds, and an establishment proportion of 51% (see results). The slope at this point was $0 \cdot 00102$ t/m$^2 \cdot$ha$\cdot$plant. A second set of analyses was also performed assuming a 50% opportunity cost.

Statistical analyses

All measurements were statistically analysed using analysis of variance. Each trial was analysed separately because of differences in soil type, season, and location. The relationship between optimal plant density and potential seed yield was calculated by linear regression.

Results

Weather

In 1994, at Merredin and Northam, the first autumn rain was received during the third week of May. This was followed by below average rainfall in June and July and, subsequently, lower rainfall than the long-term seasonal average. Merredin received only 168 mm rainfall during May–October, compared with the long-term average of 212 mm, and Northam received 256 mm, compared with the average of 368 mm (Table 1). Mean temperatures were above average for most of the season, and the crops experienced mild moisture stress during winter and spring at both sites. Consequently, plant development was generally advanced compared with other years.

In 1995, Merredin and Three Springs received significant summer rainfall in January and February. The first autumn rain occurred in late April in the northern cropping areas (Three Springs, Dongara, and Mullewa) and in mid-May at other sites. Growing season rainfall was at least 20 mm more than average at Merredin, Northam, Bencubbin, and Pingaring, but similar to the long-term averages at other sites, apart from Three Springs which was 22 mm below average.

In 1996, seasonal rainfall was 28, 43, 5, and 24 mm greater than the long-term average at Cunderdin, Merredin, Bencubbin, and Three Springs, respectively. All sites received opening rains in April and May, and heavy rain after sowing resulted in transient waterlogging at Three Springs. Consistent rain was experienced for the rest of the growing season through to October, with late rains in November.

Plant establishment

There was a significant linear relationship between plant density and sowing rate across all sites and seasons ($r^2 = 0 \cdot 680$, $P < 0 \cdot 01$), which can be described by the equation:

$$\mathrm{PD} = \mathrm{SR} \times 1 \cdot 374$$

where PD is plant density (plants/m^2) and SR is sowing rate (kg/ha). Across all sites and seasons, plant densities ranged from 14 plants/m^2 when sown at 20 kg/ha to 241 plants/m^2 when sown at 120 kg/ha (Fig. 1). Establishment was relatively poor at some

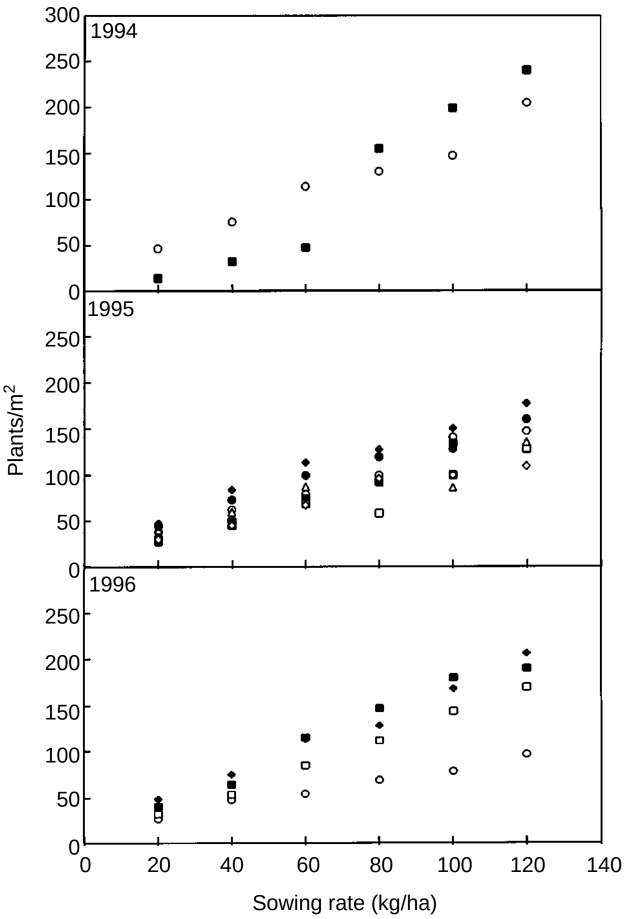

Fig. 1. Effect of sowing rate on plant establishment at Bencubbin (□), Cunderdin (▲), Dongara (△), Merredin (○), Mullewa (◇), Northam (■), Pingaring (●), and Three Springs (◆) between 1994 and 1996.

sites, such as Bencubbin and Mullewa in 1995 and Merredin in 1996 where soil crusting occurred after sowing, whereas at other sites, such as Three Springs in 1995 and 1996, plant densities were relatively high. By calculating the percentage of emerged plants compared with the target density across each density and site, and assuming that 80% of sown seeds were viable, it was estimated that, on average, only 64% of viable seeds (i.e. 51% of sown seeds) established into plants.

Phenology

Time from sowing to each phenological stage was similar at Merredin and Northam in 1994, and slightly longer at Merredin in 1996 (Table 2). First flower and maturity occurred 92 and 146 days after sowing, respectively, at Merredin and Northam in 1994, and 98 and 157 days after sowing at Merredin in 1996. There was a trend of a 1- or 2-day delay in the time to reach each phenological stage in the low sowing rate treatments (data not presented); however, this generally was not significant ($P > 0 \cdot 05$).

Table 2. Mean duration (days) from sowing to first flower, first pod, end of flowering, and maturity at Merredin and Northam in 1994, and at Merredin in 1996

Differences between sowing rate treatments were generally not significant ($P > 0 \cdot 05$)

Phenological stage	1994 Merredin	1994 Northam	1996 Merredin
Flowering	92	92	98
Podding	106	102	105
End of flowering	121	122	125
Maturity	146	146	157

Dry matter production at flowering

In general, there was a significant trend ($P < 0 \cdot 05$) of greater dry matter production per unit area at first flower as sowing rate was increased at all sites and years (Table 3). Dry matter production was lowest at Merredin in the dry 1994 season (<140 g/m^2), and greatest at Dongara in 1995, and at Merredin and Cunderdin in 1996 (up to 320 g/m^2).

Seed yield and harvest components

Despite the dry season in 1994, seed yields were up to 835 kg/ha at Merredin (Table 4). Despite the greater rainfall at Northam, the acidic coarse sandy

Table 3. Dry matter production (g/m^2) at, or near, first flower for lentil at sites in south-western Australia

Sowing rate (kg/ha)	1994 Merredin	1995 Three Springs	1995 Dongara	1995 Mullewa	1996 Merredin	1996 Cunderdin	1996 Bencubbin
20	88	138	212	112	197	165	89
40	87	157	274	193	232	212	99
60	132	183	386	226	256	268	125
80	97	206	258	217	297	313	132
100	108	210	296	244	292	336	148
120	120	254	308	248	320	291	176
l.s.d. ($P = 0 \cdot 05$)	41·4	33·8	60·3	39·6	74·3	64·9	67·5

Table 4. Machine harvest seed yield (kg/ha) of lentil at sites in south-western Australia, 1994–1996

Site	Sowing rate (kg/ha) 20	40	60	80	100	120	Mean	l.s.d. ($P = 0{\cdot}05$)
				1994				
Merredin	286	549	682	643	611	835	601	233·3
Northam	104	238	270	427	389	391	303	90·1
				1995				
Merredin	1641	2085	2155	2182	2150	2353	2095	237·8
Northam	356	508	612	518	449	536	497	217·4
Bencubbin	648	931	1059	1153	1174	1389	1059	170·7
Three Springs	584	1005	1142	1124	1425	1754	1172	374·1
Dongara	1215	1463	1503	1438	1550	1510	1446	296·3
Mullewa	561	842	935	918	993	881	855	156·3
Pingaring	949	1058	995	1025	1044	1049	1020	144·0
				1996				
Merredin	910	1157	1188	1491	1555	1504	1301	256·0
Cunderdin	1513	1514	1688	1547	1617	1622	1584	126·0
Bencubbin	451	674	717	929	775	924	745	228·4
Three Springs	555	714	858	934	928	945	822	119·0

loam soil appeared to limit crop growth, and yields were about half those at Merredin. On average, over all treatments in the favourable 1995 season, seed yields exceeded 800 kg/ha at Bencubbin, Three Springs, Dongara, Mullewa, and Pingaring, whereas they exceeded 2000 kg/ha at Merredin. For the second consecutive year, mean yields were <700 kg/ha at Northam. In 1996, mean yields were in excess of 700 kg/ha at Bencubbin and Three Springs, whereas they exceeded 1300 kg/ha at Merredin and Cunderdin.

Of the parameters, pod number per plant was most affected by sowing rate, decreasing significantly ($P < 0{\cdot}05$) as sowing rate was increased at all sites where measured (Table 5). The dry matter production at maturity was greatest at Cunderdin in 1996 (up to 931 g/m^2). There was a significant trend of greater dry matter production at maturity and reduced harvest indices as sowing rate was increased at Cunderdin and Bencubbin in 1996 ($P < 0{\cdot}05$). On average, harvest indices varied from 0·31 to 0·36 among the sites. At Merredin in 1994 and Bencubbin in 1996, the lowest sowing rate treatment had a significantly greater number of seed per pods than higher sowing rate treatments. Mean seed weight (2·9–3·6 g/100 seeds) was not affected significantly by sowing rate at all sites ($P > 0{\cdot}05$).

Optimum density and yield potential

At Pingaring in 1995 where sowing rate appeared to have no effect on seed yield (Table 4), neither the asymptotic nor the 3-parameter model provided an adequate fit to the data. Across other sites, the asymptotic model accounted for 1% (Northam in 1995, data not presented) to 73% (Northam in 1994) of the total variance (Table 6).

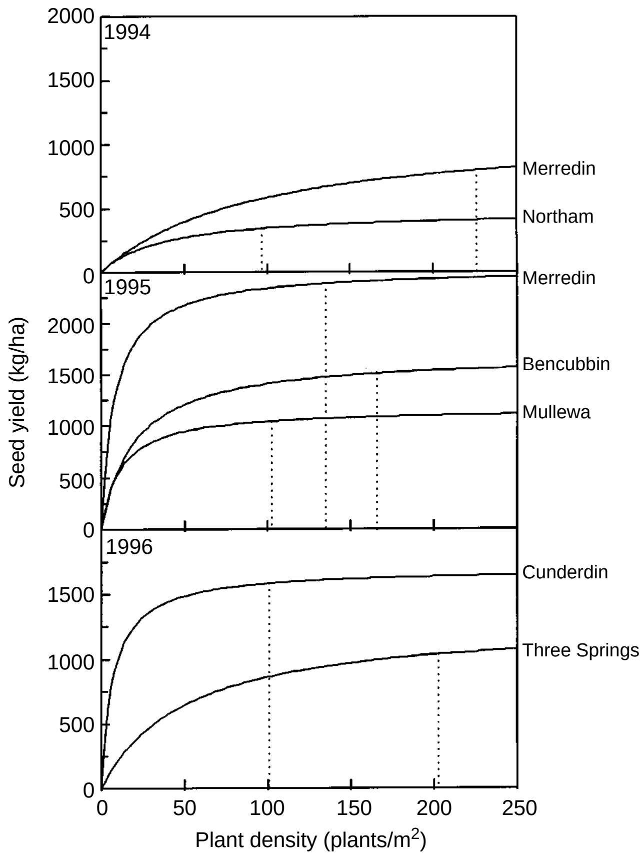

Fig. 2. Fitted curves of seed yield response to plant density at various sites between 1994 and 1996. Vertical dotted lines indicate the economic optimum density for each site.

At Three Springs in 1995, and at Merredin in 1996, the predicted economic optimum densities and seed yield potentials were well beyond the range of

Table 5. Harvest components of lentil at Merredin in 1994, and at Merredin, Cunderdin, and Bencubbin in 1996

Seeding rate (kg/ha)	Biological yield (g/m^2)	Harvest Index	Pod number per plant	Seed number per plant	Mean seed weight (g/100 seeds)
		Merredin 1994			
20	206	0·38	23	1·34	3·49
40	208	0·36	16	1·13	3·56
60	236	0·33	16	1·25	3·51
80	230	0·37	17	1·24	3·46
100	236	0·38	11	1·16	3·57
120	239	0·37	7	1·26	3·60
Mean	226	0·36	15	1·23	3·53
l.s.d. ($P = 0 \cdot 05$)	41	0·05	7	0·18	0·24
		Merredin 1996			
20	328	0·34	121	1·84	3·35
40	326	0·30	106	1·50	3·27
60	371	0·32	68	1·43	3·53
80	409	0·33	62	1·81	3·42
100	396	0·32	66	1·72	3·41
120	379	0·32	52	1·66	3·47
Mean	368	0·32	79	1·66	3·41
l.s.d. ($P = 0 \cdot 05$)	97	0·04	44	0·59	0·30
		Cunderdin 1996			
20	735	0·38	90	1·31	3·22
40	706	0·37	74	1·24	3·08
60	762	0·33	47	1·35	3·02
80	811	0·35	34	1·27	3·02
100	931	0·31	27	1·30	2·94
120	781	0·33	34	1·31	2·95
Mean	788	0·34	51	1·30	3·04
l.s.d. ($P = 0 \cdot 05$)	166	0·04	34	0·13	0·14
		Bencubbin 1996			
20	211	0·26	108	1·48	2·99
40	284	0·39	78	1·30	3·22
60	327	0·33	32	1·14	2·95
80	328	0·25	41	1·32	3·07
100	358	0·32	36	1·37	3·13
120	300	0·30	23	1·31	3·19
Mean	285	0·31	53	1·32	3·09
l.s.d. ($P = 0 \cdot 05$)	99	0·09	0·19	40	0·30

the data, and their standard errors were large. Also, the percentage variance accounted for was <25% at Northam and Dongara in 1995 and Bencubbin in 1996. Therefore, these sites together with Pingaring in 1995 were excluded from further consideration. The fitted curves for the remaining 7 sites are presented in Fig. 2.

The economic optimum densities of the remaining sites ranged from 96 to 228 plants/m^2 (equivalent to sowing rates of 66–156 kg/ha), with a mean of 146 plants/m^2 (101 kg/ha). Seed yield potential ranged from 477 to 2531 kg/ha at Northam in 1994 and Merredin in 1995, respectively. Averaged across all 7 sites, yield potential was 13% greater than the maximum observed yield. There was no significant linear relationship ($P > 0 \cdot 05$) between the estimated economic optimum densities and potential seed yields at the sites. When assuming a 50% opportunity cost, the predicted optimum densities were reduced by about 20% (data not presented).

Discussion

To the best of our knowledge, this is the first investigation in Australia of the effect of sowing rate on the profitability of lentil production. Although the economic optimum plant densities estimated in this study varied considerably (96–228 plants/m^2), the results suggest that in many cases lentil yields can be improved by increasing sowing rates beyond those currently targeted in southern Australia (100–125 plants/m^2). The mean optimum density of 146

Table 6. Curve parameters (*a* and *b*), percentage of variance accounted for, economic optimum density (plants/m²), and seed yield potential (kg/ha) estimated by the asymptotic model for experimental sites

Location	Curve parameters *a*	*b*	Variance accounted for (%)	Economic optimum density	Seed yield potential
			1994		
Merredin	12·2	0·01094	34·3	228±88	1120±308
Northam	12·9	0·02705	73·0	96±13	477±37
			1995		
Bencubbin	84·7	0·05010	66·2	164±30	1692±168
Merredin	311·6	0·12310	46·8	135±22	2531±129
Mullewa	101·5	0·08740	42·7	104±23	1162±114
			1996		
Cunderdin	241·5	0·14260	26·5	102±19	1694±50
Three Springs	25·9	0·02007	51·5	204±39	1291±133

plants/m² and mean optimum sowing rate of 101 kg/ha estimated in this study are similar to those recommended for lentil in Mediterranean environments in northern Syria (Silim *et al*. 1990), but the sowing rate is much greater than those used in the Indian subcontinent (35–60 kg/ha) where winter rainfall is unreliable and lentil crops largely rely on moisture stored in the soil at sowing.

The causes for the large variation in estimated optimum plant density between sites in the present investigation are not clear. As has also been reported for faba bean in a similar study (Loss *et al*. 1998), the optimum plant density appeared to be unrelated to potential yield at the sites for lentil. Other studies with narrow-leafed lupin (French *et al*. 1994) and chickpea (R. Jettner, K. H. M. Siddique, S. P. Loss, and R. J. French unpubl. data) in a similar set of environments found that the economic optimum sowing rate tended to be greater at sites with a high potential seed yield. These results contrast with our findings with lentil. For instance, at Dongara in 1995 and Cunderdin in 1996, which produced seed yields >1500 kg/ha, the predicted economic optimum densities of 89 and 102 plants/m², respectively, were relatively low.

The lentil plant is smaller and more determinate in its growth habit than chickpea and other pulses (Erskine and Goodrich 1991). Hence, its capacity to compensate for low plant density by producing more branches and pods per plant is less than other crops. Even though we observed a greater number of pods per plant at low sowing rates at most sites, the increase was not sufficiently great to compensate for the low plant densities, and seed yield was reduced. Dry matter production at flowering and maturity was also reduced as sowing rate was decreased, whereas there was little change in harvest index, number of seeds per pod, and mean seed weight. In similar environments of northern Syria, Saxena (1981) and Silim *et al*. (1990) demonstrated that a high plant density is necessary to maximise dry matter production and seed yield of lentil, particularly at low rainfall sites where the ability of individual plants to compensate for low density was limited by the dry growing conditions.

The short growing seasons at the sites in this study, and the early flowering and maturing nature of the cultivar Digger compared with other cultivars such as Laird, may explain why the optimum plant densities estimated in Western Australia are generally larger than those suggested for other parts of southern Australia and other countries. Although the interaction between sowing time and sowing rate has not been studied in Australia, delayed sowing (after mid-May) can reduce lentil yield significantly, particularly in low rainfall environments (Siddique *et al*. 1998*b*), and it is likely that high sowing rates are optimum for situations in Australia where sowing is delayed. Similar results have been reported for lentil in India (Ali *et al*. 1993).

Broad-leafed weed management within pulse crops is a serious problem for the Australian pulse industry, particularly lentil. At present there are no registered selective herbicides in Australia that are effective on broad-leafed weeds within lentil crops, and lentil plants are generally poor competitors with weeds compared with other species that have greater dry matter production during the seedling stage of growth (Singh *et al*. 1996). In North America, weed density and dry matter production were reduced by increasing the sowing rate of lentil (Ball *et al*. 1997). In addition, lentil can be a difficult crop to harvest due to its short stature, and increasing sowing rate to achieve greater dry matter at maturity will help increase crop height (Wilson and Teare 1972), which will in turn improve harvestability.

High sowing rates in lentil crops may also reduce the spread of aphids and the viruses they transmit. Aphids appear to be attracted to bare soil, and rapid canopy closure through large sowing rates reduces the infection of viruses in narrow-leafed lupin (Bwye *et al.* 1994). Rapid dry matter production in the seedling stage can also suppress the growth of plants infected with seed-transmitted viruses and, hence, reduce any secondary infection within the crop and subsequent transmission into other crops through seed. High sowing rates and early canopy closure may also reduce water loss through evaporation from the soil. Under chickpea crops in south-western Australia, moisture lost through evaporation from the soil surface can account for up to 60% of crop water-use (Siddique and Sedgley 1987), and similar results could be expected under lentil crops.

Increased sowing rate and early sowing (before mid-May) can increase the level of fungal diseases such as Botrytis grey mould (*Botrytis cinerea*) and Ascochyta blight (*Ascochyta lentis*) in lentil in medium rainfall areas (>400 mm p.a.), particularly in wet years (Anon. 1992). Therefore, we recommend lower sowing rates in medium rainfall regions than in low rainfall areas to help minimise disease infestation, along with other management packages such as the application of foliar fungicides, seed dressings, and appropriate crop rotations.

In this study we sowed seeds with a germination of 80%, yet only 64% of these viable seeds emerged and established into plants. In other words, only 51% of the seeds sown became established as plants. This is lower than the 58% observed for narrow-leafed lupin (French *et al.* 1994) and 71% for faba bean (Loss *et al.* 1998) in similar environments. At the low establishment rates observed in this study, the current sowing rates recommended in Australia of up to 75 kg/ha (Anon. 1992) would result in plant densities up to 109 plants/m^2, only just within the range of the estimated optimum densities. This density would have resulted in reduced profit at many sites in this study. For example, at Three Springs in 1996, 109 plants/m^2 would have produced a seed yield of 886 kg/ha, and assuming a production cost of $A130/ha (excluding seed costs), the resulting profit would have been $179/ha. However, at the optimum density of 204 plants/m^2, 1037 kg/ha would have been produced with a profit of $201/ha.

Some pulse producers are reluctant to spend an extra $1·00 on seed for a return of $1·10 from increased yield, particularly on a crop such as lentil, which is considered more risky than cereals and other crops. Assuming an opportunity cost of 50% rather than 10% reduced the estimated optimum plant densities by about 20% (data not presented). Although reducing sowing rate may result in reduced risk, particularly for inexperienced producers, profit is ultimately compromised.

Pulse seed, particularly lentil, can suffer from physical damage and reduced viability caused by mechanical handling between harvest and planting, and hence, care is recommended to minimise handling the seed (Bergen *et al.* 1993). The more frequently the grain is handled, particularly with screw-type augers, the greater the damage to the seed, and this can result in a reduction in germination percentage and plant establishment. Additionally, lentil is more susceptible to poor emergence caused by crusting of the surface soil than other large-seeded pulses (Siddique and Loss 1998). Therefore, sowing rates may need to be increased to compensate for these factors.

Of the 13 experiments conducted in this study, the asymptotic and quadratic models failed to give fit to the data at Pingaring in 1995. Three other experiments were excluded because of excessive variation in the data. In addition, the models predicted that seed yields were continuing to increase at the highest sowing rate treatment of 120 kg/ha at Three Springs in 1995 and Merredin in 1996, and the estimated economic optimum densities were well beyond the range of the observed data. It would be unwise to place any confidence in the estimated optimum densities at these 2 sites, other than to say that they were larger than the densities measured in these experiments. Clearly, future experiments should include sowing rates exceeding 120 kg/ha to estimate optimum plant density more accurately. Further work is required to define factors affecting optimum plant density in lentil crops in Mediterranean-type environments of southern Australia, but in the meantime, our general recommendation of about 150 plants/m^2 is the best information currently available in south-western Australia.

In conclusion, our results demonstrate that, on average, the profitability of lentil crops in south-western Australia can be maximised by targeting a plant density of about 150 plants/m^2. This density will be equivalent to 90–110 kg/ha, depending on the mean seed weight and germination percentage of the seed. It is likely that higher plant densities (up to 230 plants/m^2) are optimal when growing conditions are unfavourable and the growth of the individual plants is limited (e.g. in low rainfall environments, through delayed sowing or with early-maturing cultivars). Lentil crops sown at high densities may also be better able to compete with weeds, be less prone to aphids and viruses, and help reduce soil evaporation, and are likely to be taller and, hence, easier to harvest than thin crops. In contrast, lower plant densities may reduce the infection of fungi in situations where disease risk is high.

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