Growth response of cool tolerant soybean to variation in sowing date

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Abstract

Sowing date trials were conducted in two seasons (1999/2000 and 2000/2001) at the same site at Lincoln University, Canterbury to determine the effect of sowing date on soybean dry matter accumulation, partitioning, and seed growth rate and duration, and their relationship with seed yield. Three sowing dates (15 November and 7 and 29 December) and four cultivars (Northern Conquest, March, Maypole and Alta) were used in 1999/2000 and four sowing dates (2 and 17 October, 1 and 16 November) and two cultivars (Northern Conquest and March) were used in 2000/2001. The maximum total dry matter (TDM_{max}) was attained around the start of seed filling (R5) in all cultivars for all sowing dates. In both seasons TDM_{max} was strongly associated with seed yield; both were significantly reduced for the 1999 December sowings. Seed growth rate (ISGR) and seed filling period (SFP) were also affected by sowing date; the highest ISGR (5.1 mg seed^{-1} day$_{-1}$) and lowest SFP (33.2 days) occurred for the 15 November sowing in 1999, while the highest ISTG and lowest SFP occurred for the 1 November sowing in 2000. WMAGR and ISGR also had significant linear relationships with seed yield, and SGR was strongly associated with WMAGR. However, seed yield was poorly associated with SFP and the partitioning coefficient. The factors that influence WMAGR and hence TDM_{max} in soybean also regulate seed yield.

***Additional keywords*:** dry matter accumulation, partitioning coefficient, seed growth rate.

Introduction

Soybean dry matter (DM) accumulation by the start of the seed-fill stage (R5) is considered to be a major determinant of seed yield (Egli *et al*., 1987; Board *et al*., 1992). Dry matter production is a function of the amount of solar radiation intercepted by the canopy and radiation use efficiency (Monteith, 1977). Canopy development will vary with the environmental conditions as determined by the ambient temperature and photoperiod. Previous research in New Zealand (Dougherty, 1969) showed that sometimes soybean produced extensive vegetative growth in Canterbury (i.e. high DM) but gave a low yield. Further reports showed the seasonal yield variability in soybean with the then US cultivars available was very high, (Hill *et al*., 1977; 1978) and this restricted the commercial development of this crop in New Zealand.

Poor soybean yield despite robust vegetative growth might be due to a reduced remobilisation of assimilates to the reproductive sink. The pattern of partitioning of dry matter to the reproductive sink can be indicated by the partitioning coefficient (ratio of reproductive pod biomass to vegetative (stem + leaf) biomass).

Seed yield also depends on the individual seed weight (Wells *et al*., 1982), which is the product of seed growth rate and duration. While both are under genetic control (Egli, 1994), they can be affected by environmental factors, particularly temperature and solar radiation (Egli, 1994). Individual seed growth rate (ISGR) depends on the cotyledon cell number, which is fixed at the beginning of seed fill (Munier-Jolain and Ney, 1998). The cotyledon cell number is related to the assimilate availability during cotyledon cell division (Egli *et al*., 1989). After the onset of seed filling, seed growth rate remains constant, while seed filling duration can be shortened if the plant's photosynthetic activity is insufficient to fulfil the assimilate demands of seeds (Munier-Jolain *et al*., 1998).

The physiological basis of soybean yield variability has not yet been investigated in New Zealand. The present research was therefore undertaken to determine the effect of sowing date on dry matter accumulation, partitioning coefficient, and seed growth rate and duration of cool tolerant soybean cultivars sourced from Northern Europe (Rahman *et al*., 2005) in Canterbury, and to examine the relationship of these growth and physiological parameters with soybean seed yield.

Materials and Methods

Sowing date trials were conducted over two seasons (1999/2000 and 2000/2001) at the Horticulture Research Area (HRA) of Lincoln University (Lat. 43°38′ S and Long. 172°30′ E) on a Wakanui silt loam soil (Hewitt, 1992). The experiment in the 1999/2000 season used four cultivars (Northern Conquest (Group V) and Maypole, Alta and March (Group VII)) with three sowing dates (15 November, 7 December, and 29 December 1999) and each cultivar/sowing date treatment was replicated three times. The experiment in 2000/2001 used two cultivars (Northern Conquest and March) with four sowing dates (2 October, 17 October, 1 November and 16 November 2000) and four replicates of each treatment. A split-plot design was used in both experiments with sowing date being the main plot and cultivar being the sub-plots. The unit plots size were 6 m x 2.7 m and 8 m x 4.2 m for the 1999/2000 and 2000/2001 seasons, respectively. Crop establishment and management were as described by Rahman *et al*. (2005a).

Meteorological data including maximum and minimum air temperatures, rainfall, and incident solar radiation for both seasons were collected from the records of the Broadfield Meteorological Station at Lincoln University. Photoperiod (day length from sunrise to sunset including civil twilight) was collected from the computer routine programme adapted from Land Information New Zealand.

Crop growth stages were monitored at 2 – 3 day intervals during the cropping season and the reproductive stages were recorded using the Fehr and Caviness (1977) scale. In both seasons, dry matter accumulation was measured from 0.2 m^2 plant samples randomly cut at ground level from each plot (leaving the middle portion of the four central rows for final harvest for seed yield (Rahman *et al*., 2005a) and one border row each side to avoid border effects). Samples were taken at 7 day intervals in 1999/2000 starting at the date of first flowering and at 10-day intervals in 2000/2001 starting at 50 days after sowing (DAS), and continued up to physiological maturity.

All sowing dates except the 16 November 2000 were used for the crop dry matter study (since a portion of the 16 November sown crop was damaged by rabbits). The sampled plants were separated into leaves (leaflet + petiole), stems and pods (when present), oven dried at 65 °C to a constant weight in a forced draft oven and weighed. Indices of partitioning of DM to reproductive yield components (PC, partitioning coefficient) were calculated using linear regression of pod harvest index (PHI; pod DM divided by total DM) as a function of time (Dapaah, 1997). The slope of the derived regressions line was regarded as PC.

Individual seed weight (ISW) accumulation was calculated by taking two replicates of 50 seeds (seeds had to have a length ≥ 3 mm) at each sampling date per plot. Pods were collected randomly from four selected plants per plot at each sampling date starting at the full pod stage (R4 stage, pod length ≥ 2.0 cm) until maturity (R8 stage, 95% pods brown) on a whole-plant basis. Seed weight was measured after oven drying seeds at 103 °C for 17 hours (Chanprasert, 1988) and expressed as mg $seed^{-1}$. The sample plants for the seed growth study were collected at 7-day intervals in 1999/2000 and at 5-day intervals in 2000/2001. Individual seed growth rate (ISGR) on a whole-plant basis was estimated for each plot using the linear regression technique outlined by Egli *et al*. (1981). The slope of the resulting line was used as ISGR and expressed as mg $seed^{-1}$ day^{-1}. The seed filling duration (SFD) was estimated by dividing the final seed dry weight by seed growth rate (Danyard *et al*., 1971). Final seed weight was recorded from 200 seeds (50 seeds x 4 replications per plot) taken randomly from the final harvest and after drying at 103 °C for 17 hours.

A functional growth analysis for dry matter accumulation was done using the MLP (Maximum Likelihood Programme) curve-fitting programme (Lawes Agricultural Trust, 1986). The simple logistic curve (Equation 1) was used to describe dry matter accumulation of the crop (Gallagher and Robson, 1984).

$$Y = C/ (1 + T \exp (-b (x - m)))^{1/T} \quad ..... (1)$$

where Y is the yield, C is the final maximum achievable above ground dry matter, x is the day number (time) and T, b and m are constants.

The weighted mean absolute growth rate (WMAGR – the mean growth rate over the period when the crop accumulated most of its dry matter), and duration of the exponential growth (DUR – duration of crop growth over which most growth occurred) were calculated using the following equations (Gallagher and Robson, 1984).

$$WMAGR = bC / 2(T + 2) \quad \ldots\ldots\ldots\ldots (2)$$

$$DUR = 2(T + 2)/b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

For the logistic curve T = 1, and therefore the above equations were rewritten as: WMAGR = bC/6, and DUR = 6/b

An analysis of variance was done for all growth parameters using the Genstat statistical package (Lawes Agricultural Trust, 1997). Means were separated using the least significance difference (LSD) test. Correlation and regression analysis was done using a Minitab package programme (Minitab Inc., 1996).

Results

Mean air temperature increased during the period of vegetative growth (emergence to flowering) in both seasons (Table 1), decreased during pod set (R1 – R5) and seed fill (R5 – R7) in the first season, but increased in the second season. Photoperiod was between 15.4 – 16.1 h during the vegetative stage depending on sowing date, and decreased as sowing was delayed during pod set and seed-fill (Table 1).

At the mid-November sowing date, mean solar radiation was greater in 2000 than 1999 during vegetative growth and pod set, but lower during seed fill (Table 1). Solar radiation during vegetative growth increased as sowing was delayed in 2000, but decreased in both years during pod set and seed fill. Rainfall was lower in 1999 during the pod set stage than in 2000, but the reverse occurred during seed fill. With the exception of the 29 December 1999 sowing, the greatest rainfall occurred during the vegetative stage in both seasons.

The duration of vegetative growth did not differ between cultivars in either season but cv. March had a longer seed fill period. The vegetative stage durations fell as sowing was delayed, but the seed fill stage duration increased as the 1999 sowings were delayed. For the mid-November sowings, the vegetative and seed fill durations were shorter in 2000 than 1999 (Table 2).

Table 1. Effect of sowing date on environmental parameters during three soybean growth stages (averaged over cultivars).

	Growth stage	Sowing date						
		1999			2000			
		15 Nov	7 Dec	19 Dec	2 Oct	17 Oct	1 Nov	16 Nov
Mean Temp (°C)	Vegetative	13.4	14.3	15.6	12.3	12.9	14.8	16.2
	Pod-set	16.1	16.0	15.4	16.6	15.9	14.7	15.3
	Seed-fill	15.0	13.7	12.7	15.1	16.0	17.3	17.1
Photoperiod (h)	Vegetative	16.1	15.9	15.5	15.4	15.7	15.9	16.1
	Pod-set	15.2	14.7	14.2	16.1	16.1	15.8	15.6
	Seed-fill	13.9	13.2	12.5	15.5	15.3	14.9	14.5
Solar radiation (MJ m^{-2} day^{-1})	Vegetative	23.1	22.0	21.5	23.0	23.5	24.6	25.4
	Pod-set	19.4	19.6	18.5	25.2	24.6	23.2	21.9
	Seed-fill	18.6	15.4	12.1	22.2	21.3	19.1	17.0
Total rainfall (mm)	Vegetative	106.8	97.7	35.7	91.8	90.0	81.6	78.4
	Pod-set	39.5	14.5	36.7	55.6	67.4	60.3	41.8
	Seed-fill	52.3	58.5	92.7	33.7	16.3	10.2	1.8

Table 2. Effect of sowing date on the observed duration of the vegetative, pod-set and seed-fill stages of two soybean cultivars in Canterbury over two seasons.

	Northern Conquest			March		
Sowing date	Vegetative	Pod-set	Seed-fill	Vegetative	Pod-set	Seed-fill
1999						
15 Nov	53	30	25	53	34	34
7 Dec	49	26	34	49	30	45
29 Dec	38	24	44	38	28	52
2000						
2 Oct	50	30	23	50	35	30
17 Oct	48	32	24	48	37	27
1 Nov	45	34	20	45	36	26
16 Nov	41	30	21	41	34	26

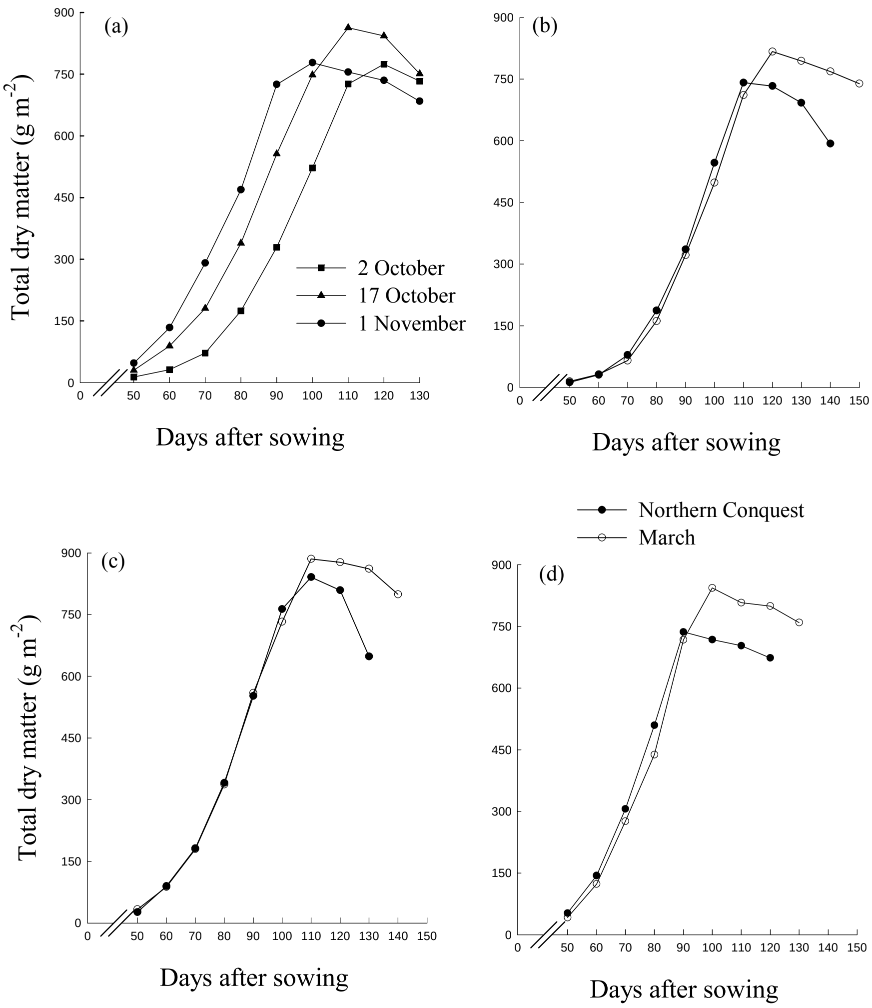

Figure 1. Seasonal total dry matter accumulation in two soybean cultivars at three sowing dates in 2000/2001 in Canterbury. (a) Average of cultivars at each sowing date; sown on (b) 2 October, (c) 17 October and (d) 1 November 2000.

Irrespective of cultivar or sowing date, total dry matter (TDM) production showed typical sigmoidal curves in both seasons (data for 2000/2001 presented in Figure 1). At the start of flowering (R1), plants had accumulated only 8 – 12% of total maximum dry matter (TDM_{max}) across all cultivars and sowing dates in both seasons. Cultivar Northern Conquest accumulated slightly more DM at R1 (about 20% more averaged over all sowing dates in both seasons) than cv. March. The TDM increased to a maximum value at around the start of rapid pod growth (R5 stage) in all the sowings in both the years for all the cultivars (data for 2000/2001 presented in Figure 1). The TDM accumulation pattern for cv. Alta and cv. Maypole was similar to that of cv. March in all the sowings in the 1999/2000 season (data not presented).

Table 3. Effect of sowing date and soybean cultivar on the maximum total dry matter production (TDM_{max}), weighted mean absolute growth rate (WMAGR) and duration of exponential growth (DUR) in Canterbury in 1999/2000 and 2000/2001.

	1999/2000				2000/2001		
	TDM_{max} ($g\ m^{-2}$)	WMAGR ($g\ m^{-2}\ day^{-1}$)	DUR (days)		TDM_{max} ($g\ m^{-2}$)	WMAGR ($g\ m^{-2}\ day^{-1}$)	DUR (days)
Sowing date				Sowing date			
15 Nov	794.7	14.8	53.9	2 Oct	921	14.3	64.8
7 Dec	622.9	12.8	48.9	17 Oct	864	14.9	58.1
29 Dec	486.6	10.8	45.4	1 Nov	836	16.1	51.7
Significance	***	***	ns	Significance	ns	ns	*
LSD	76.26	0.51	6.79	LSD	184.1	1.92	8.97
CV (%)	5.3	1.8	6.1	**CV (%)**	12.2	7.3	8.9
Cultivar				Cultivar			
Northern Conquest	623.1	12.6	49.0	Northern Conquest	854	15.2	56.5
Maypole	691.7	12.9	53.1	**March**	893	15.0	59.9
Alta	621.6	13.2	47.0	Significance	ns	ns	ns
March	602.6	12.4	48.6	LSD	64.9	0.85	3.44
Significance	*	ns	ns	CV (%)	8.0	6.1	6.4
LSD	52.20	1.18	4.39	Sign. interaction	nil	nil	nil
CV (%)	8.3	9.4	9.0				
Sign. interaction	nil	nil	nil				

In 1999/2000, TDM_{max} produced by the 15 November sown crop was 794.7 g m^{-2}, but this decreased significantly in the two later sown crops (Table 3). There was a significant cultivar effect for TDM_{max} because that for cv. Maypole was significantly higher than any other cultivar (Table 3). The duration of crop growth (DUR) was not affected by sowing date, cultivar or their interactions. The weighted mean absolute growth rate (WMAGR) was significantly affected by sowing date in that it fell as sowing was delayed, from 14.8 g m^{-2} in the 15 November sowing to only 10.8 g m^{-2} for the 29 December sowing (Table 3). This parameter did not differ for cultivars and there was no cultivar by sowing date interaction. In 2000/2001, the DUR was significantly affected only by sowing date while the effect of cultivar, and the cultivar by sowing date interaction, were not significant (Table 4). The TDM_{max}, and the WMAGR were not influenced significantly either by sowing date, cultivar or their interactions (Table 3).

Vegetative (leaf + stem) dry matter increased initially and then declined coincidently with the start of rapid pod growth (data for 2000/2001 presented in Figure 2). This pattern of change in vegetative dry matter was apparent in all the cultivars at all sowing

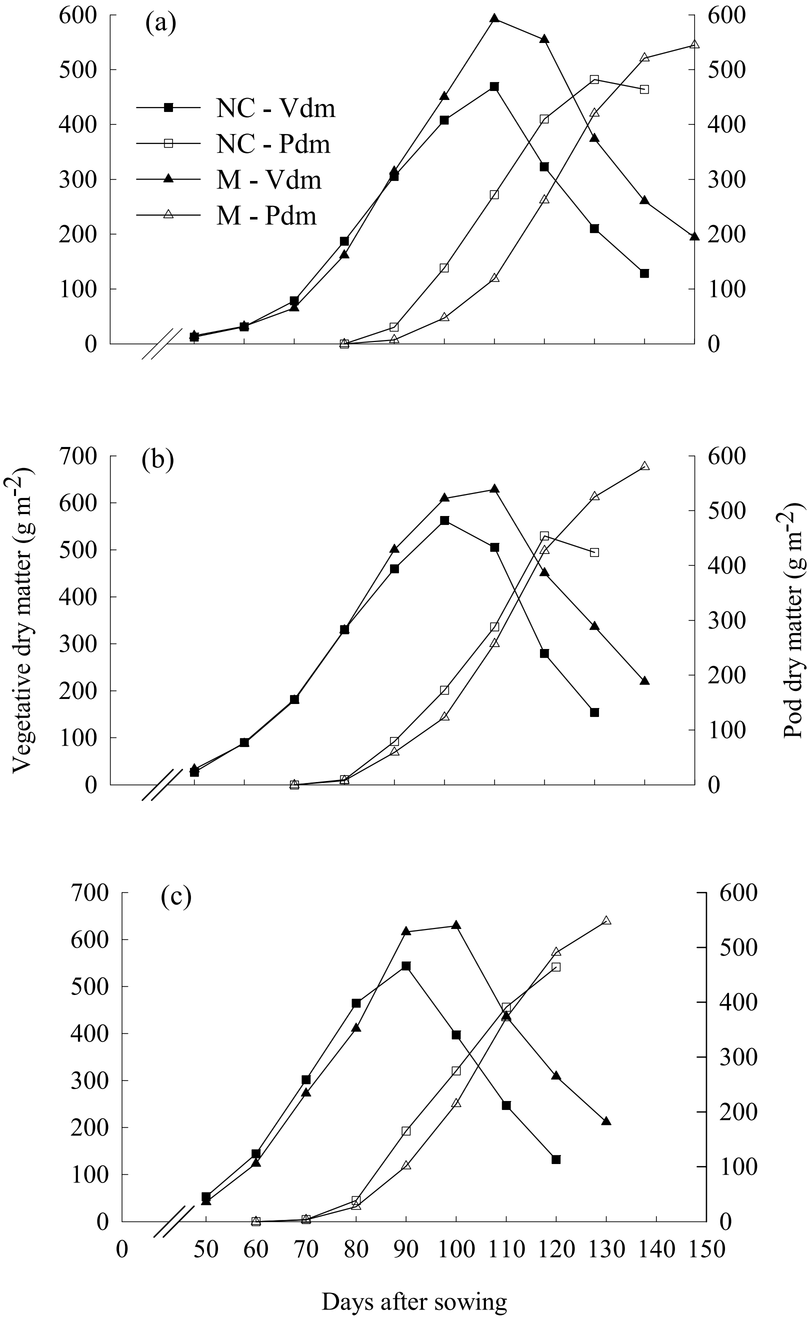

Figure 2. Vegetative (stem + leaf) dry matter (Vdm, closed symbol) and pod dry matter (Pdm, open symbol) over the growing season in two soybean cultivars grown at three sowing dates in Canterbury in 2000/2001. Sown on: (a) 2 October, (b) 17 October and (c) 1 November 2000. NC = Northern Conquest, M = March.

dates in both seasons. The vegetative dry matter weight during the pod growth stage was lower in cv. Northern Conquest than in cv. March at all sowing dates (Figure 2). Reproductive dry matter (pod dry matter) increased slowly at early pod filling stage, then linearly during the seed filling period to reach a maximum value of between 450 – 500 g m^{-2} for cv. Northern Conquest and 550 – 600 g m^{-2} for cv. March depending on sowing date. (Figure 2).

Pod harvest index (PHI) initially reased slowly and then increased linearly in all cultivars at all sowing dates (Figure 3). The

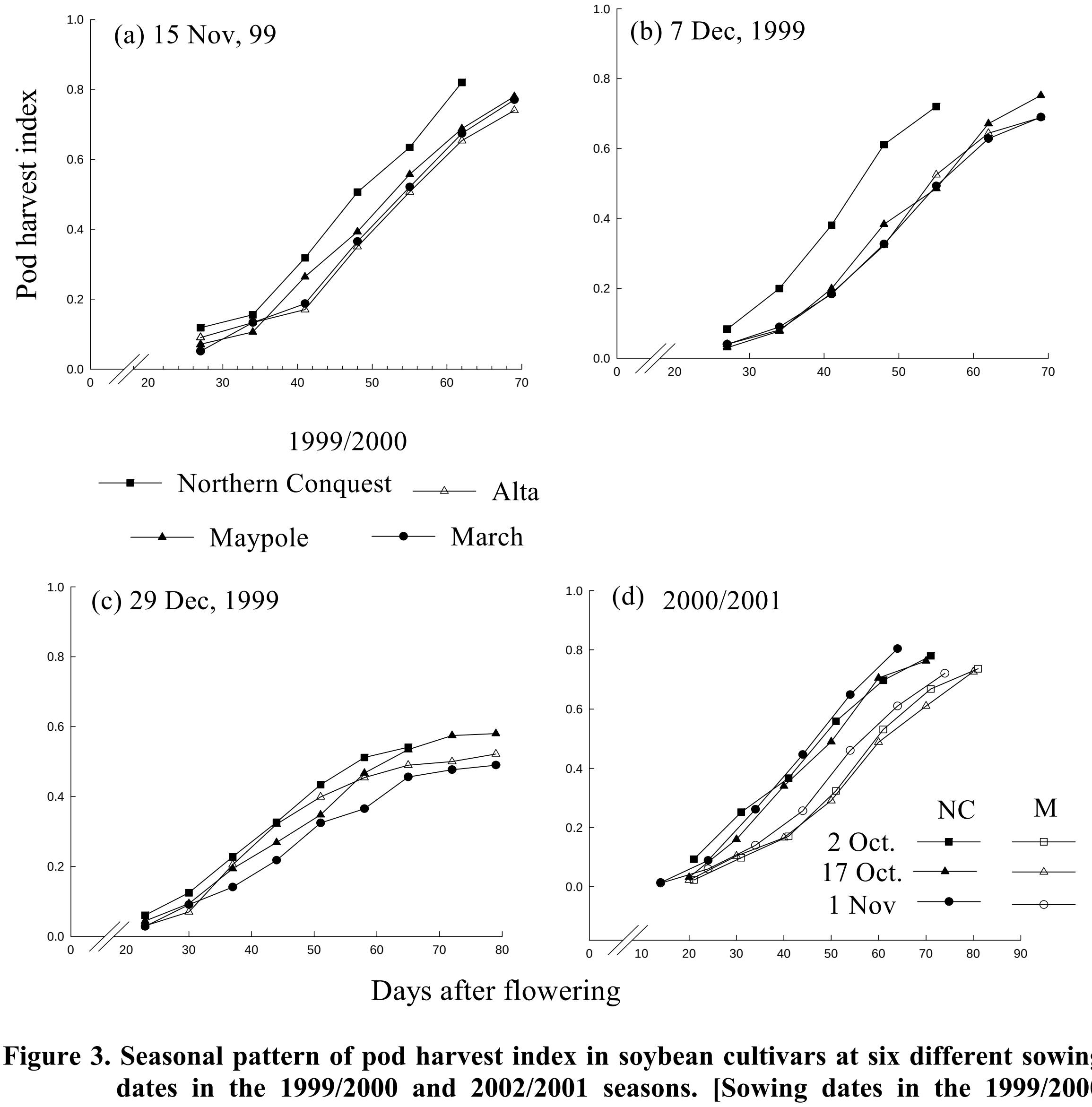

Figure 3. Seasonal pattern of pod harvest index in soybean cultivars at six different sowing dates in the 1999/2000 and 2002/2001 seasons. [Sowing dates in the 1999/2000 season are (a), (b) and (c) and in 2000/2001, (d)]. NC = Northern Conquest, M = March.

Table 4. Effect of sowing date and soybean cultivar on seed growth rate (SGR) and seed filling duration (SFD) in 1999/2000 and 2000/2001.

	1999/2000				2000/2001		
	SGR (mg seed^{-1} day^{-1})	SFD (days)	PC (day^{-1})		SGR (mg seed^{-1} day^{-1})	SFD (days)	PC (day^{-1})
Sowing date				Sowing date			
15 Nov	5.1	33.2	0.019	2 Oct	5.4	27.5	0.0136
7 Dec	3.6	40.7	0.018	17 Oct	5.6	25.9	0.0137
29 Dec	2.4	50.9	0.009	1 Nov	5.9	24.3	0.0146
Significance	**	*	***	Significance	ns	ns	*
LSD	0.86	12.79	0.0014	LSD	1.03	5.19	0.0008
CV (%)	10.3	13.6	3.8	CV (%)	11.6	12.2	3.2
Cultivar				Cultivar			
Northern Conquest	3.7	36.7	0.018	Northern Conquest	5.5	23.8	0.0153
Maypole	3.9	42.9	0.016	March	5.7	29.5	0.0127
Alta	3.8	42.9	0.015	Significance	ns	**	***
March	3.5	43.9	0.015	LSD	0.77	3.50	0.0004
Significance	ns	ns	***	CV (%)	18.0	17.1	3.0
LSD	0.60	6.68	0.0012	Sign. interaction	nil	nil	***
CV (%)	16.2	16.2	7.7				
Sign. interaction	nil	nil	nil				

Table 5. Interaction between sowing date and cultivar for partitioning coefficient of soybean in Canterbury in 2000/2001.

	Cultivar	
	Northern Conquest	March
Sowing date		
2 October	0.0143	0.0130
17 October	0.0150	0.0123
1 November	0.0166	0.0127
	LSD = 0.0007	

departure from linearity came at around physiological maturity, when PHI began to exhibit curvilineality (convex upward) approaching the final values. All cultivars accumulated about 10 – 15% of their total pod dry matter at the beginning of the rapid pod filling stage (slightly before R5) at all the sowing dates. The linear increase in PHI started earlier in cv. Northern Conquest than in the other cultivars at any given sowing date (Figure 3). The linear regression of PHI as a function of time showed an r^2 value of above 95% at all the sowing dates for the cultivars under study (data not presented). The analysis of variance of the slope of the regression line (defined as PC, partitioning coefficient) indicated that in both seasons sowing date and cultivar had a significant influence on PC. In 1999/2000, PC decreased with delay in sowing and the crop sown on 29 December 1999 had a significantly lower PC (Table 4). On the other hand, the 1 November sown crop had a significantly higher PC than the earlier sowings in 2000/2001 (Table 4). In both seasons, cv. Northern Conquest had a significantly higher PC than cv. March. The estimated PC for cv. March was statistically similar to that of cv. Maypole and cv. Alta (Table 4). The significant cultivar by sowing date interaction in 2000/2001 was because the PC of cv. Northern Conquest increased with delays in sowing while that for cv. March was the highest for the 2 October sowing (Table 5). However, at all the sowings in 2000/2001 cv. Northern Conquest had a significantly higher PC than cv. March (Table 5).

Seed growth rate (SGR) and seed filling duration (SFD) were significantly affected by sowing date in 1999/2000 (Table 5). The SGR for the 15 November sowing was 5.1 mg seed^{-1} day^{-1} but this was reduced by 29% and 53% for the 7 and 29 December sowings, respectively. The seed filling duration (SFD) required for the 7 and 29 December sowings was about 8 and 18 days longer respectively than for the 15 November sowing (Tables 2 and 4). SGR and SFD were not affected by cultivar, and there was no cultivar by sowing date interaction.

In 2000/2001, SGR and SFD did not change with sowing date, and there was no sowing date by cultivar interaction. Although SGR was not affected by cultivar, SFD differed significantly between the two cultivars in that the SFD required for cv. Northern Conquest was about 24 days while that for cv. March was about 30 days (Table 4).

Seed yields fell from 277 g m^{-2} for the 15 November sowing to 76 g m^{-2} for the 29 December sowing in 1999, but did not differ (mean = 248 g m^{-2}) with sowing date in the following season (Rahman *et al*., 2005a).

Table 6. Simple correlation between soybean seed growth rate (SGR) and seed filling duration (SFD) and the partitioning coefficient in 1999/2000 and 2000/2001

Parameters	1999/2000	2000/2001
SGR	0.721**	-0.045ns
SFD	-0.676**	-0.528**
df	23	35

There was a linear relationship between TDM_{max} and seed yield (r^2 = 0.73, Figure 4a). The crop growth rate (WMAGR) was also linearly related with seed yield, (r^2 = 0.86, Figure 4b) and TDM_{max} (r^2 = 0.71, Figure 4c). The relationship between TDM_{max} and duration of exponential growth (DUR) was not as strong (r^2 = 0.56, Figure 4d). The relationship between seed yield and seed growth rate (SGR) was also positive and linear (r^2 = 0.81, Figure 5a). In contrast, SFD was negatively associated with seed yield (r^2 = 0.67, Figure 5b). There was a very strong positive relationship between crop growth rate (WMAGR) and seed growth rate (r^2 = 0.91, Figure 5c). There was no relationship between seed yield and PC, (Figure 5d). Seed growth rate showed a significant positive association with PC in 1999/2000 (r = 0.72**) but this was negative and non significant in 2000/2001. In contrast, seed filling duration showed a significant negative correlation with PC in both seasons (Table 6).

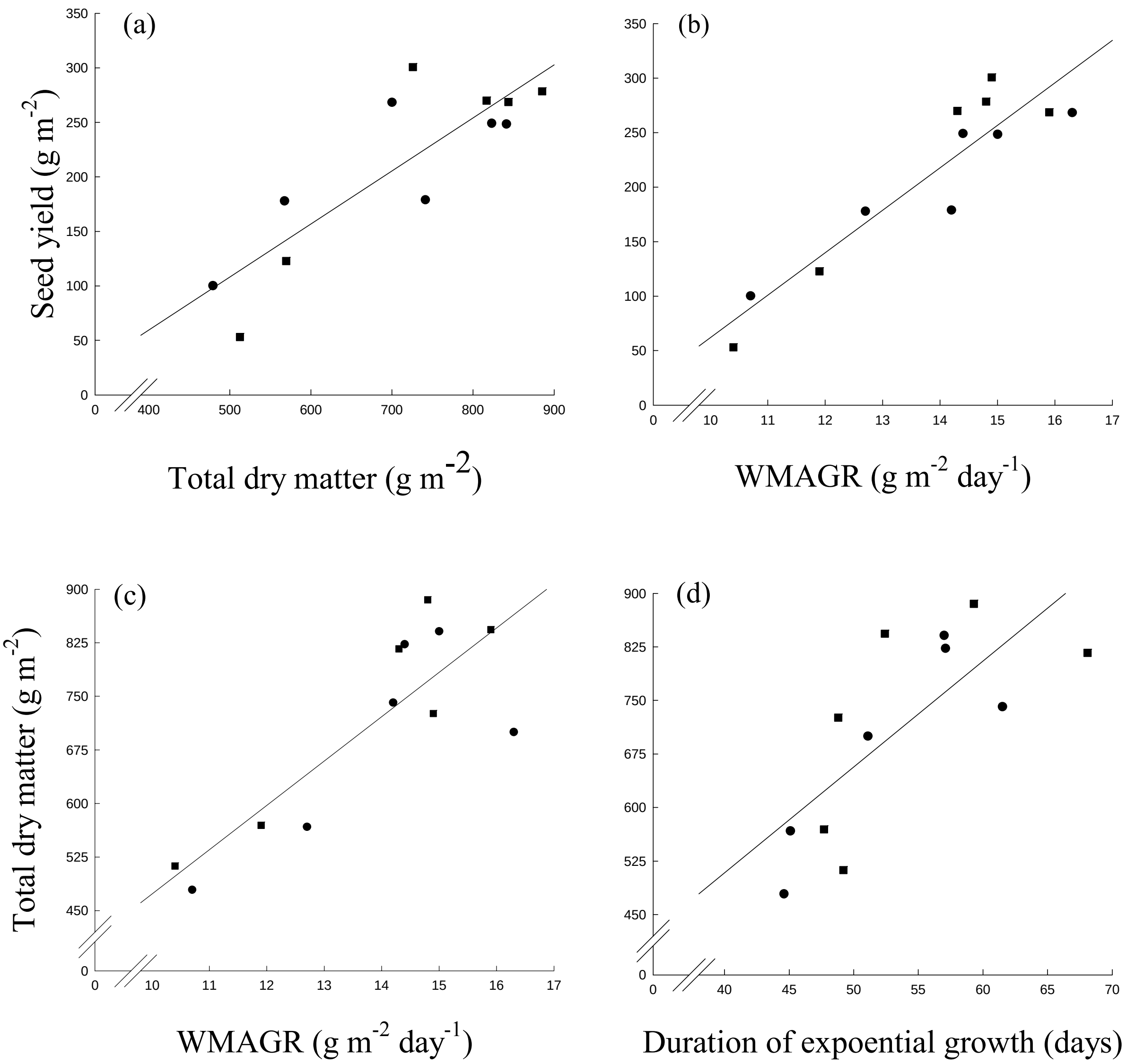

Figure 4. Relationships among the total dry matter (TDM), weighted mean crop growth rate (WMAGR), crop growth duration (DUR) and seed yield of soybean grown at six sowing dates for two cultivars : Northern Conquest (●) and March (■).
(a) TDM vs SY, Y = -135 + 0.49X, r^2 = 0.73
(b) WMAGR vs SY, Y = -327 + 38.9X, r^2 = 0.86
(c) WMAGR vs TDM; Y = -148 + 62.1X, r^2 = 0.71
(d) DUR vs TDM, Y = -85 + 14.8X, r^2 = 0.56

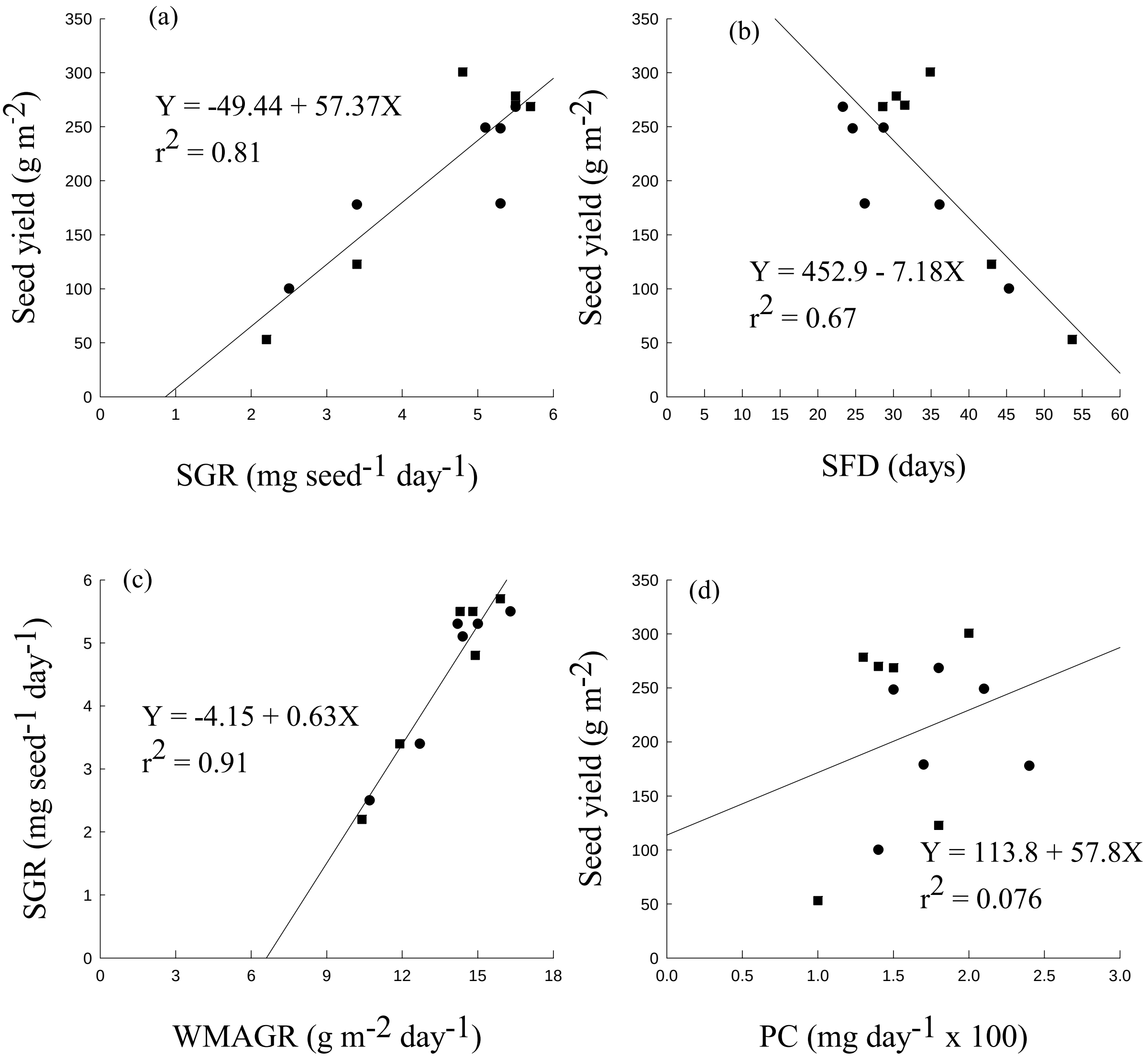

Figure 5. Relationship between seed yield and (a) seed growth rate (SGR), (b) seed filling duration (SFD), (d) partition coefficient (PC), and (c) between seed growth rate and crop growth rate (WMAGR) for two cultivars, Northern Conquest (●) and March (■) at six sowing dates.

Discussion

The TDM_{max} which occurred at around the R5 (start of seed-fill) stage was closely related to seed yield (r^2 = 0.73). This result supports the conclusion that TDM at R5 is important in determining soybean seed yield (Duncan, 1986; Egli *et al*., 1987; Board *et al*., 1992), and substantiates the need for the production of high TDM by the R5 stage for high seed yield in soybean (Rahman *et al*., 2004). The TDM_{max} obtained in the present study for the October and November sowings was consistent with those reported elsewhere for indeterminate soybeans (Parvez *et al*., 1989; Sovoy *et al*., 1992).

There was also a close relationship between TDM_{max} and crop growth rate in the present study (r^2 = 0.71), and hence growth rate was also strongly related to seed yield (r^2 = 0.86). The present result confirms that total dry matter accumulated is largely determined by crop growth rate and duration (Board *et al*., 1992), particularly in the period between R1 (start of flowering) and R5 (pod set). This in turn is determined by both photoperiod and temperature (Egli, 1998; Rahman *et al*., 2005b).

There was a highly significant linear relationship between crop growth rate and seed growth rate (r^2 = 0.91). This relationship was very high for both cultivars as indicated by the r^2 values of 0.89 and 0.92, respectively for cv. Northern Conquest and March. This result is also in agreement with Egli (1993) who reported that individual soybean seed growth rate was linearly related to crop growth rate during the period from R1 to R5. Several workers have found a linear increase in number of seeds m^{-2} with increasing soybean crop growth rate (Egli and Zhen-Wen, 1991; Egli, 1993).

The partitioning coefficient (PC) decreased significantly in 1999/2000 for the December sowings probably because of reduced assimilate availability for pod filling either from canopy photosynthesis or remobilisation of stored carbohydrates associated with lower temperatures. In 2000/2001, PC was significantly higher for the 1 November sown crop, which was probably because of rapid leaf senescence caused by increasing temperature and evapotranspiration as well as a shortening of the seed filling period.

The PC was significantly higher in cv. Northern Conquest than cv. March in both seasons. Cv. Northern Conquest exhibited earlier leaf senescence and a shorter seed filling period than cv. March which has “stay green” characteristics (Rahman, 2002) during seed filling and a longer seed-filling duration (Rahman *et al*., 2005b).

There was a significant negative correlation between the duration of seed filling and PC indicating that when PC was higher, the daily supply of assimilates through current photosynthesis was not sufficient to maintain the seed growth rate. As a consequence, more assimilates were needed to be remobilized from vegetative to reproductive organs to meet those SGR demands. This may deplete vegetative dry matter and possibly photosynthetic apparatus, thus shortening the seed-filling duration (Salado-Navarro *et al*., 1986). During seed fill, current photosynthesis (rather than remobilization of stored carbohydrates) is considered to be the main source of assimilate for seed growth (Salado-Navarro *et al*., 1986). However, soybean seed yield under most field conditions is thought to be source restricted during the late reproductive stage (Shibles *et al*., 1987; Egli and Crafts-Brander, 1996) because of a decline in canopy photosynthetic activity due to leaf senescence. Therefore, PC explains the intensity of senescence in the soybean plant during seed growth and appears to be a major limiting factor for the duration of seed-filling.

The relationship between seed yield and seed growth rate was very strong and positive while that with the seed filling duration was poor and negative. The negative association between seed filling duration and seed yield in the present study might be due to the effects of temperature (in 1999/2000) and solar radiation (in both seasons) during the seed-fill period. The crops sown on 7 and 29 December 1999 in particular experienced low temperatures and solar radiation during the seed-fill period (R5–R7) and photosynthesis was therefore decreased. As a result, seed growth rate decreased and the seed filling duration increased in an attempt to attain a certain seed size. When the December 1999 sowings were excluded from the regression analysis, the relationship between seed filling duration and seed yield became positive, but was not significant (r^2 = 0.29), a result also reported by others (Dunphy *et al.*, 1979; Egli *et al.*, 1984; Salado-Navarro *et al.*,1986).

Seed growth rate explained about 81% of the seed yield variation recorded. Salado-Navarro *et al*. (1986) also found a very close relationship between seed growth rate and seed yield. Egli *et al*. (1978) reported that SGR is mainly under genetic control, and is associated with variation in the number of cells in the cotyledons (Egli *et al.*, 1981). This is fixed before the start of the seed-filling period (Munier-Jolain and Ney, 1998) and is dependent on assimilate availability during cell division (Egli *et al.*, 1989). The present study showed that seed growth rate was related to crop growth rate, indicating that the factors that influence soybean crop growth rate also regulate seed growth rate.

Conclusions

1. Irrespective of sowing date or cultivar, soybean plants produced their maximum dry matter at R5, the start of the seed filling stage of crop development.
2. Total dry matter at R5 was closely related to seed yield.
3. Seed yields were reduced for December sowings because while higher temperature accelerated vegetative development, a lower growth rate resulted in reduced total dry matter at R5. Crop growth rate was strongly related to seed yield.
4. Sowings in October or November at this site did not differ in seed yield because there were no differences in dry matter accumulated by R5, crop growth rate, seed growth rate or seed fill duration.

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References

Board, J. E., Kamal, M. and Harville, B. G. 1992. Temporal importance of greater light interception to increase yield in narrow-row soybean. *Agronomy Journal* **84**: 575-579.

Chanprasert, W. 1988. The effects of plant competition on vegetative and reproductive growth in soybean (*Glycine max* (L.) Merrill) with particular reference to reproductive abortion. Unpublished PhD Thesis, Massey University, Palmerston North, New Zealand.

Danyard, T. B., Tanner, J. W. and Duncan, W. G. 1971. Duration of the grain filling period and its relation to grain yield in corn. *Crop Science* **11**: 45-48.

Dapaah, H. K. 1997. Environmental influences on the growth, development and yield of pinto beans (*Phaseolus vulgaris* L.). Unpublished PhD Thesis, Lincoln University, Canterbury, New Zealand.

Dougherty, C. T. 1969. The influence of planting date, row spacing and herbicides on the yield of soybeans in Canterbury. *New Zealand Journal of Agricultural Research* **12**: 703-726.

Duncan, W. G. 1986. Planting patterns and soybean yield. *Crop Science* **26**: 584-588.

Egli, D. B. 1994. Mechanisms responsible for soybean yield response to equidistant planting patterns. *Agronomy Journal* **86**: 1046-1049.

Egli, D. B. 1998. Seed Biology and the Yield of Grain Crops. CAB International, New York.

Egli, B. D. and Crafts-Brander, S. J. 1996. Soybean. *In* Photoassimilate Distribution in Plants and Crops: Source Sink Relationship (eds. E. Zamaski and A. A. Schaffer), pp. 595-623, Marcel Dekker, Inc., New York.

Egli, D. B., Fraser, J., Leggett, J. E. and Poneleit, C. G. 1981. Control of seed growth in soybeans (*Glycine max* L. Merrill*). Annals of Botany* **48**: 171-176.

Egli, D. B., Guffy, R. D. and Heitholt, J. J. 1987. Factors associated with reduced yields of delayed plantings of soybean. *Journal of Agronomy and Crop Science(Berlin)* **159**: 176-185.

Egli, D. B., Leggett, J. E. and Wood, J. M. 1978. Influence of soybean seed size and position on the rate and duration of filling. *Agronomy Journal* **70**: 127-130.

Egli, D. B., Ramseur, E. L., Zhen-Wen, Y. and Sullivan, C. H. 1989. Source-sink affects the number of cells in soybean cotyledons. *Crop Science* **29**: 732-735.

Fehr, W. R. and Caviness, C. E. 1977. Stages of soybean development. *Iowa Cooperative Extension Services Special Report 80*.

Gallagher, J. N. and Robson, A. B. 1984. Fitting growth sigmoidal curves using MLP-an interim guide, Lincoln College, Canterbury, New Zealand, 9p.

Hewitt, A. E. 1992. New Zealand soil classification. *DSIR Land Resources Scientific Report, No* 19, Lower Hutt, New Zealand.

Hill, G. D., Briones, V. P. and Porter, N. G. 1978. Effect of time of sowing and row spacing on yield and seed composition of *Glycine max* cv. Fiskeby V and *Lupinus angustifolius* cv. Unicrop. *Proceedings of the Agronomy Society of New Zealand* **8**: 37-42.

Hill, G. D., Horn, P. E. and Porter, N. G. 1977. A comparison of seed and nutrient yield of spring sown grain legumes. *Proceedings of the Agronomy Society of New Zealand* **7**: 65-68.

Lawes Agricultural Trust. 1986. Maximum Likelihood Programme. Rothamsted Experimental Station, Rothamsted.

Lawes Agricultural Trust. 1997. Genstat 5, Release 4.1 (PC/ Windows NT). Rothamsted Experimental Station, Rothamsted.

Minitab Inc. 1996. Minitab Release 11.12 for Windows. Minitab Inc.

Monteith. 1977. Climate and efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society, London,* Series B 281, 277-294.

Munier-Jolain, N. G. and Ney, B. 1998. Seed growth rate in grain legumes II. Seed growth rate depends on cotyledon cell number. *Journal of Experimental Botany* **49**: 1971-1976.

Munier-Jolain, N. G., Munier-Jolain, N. M., Ney, B., Roche, R. and Duthion, C. 1998. Seed growth rate in grain legumes. I. Effect of photoassimilate availability on seed growth rate. *Journal of Experimental Botany* **49**: 1963-1969.

Parvez, A.Q., Gardner, F.P. and Boote, K. J. 1989. Determinate and indeterminate type of soybean cultivar responses to pattern, density, and planting date. *Crop Science* **29**: 150-157.

Rahman, M. M. 2002. Effects of the field production environment on soybean seed yield and quality. Unpublished PhD thesis, Lincoln University, Canterbury, New Zealand.

Rahman, M. M., Hampton, J. G., and Hill, M. J. 2005a. The effect of time of sowing on soybean seed yield in a cool temperate environment. *Journal of New Seeds* **7**: (in press).

Rahman, M. M., Hampton, J. G., and Hill, M. J. 2005b. Soybean development under the cool temperate environment of Canterbury, New Zealand. *Journal of New Seeds* (submitted).

Rahman, M. M., Mwakangwale, M. G., Hampton, J. G., and Hill, M. J. 2004. The effect of plant density on seed yield of two cool tolerant soybean cultivars in Canterbury. *Agronomy New Zealand* **34**: 149-159.

Salado-Navarro, L. R., Sinclair, T. R. and Hinson, K. (1986). Yield and reproductive growth of simulated and field grown soybean. II. Dry matter allocation and seed growth rates. *Crop Science* **26**: 971-975.

Savoy, B. R., Cothren, J. T. and Shumway, C. R. (1992). Soybean biomass accumulation and leaf area index in early-season production environments. *Agronomy Journal* **84**: 956-959.

Shibles, R., Secor, J. and Ford, D. M. (1987). Carbon assimilation and metabolism. *In* Soybeans: Improvement, Production and Uses (ed. J. R. Wilcox), pp. 535-588, Agronomy Monograph No. 16 (2nd edition), ASA, CSSA and SSSA, Madison, Wisconsin:

Wells, R., Schulze, L. I., Ashley, D. A., Boerma, H. R. and Brown, R. H. (1982). Cultivar differences in canopy apparent photosynthesis and their relationship to seed yield in soybeans. *Crop Science* **22**: 886-890.