Variability in yield of four grain legume species in a subhumid temperate environment I. Yields and harvest index

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SUMMARY

In 1998/99 and 1999/2000, field trials were conducted to try to explain why grain legume yields and harvest index are more variable than many other crops. Treatments involved varying plant populations and sowing depths and were selected to maximize plant variability. Both yields and harvest index were variable. Total dry matter (TDM) production generally increased as plant population increased up to twice the optimum population. Increases ranged from 80 to 130% with lupins producing the highest yields of 878 and 972 g/m² of TDM in 1998/99 and 1999/2000 respectively. While plants sown at 10 cm depth produced more TDM than did plants sown at 2 cm, the difference was only 3%. Seed yields followed similar trends to TDM, with maximum yields (mean of 403 g seed/m²) produced at twice the optimum population. Crop harvest index (CHI) was quite variable and ranged from 0·31 to 0·66. Crop HI was lowest (0·43) at the lowest population and increased to 0·55 at twice the optimum plant population. In both seasons, lentil had the highest CHI and lupin the lowest. While CHI was variable there were very close relationships between seed yield and TDM which suggested that maximum seed yield depends on maximizing TDM production. The results also suggest that growers should increase population by a factor of two to obtain maximum seed yields.

INTRODUCTION

Grain legumes can produce high seed yields under favourable conditions (McKenzie & Hill 1991; Moot 1997). However, yield instability within and between grain legume species at different sites and among seasons has been recognized as a persistent problem (Moot & McNeil 1995; Ma *et al.* 1998), even when agronomic variation is minimized (Ambrose & Hedley 1984). This yield instability has also been reported in Canterbury. Variation in harvest index (HI), which can lead to low average yields (Hedley & Ambrose 1985), has been identified as the main cause (Moot & McNeil 1995). To overcome the challenge of yield variability, breeders need to produce plants with high and stable yields that are adapted to diverse environments and are disease resistant (Moot & McNeil 1995). Manipulating plant population and sowing pattern can reduce some of this variability. More uniform sowing may give less variable plant populations with reduced plant-to-plant variation and increased yield (Hedley & Ambrose 1981).

Most grain legumes are reasonably plastic in their response to changed plant population. However, in many grain legumes the response to increased plant population has been variable. Seed yield, total dry matter (TDM) and HI of lentil (*Lens culinaris*), chickpea (*Cicer arietinum*), field pea (*Pisum sativum*) and faba bean (*Vicia faba*) all increased as plant population increased (Siddique & Loss 1999). However, McKenzie *et al.* (1986) reported no yield increase in lentils as plant population increased from 100 to 400 plants/m², while HI was significantly reduced. Some researchers have reported optimum yield at equidistant inter- and intra-row spacings (Moot 1993). Variable HI is an important contributor to yield instability among grain legumes. Husain *et al.* (1988) and Anwar *et al.* (1999) reported HIs in grain legumes, which varied from 0·00

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Table 1. *MAF soil quick test for 0–30 cm depth for the Horticultural Research area (1998/99) and the Henley Research farm (1999/2000) of Lincoln University, Canterbury. Ca, K, P, Mg, Na and S and NH_4^+, NO_3^- are expressed as μg/g soil, and total N (TN) and C as g/kg*

Season	pH	Ca	K	P	Mg	Na	S	C	NH_4^+	NO_3^-	TN
1998/99	5·4	7	8	27	16	5	9	2·4	–	1	2·0
1999/2000	5·8	10	9	12	28	8	9	–	5	<1	2·7

to 0·74. Moot & McNeil (1995) reported variable HIs in pea cultivars, which ranged from 0·53 to 0·62 in a single plant study.

Increased sowing depth may benefit crop establishment and performance because there is more available moisture in the subsoil. Alternatively, it may lead to increased variability in time to emergence. However, with the exception of Russell lupin (*Lupinus arboreus* × *L. polyphyllus*) (Wangdi *et al.* 1990), there is no published data on the effect of sowing depth on large-seeded legumes under field conditions in Canterbury. Deep sowing may help ensure good crop establishment (Stucky 1976). Sowing at 10 cm has been shown to increase seed yield in chickpea, faba bean, lentil and field pea (Saxena 1987; Siddique & Loss 1999). In contrast, Wangdi *et al.* (1990) found no significant effect of sowing depth on early TDM production of Russell lupins, while Siddique *et al.* (1993) reported reduced yield with deep sowing in chickpea.

Vellasamy *et al.* (2000) and McKenzie *et al.* (1986) have shown that more than 27 t of lupin TDM/ha and 13 t of lentil TDM/ha can be produced under experimental conditions in Canterbury. McKenzie & Hill (1995) reported experimental seed yields of more than 4 t/ha from chickpea. Anwar *et al.* (1999) reported 12 t TDM/ha with more than 6 t seed/ha in Kabuli chickpea. Moot & McNeil (1995) reported a TDM production of up to 12 t/ha from field pea.

There is little published data on the effect of a combination of plant population and sowing depth on grain legume yield. Therefore, the present study was conducted to investigate whether agronomic practices such as plant population, sowing depth and their interaction had any impact on TDM, seed yield and HI in a range of grain legume species.

MATERIALS AND METHODS

Grain legume species

The four grain legume species selected were land race chickpea (*Cicer arietinum*), field pea (*Pisum sativum*) cv. Beacon, lentil (*Lens culinaris*) cv. Rajah and narrow-leafed lupin (*Lupinus angustifolius*) cv. Fest.

Site and soil characteristics

The experiment was located at the Horticultural Research Area in 1998/99 and at the Henley Research Farm in 1999/2000. Both sites are at Lincoln University, Canterbury, New Zealand (latitude 43°39′S, longitude 172°28′E). The soil is a Wakanui silt loam soil (Hewitt 1992). A Chinese cabbage (*Brassica campestris*) crop had been grown in the previous season to the 1998/99 experiment, and the Henley site, used in 1999/2000, was previously in perennial ryegrass (*Lolium perenne*). The climate data for the two experiments were recorded at Broadfield Meteorological station, Lincoln University, situated about 1 km from the experimental sites. A Ministry of Agriculture and Fisheries (MAF) soil quick test was done in each season to determine available soil nutrient levels (Table 1).

Experimental design

The first experiment (1998/99) was a split-plot randomized block design, with the four grain legume species (chickpea, lentil, narrow-leafed lupin and field pea) as main plots. Subplots consisted of four plant populations (one-tenth of the optimum population, the optimum population, twice the optimum population or four times the optimum population). Optimum plant populations were 50 plants/m² for chickpea, 150 plants/m² for lentil, 100 plants/m² for narrow-leafed lupin and 100 plants/m² for field pea. There were three replicates.

Each subplot was 10 m long and had 16 rows each 15 cm apart. Sowing was on 30 October 1998. Seed was sown at 4–5 cm depth using a tractor-driven cone seeder.

The second experiment (1999/2000) was a split split-plot design. The trial had the same four legume species as main plots. Subplots were three plant populations, and three sowing depths (2, 5 or 10 cm) were allocated to sub-subplots. There were three replicates.

Plots were hand sown, one replicate per 2 days between 19 and 24 October 1999 in equidistant arrangements. Sowing was on the square at 31·5 × 31·5, 10 × 10 and 5 × 5 cm to give plant populations of 10, 100 and 400 plants/m². Each sub-subplot was 5·67 × 3·15, 1·5 × 2 and 0·8 × 0·2 m for the low, medium and high plant populations, respectively.

Crop management

Intensive crop management was used to minimize possible yield variation caused by agronomic factors.

Table 2. *Days from sowing to emergence of four grain legumes sown at three sowing depths and from sowing to harvest at three populations of four legume species sown in Canterbury, 1999/2000*

	Sowing depth (cm)			Plant population (plants/m^2)		
Species	2	5	10	10	100	400
Chickpea	7	8	11	159	154	150
Lentil	7	9	11	136	132	128
Lupin	6	9	14	168	163	159
Pea	6	9	11	109	106	102
S.E. (D.F. = 48)		0·3			0·06	

Prior to sowing, the fields were cultivated by ploughing, harrowing and rolling to produce high standard seedbeds. As well as a pre-sowing application of Treflan (trifluralin, 400 g a.i./l in 237 litres of water/ha) in the first experiment and of Round-up (glyphosate 360 g a.i./l in 237 litres of water/ha) in the second experiment, a pre-emergence application of Bladex (cynazine 500 g a.i./l in 237 litres of water/ha) was used in both trials. Gallant (haloxyfop, 100 g a.i./l in 237 litres of water/ha) was used as a post-emergence spray for grass control. No weed control was necessary at the highest plant population. At lower plant populations weeds were controlled by hand hoeing.

No fertilizers were applied. Seed was treated with a fungicide, Apron 70 SD (metalaxyl 350 a.i./kg and captan 350 g/kg), at 200 g (dissolved in 500 ml of water) per 100 kg seed.

Sprinklers were used to apply 75 mm of water in three irrigations each of 25 mm during the first experiment on 18 November and 30 December 1998 and 15 January 1999. In the second experiment, no irrigation was necessary due to adequate rainfall.

Mesurol (methiocarb, 750 g a.i./kg in 200 litres of water) was sprayed onto the second trial to control bird attacks on the mature crops close to harvest.

Measurements

In the 1998/99 season, seed yield, TDM production and the crop harvest index (CHI; total seed yield per unit area divided by total yield per unit area) were calculated from a 2 m^2 harvested area. This was taken randomly from four places using a 0·5 m^2 quadrat along the central rows of each subplot at harvest maturity (when 95 % of the plants within a species had turned brown). The four species (field pea, lentil, chickpea and narrow-leafed lupin) were harvested at 91, 112, 126 and 133 days after sowing (DAS) respectively. Plants were cut to ground level, air dried and threshed in a Kurtpelz stationary thresher.

In 1999/2000, at crop maturity, a 0·2 m^2 area was cut to ground level. Because of differential maturity, plots were harvested on different days (Table 2). Samples were air-dried; pods were separated and bagged. Samples were then oven dried at 70 °C to a constant weight and seed and straw was weighed.

All variates were analysed using analysis of variance procedures with the statistical programme Genstat (Genstat 5 Committee of the Statistics Department, Rothamsted Experimental Station, Hertfordshire, UK).

RESULTS

Climate

The weather from October 1998 to April 1999 was dry and the rainfall was about 40 % less than the long-term average. Rainfall in October, November, December, January, February, March and April was 57, 20, 24, 36, 38, 56 and 36 mm, respectively, compared to 55 year corresponding mean values of 55, 56, 61, 50, 51, 59 and 52 mm (Fig. 1). Overall rainfall during the entire growing season (to 95 % physiological maturity) was about 200 mm.

Maximum and minimum temperatures were similar to the long-term average, but the mean temperature was increased by about 5 % from January to March 1999. Solar radiation from January to March 1999 was also about 7 % higher than the long-term average.

Rainfall from October 1999 to April 2000 was 353 mm. This was about 90 % of the long-term average of 385 mm. Rainfall during the growing season (sowing to physiological maturity) was approximately 260 mm. Maximum and minimum temperatures were similar to long-term averages (Fig. 1). However, mean monthly maximum temperatures during December 1999 to January 2000 were 18·9 and 19·5 °C, respectively. These are lower than the 55-year mean values of 21·3 and 22·6 °C respectively. Solar radiation from December 1999 to March 2000 was about 10 % higher than the long-term mean.

Emergence

In the first trial, all species emerged (> 50 %) by about 7–9 DAS. In the second trial, the species × depth interaction was highly significant ($P < 0·001$), while population, species and/or their interaction were not

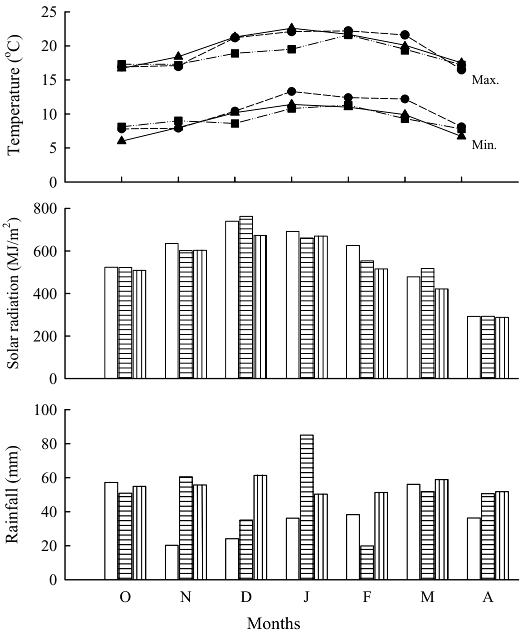

Fig. 1. Weather data for 1998/99 (□, ●) and 1999/2000 (▤, ◆) growing seasons and long-term means (▥, ▲) for Lincoln University, Canterbury, New Zealand. Long-term means for rainfall and temperature (1944–99) and solar radiation (1975–99).

significant (Table 2). When sown at 2 cm, lupin and pea emerged the fastest (6 DAS) and lentil and chickpea the slowest at 7 DAS. There was no difference in time of emergence from 5 cm depth. At the deepest sowing lupin was the last to emerge (14 DAS) and the other three species were the fastest (11 DAS).

Total dry matter production

In 1998/99, TDM production differed among both plant species and plant population (Table 3). Among the four species, the highest mean TDM production over all populations was 878 g/m^2 from lupin followed by chickpea at 701 g/m^2. The species by population interaction (Fig. 2*a*) showed that increased plant population increased TDM production in lentil and narrow-leafed lupin but decreased it in chickpea and field pea. For lentil and narrow-leafed lupin the lowest TDM (186 and 771 g/m^2, respectively) was at the lowest plant population (15 and 10 plants/m^2, respectively) and the highest TDM (513 and 971 g/m^2) at the highest plant populations (600 and 400 plants/m^2, respectively). In chickpea and pea the lowest TDM yields (430 and 292 g/m^2, respectively) were also from the lowest plant populations (5 and 10 plants/m^2), but the highest TDM (869 and 670 g/m^2) was produced at 100 and 200 plants/m^2, respectively.

Table 3. *Total dry matter, seed yield and crop harvest index (CHI) of four legume species grown at different plant populations and sowing depths in Canterbury, 1998/99 and 1999/2000*

	TDM (g/m^2)	Seed yield (g/m^2)	CHI
	1998/99		
Species			
Chickpea	701	384	0·52
Lentil	418	244	0·57
Lupin	878	386	0·44
Pea	532	286	0·53
S.E. (D.F. = 6)	5·0	3·8	0·008
Population			
One-tenth optimum	420	173	0·43
Optimum	664	340	0·52
Twice optimum	738	403	0·55
Four times optimum	708	384	0·55
S.E. (D.F. = 24)	8·3	4·7	0·010
CV %	4·5	5·1	6·1
	1999/2000		
Species			
Chickpea	800	458	0·55
Lentil	468	293	0·61
Lupin	972	527	0·54
Pea	595	351	0·58
S.E. (D.F. = 6)	7·2	5·3	0·050
Population			
10 plants/m^2	484	236	0·50
100 plants/m^2	742	423	0·58
400 plants/m^2	900	563	0·63
S.E. (D.F. = 16)	3·7	2·8	0·004
Sowing depth			
2 cm	696	394	0·56
5 cm	711	407	0·57
10 cm	720	420	0·58
S.E. (D.F. = 48)	1·8	1·6	0·003
CV %	1·5	2·4	3·4

In 1999/2000, TDM production was significantly influenced by legume species, plant population and sowing depth (Table 3). Averaged over both seasons the highest population density produced 80% more TDM than the lowest population. Total DM production ranged from 595 g/m^2 in lentil to 972 g/m^2 in narrow-leafed lupin. The plant population by species interaction was significant ($P < 0{\cdot}05$) (Fig. 2*b*). It showed that lentil TDM had the highest percentage variation over the three populations. There was nearly a 200% increase in TDM from 10 to 400 plants/m^2. In narrow-leafed lupins, however, the increase in TDM production between 10 and 400 plants/m^2 was only 35%. The other two species had intermediate values. The significant species by sowing depth interaction

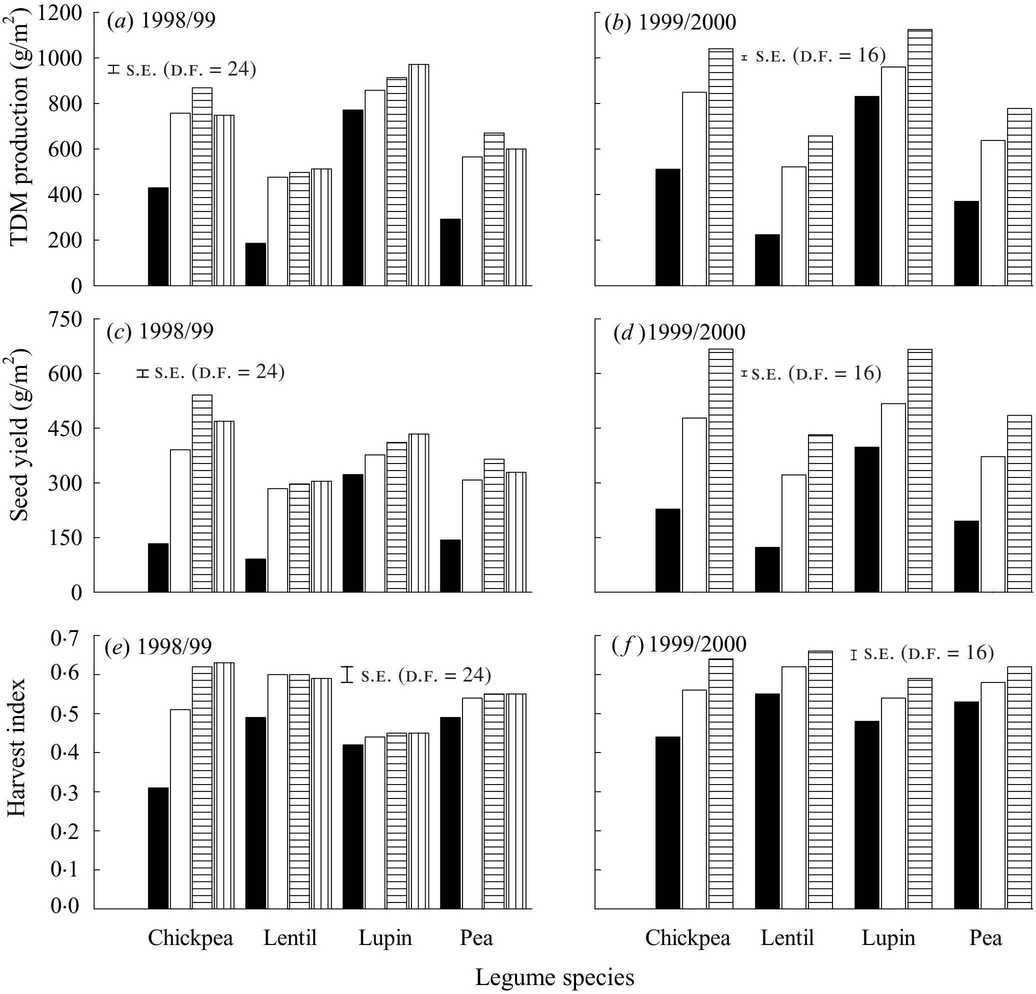

Fig. 2. The interaction between crop population and four grain legume species on yield and crop harvest index in Canterbury, 1998/99 (*a*, *c*, *e*); one-tenth of the optimum population (■), the optimum population (□), twice the optimum population (▤), four times the optimum population (▥), and 1999/2000 (*b*, *d*, *f*); 10 plants/m² (■), 100 plants/m² (□), 400 plants/m² (▤).

(Table 3) indicated that as sowing depth increased from 2 to 10 cm, there was a very small increase in TDM production in narrow-leafed lupin. However, the response in lentil was larger at about 8%. The TDM at final harvest over the two seasons ranged from 418–972 g/m². In 1999/2000 the species produced about 20% more TDM, on average, than in 1998/99.

Seed yield

In 1998/99, seed yield was significantly affected by both species and population, and their interactions. Chickpea and narrow-leafed lupin yielded more than lentil and field pea (Table 3). The species by population interaction (Fig. 2*c*) showed that only lentils and narrow-leafed lupin increased their seed yield (from 91 to 304 and 323 to 434 g/m², respectively) as plant population increased from 15 to 600 and 10 to 400 plants/m², respectively. Chickpea and field pea produced their highest seed yield (541 and 365 g/m²) when sown at 100 and 200 plants/m², respectively. At the highest plant density seed yield declined in both species.

In 1999/2000, as in 1998/99, chickpea and narrow-leafed lupin out-yielded lentil and field pea (Table 3). The species by plant population interaction (Fig. 2*d*) showed that lentil seed yield varied most across populations. Seed yield increased from 123 to 432 g/m², an increase of 250%, as plant population increased from 10 to 400 plants/m². In narrow-leafed lupin, seed yield was not affected by increased sowing depth, but

Table 4. *The species by sowing depth interaction for TDM production (g/m²) and seed yield (g/m²) in Canterbury, 1999/2000*

	TDM production			Seed yield		
	Sowing depth (cm)					
Species	2	5	10	2	5	10
Chickpea	788	802	810	443	455	475
Lentil	447	469	487	276	291	310
Lupin	968	973	976	518	530	533
Pea	580	599	607	338	352	362
S.E. (D.F. = 48)		7·8			6·0	

lentil yield increased significantly ($P < 0.001$) from shallow to deep sowing by 12% (Table 4). The other two species were intermediate to these values. Overall the 1999/2000 growing season yielded 25% more seed than the 1998/99 season.

Crop harvest index

In 1998/99, crop harvest index (CHI) was significantly affected ($P < 0.001$) by both species and plant population (Table 3). Averaged over all populations lentil had the highest CHI (0·57) and narrow-leafed lupin the lowest (0·44). The species by population interaction (Fig. 2*e*) shows that the CHI for the four species increased between the low and medium populations. At high populations, however, there was only a yield increase in chickpea. The highest CHIs (0·62 and 0·63) were recorded in chickpeas sown at the high (100 plants/m²) and very high plant populations (200 plants/m²).

In 1999/2000, CHI was higher than in 1998/99. Lentil and narrow-leafed lupin increased their respective CHIs by 7 and 23% between the two seasons from 0·57 to 0·61 and 0·44 to 0·54, respectively. In chickpea, the increase was greater over the three populations (Fig. 2*f*). The increase in CHI between 10 and 400 plants/m² was from 0·44 to 0·64, respectively. For field pea, however, the increase in CHI from the low to high populations was from 0·53 to 0·62.

There was a positive, linear and highly significant ($P < 0.01$) relationship between TDM and seed yield (Fig. 3). The regression coefficients were greater than 0·95 in both trials.

DISCUSSION

In the present study, both TDM and seed yield at final harvest were influenced by both legume species and plant population. There were very high correlations ($R^2 > 0.95$) between seed yield and TDM in all four species in both growing seasons. Thus high DM production contributed to higher seed yield. High TDM production is a prerequisite for high seed yield in chickpea (Saxena 1987; Siddique *et al.* 1993; Omar & Singh 1997), pinto bean (*Phaseolus vulgaris*; Dapaah *et al.* 2000) and *Vicia faba* and peas (Thomson *et al.* 1997).

Species differences in TDM production depended on growth duration. Lupin and chickpea had much longer durations than pea or lentil. The former two species intercepted more light and had delayed senescence. This resulted in more TDM production. The extra yield may also have been due to differences in the radiation use efficiency (RUE) among these species (Ayaz *et al.*, in press). Similar results were reported for *Lupinus mutabilis* and pinto beans (Hardy *et al.* 1996; Dapaah 1997), respectively.

In the present study, the species × population interaction for TDM production was significant as it increased from low to high plant populations. High plant populations close their canopies quickly and intercept more sunlight more rapidly than low plant populations (McKenzie & Hill 1991; Hardy *et al.* 1996). This results in high early crop growth rates, which can be sustained if the crops have adequate soil moisture and fertility. Only in narrow-leafed lupin, which had a very long growth duration, did the low plant population yield nearly as much as at the highest population (Ayaz *et al.* 1999). This was again related to increased radiation interception, as the low population lupin plants produced extensive basal branches which helped increase radiation interception.

Averaged over all species TDM production was 40% higher in 1999/2000 than in 1998/99. This might have been due to the lower temperatures in 1999/2000, which lengthened crop duration in all four species (Saxena & Goldsworthy 1988). There was also more rainfall. In Western Australia, in a high rainfall year, legume species also responded by increasing yield (Thomson *et al.* 1997).

Increasing the sowing depth increased TDM and seed yield in all four species in the present study. Similar results have been reported for chickpea, faba bean, lentil and pea (Saxena 1987; French & Pritchard 1993; Siddique & Loss 1999). The increased yield from sowing at depth was probably due to greater moisture availability in the subsoil (Siddique & Loss 1999).

The regressions of TDM against $\log_{(e)}$ (population) indicated a high degree of linearity. The slopes and regression coefficients are presented in Table 5. When the slopes of the regressions are compared, chickpea was most responsive and narrow-leafed lupin the least. Narrow-leafed lupin had a very long crop duration and most growth occurred after canopy closure, irrespective of plant population. Consequently, they were less responsive to population density than the other three species.

Highest seed yields were from narrow-leafed lupin followed by chickpea. Lentil had the lowest seed yield.

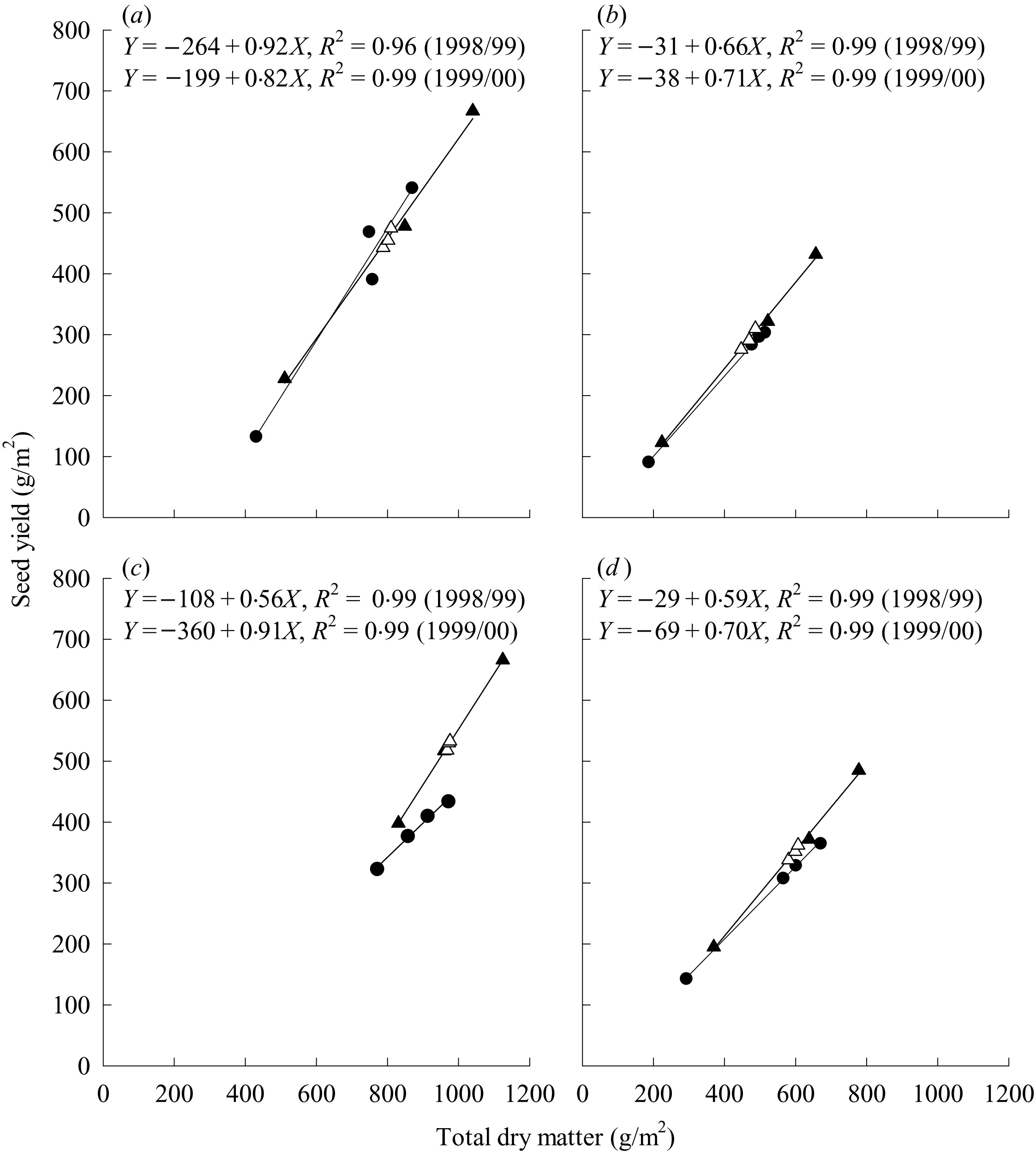

Fig. 3. The relationship between seed yield and total dry matter production at final harvest for (*a*) chickpeas, (*b*) lentils, (*c*) lupins, (*d*) peas sown at four plant populations (●) in 1998/99, and three plant populations (▲) and three sowing depths (△) in 1999/2000.

Lentil plants are smaller and more determinate in their growth habit than chickpea and other legumes (Erskine & Goodrich 1991). Their capacity to compensate for low plant population by producing more branches and pods/plant is less than in lupin, chickpea and pea. Although a greater number of pods/plant was produced at the low population of lentils (Ayaz *et al.* 2004) the increase was not enough to compensate for the low plant density and seed yield was reduced at the low population. Silim *et al.* (1990) advocated that a high plant population was necessary for high seed yield and TDM production in lentil.

Table 5. *Gradients* (*b*) *and regressions* (R^2; *%*) *for plots of species* v. *log* $_{(e)}$ *plant population, 1998/99 and 1999/2000*

	1998/99						1999/2000					
	TDM*		SY		CHI		TDM		SY		CHI	
Species	b	R^2	b	R^2	b	R^2	b	R^2	b	R^2	b	R^2
Chickpea	105	79	105	89	0·10	97	143	99	118	99	0·10	99
Lentil	94	93	61	92	0·03	82	118	99	84	99	0·03	99
Lupin	52	95	30	98	0·01	97	77	96	70	96	0·03	99
Pea	97	87	58	88	0·02	95	111	99	78	99	0·02	99

* TDM = total dry matter, SY = seed yield, CHI = crop harvest index.

High seed yields were also the result of high TDM production in the present study and yields were 25 % higher in 1999/2000. This was caused by the cooler wetter conditions in 1999/2000 which resulted in longer crop durations, increased radiation interception and in greater yields. The equidistant sowing of the crops may have contributed to the higher yields observed in 1999/2000. When two plants compete, the outcome is 'one-sided', i.e. the relative growth rate of the smaller plants is decreased while the larger plant is unaffected. Weiner *et al.* (1990) also suggested that this asymmetry is primarily due to competition for light and soil resources. Several other workers have reported optimum yields at equidistant inter- and intra-row spacings (Parvez *et al.* 1989). In the present study, competition was high within a row for rectangular sown plants compared with on-the-square sown plants, where the competition was low and slower to develop for light and nutrients. In the rectangular sowing, larger plants met and shaded smaller plants quickly. Similarly, below-ground competition for nutrients would have been greater in the rectangular sowings.

Overall, seed yield approximately doubled as plant population increased from one-tenth of the optimum to the optimum in 1998/99 and from 10 to 100 plants/m² in 1999/2000. However, with an additional four-fold increase in plant population, the species did not respond in the same way and yield only increased by about 30 % in 1999/2000. In 1998/99, increasing population density from one-tenth of the optimum to the optimum increased seed yield while at the four-fold population increase there was a yield plateau. This may have been associated with reduced branching and slower leaf formation at the highest population (Stern 1965). At very high plant populations, competition develops earlier and becomes progressively more intense. If the population is sufficiently high, some plants will die as shading reduces their capacity to exploit nutrient supply and competition develops for nutrients as well as for light (Stern 1965). Moot (1993) also reported an asymptotic relationship in peas as plant population was increased. The increase in seed yield with increased plant population, up to 400 plants/m² in all species, during the 1999/2000 trial is supported by the results of Effendi *et al.* (1989) and McKenzie *et al.* (1989) with lentil. Increasing plant population from 10 to 100 plants/m², almost doubled seed yield. However, further increase in plant population only increased the yield by 30 %. Moot (1993) reported similar results for peas in Canterbury.

Seed yield in chickpea responded strongly to increased plant population while narrow-leafed lupin responded the least (Table 5). The effect of plant population on seed yield is consistent with other published data (Pilbeam *et al.* 1991; Ayaz *et al.* 1999). In the present study, seed yield of legume species continued to increase from one-tenth of the optimum to four times the optimum plant population except in chickpea and field pea in which yield declined at the highest population. In 1998/99, lentil seed yield tended to increase up to 600 plants/m². Moot & McNeil (1995) reported that, in their experiments, seed yield of some pea cultivars had an asymptotic response to increased plant population while others exhibited a parabolic response. This indicates that maximum seed yield might be produced beyond the populations tested. In the present study, however, there was only a small increase in seed yield as plant population was increased from the optimum to four times the optimum. This may result in an economic loss through increased seed costs needed to maximize seed yield.

In the present study, the CHI was variable over species, populations and sowing depths. Averaged over all treatments, the highest CHI was in lentil and the lowest in lupin, in both seasons. This may have been due to the shorter lentil stems. In cereal crops, improvements in HI have generally been made through a reduction in stem length and the increased diversion of assimilates to grain production (Stanforth *et al.* 1994). This variation in CHI may also have been due to the conversion of a higher proportion of the dry matter of the lentil to seed than in narrow-leafed lupin, which consequently gave a higher CHI as Moot (1993) reported in different pea genotypes. Also in a range of grain legumes, chickpea (0·42), common vetch (0·44) (Siddique *et al.* 1999), lentil (0·50) and faba bean (0·55) tended to have higher HIs than *L. angustifolius* (0·25) *L. albus* (0·21) (Thomson *et al.* 1997). Saxena (1984) reported that HI has been found to be low in grain legume crops with longer crop growth duration, mainly because of the extended period of vegetative growth. The partitioning efficiency of mung bean (*Vigna radiata*) (0·52) at maturity (65 DAS) was higher than that of soybean (*Glycine max*) (0·34) at 72 DAS (Angus *et al.* 1983). Similar results were reported in maize (*Zea mays*) (Birch *et al.* 1999). A similar conclusion can be drawn from plant population densities where plants matured earlier at high populations than at lower populations.

In both seasons CHI increased as plant population increased up to about twice the optimum. After this level the CHI plateaud. In 1998/99, it increased from 0·43 at one-tenth of the optimum plant population to 0·55 at twice the optimum population, but further increase in plant population to four times the optimum gave no further increase in CHI. This plateau may have been due to the high competition at the highest population for light and nutrients (Ambrose & Hedley 1984). Also, where plants had the highest competition within the row, there was increased variability in plant size (Weiner *et al.* 1990). If plant density is sufficiently high, some plants produce pods with no seed and this was a major reason for a low CHI in peas (Moot 1993). In 1999/2000, the increase in CHI may have been due to the use of uniform, on the square, hand sowing to reduce agronomic variability (Ambrose & Hedley 1984) and the wetter season (de Costa *et al.* 1999).

The species × population interaction indicated that CHI varied in all four legume species as the population changed. The trend for higher HIs with increased population is similar to results obtained from lentils (Effendi *et al.* 1989), *Vicia faba* (Attiya *et al.* 1983) and lupins (Herbert 1977) in Canterbury. This was due to increased TDM production with a corresponding increase in seed yield (Ashraf *et al.* 1994). However, in 1998/99, the CHI increased, in all species, between one-tenth of the optimum population and the optimum. Further increases in plant population only produced a further increase in chickpea yield. The highest CHI (0·62 and 0·63) was observed in chickpea sown at twice the optimum (100 plants/m^2) and four times the optimum (200 plants/m^2) plant populations. The lack of an increase with increased population in CHI in the other species may have been due to pod dehiscence at the higher plant populations. Pea pods have been reported to be highly dehiscent (Knott 1987) and loss of seed will affect HI (Owens y de Novoa 1980). However, in a population study with lentil, McKenzie *et al.* (1986) found that as plant population increased from 100 to 400 plants/m^2 the CHI declined from 0·33 to 0·30. This reduction or lack of response of CHI to increased population was due to a lack of response of seed yield as there was an attack of *Botrytis cinerea* on the crop, which curtailed pod filling.

The CHI was consistently positively and strongly correlated ($R > 0{\cdot}90$) with seed yield in all four legume species in both years. Thus the CHI was a good indicator as a selection criterion to improve the yield of these grain legumes by increasing their TDM production.

CONCLUSIONS

The currently recommended population for chickpeas, lentils, lupins and peas of 50–100, 100–150, 100 and 100 plants/m^2, respectively, do not generally give maximum TDM and seed yield in New Zealand. A sowing depth of 5 cm appears to be suitable for all four of the legume species tested. Chickpea and narrow-leafed lupin both have the potential to yield more than 6·5 t/ha of seed in New Zealand. The greater response of chickpea CHI to plant population was probably due to improved reproductive structure as branching was reduced by increased plant population. Seed yield can be increased by increasing the biological yield without changing the CHI or by improving the CHI by partitioning more of assimilates to seed, or by both.

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