The influence of plant population, nitrogen and irrigation on yield and yield components of linseed

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Abstract

A field trial was carried out on a Wakanui silt loam from December 2003 to April 2004 at Lincoln University, Canterbury to determine the influence of irrigation level (nil and full), nitrogen (N) (0 and 150 kg/ha N) and a range of plant populations (238, 389, 583 and 769 plants/m^2) on yield and yield components of linseed (*Linum usitatissimum* (L.) Griesb.). The design was a split plot with irrigation as main plots and factorial combinations of N and plant population as sub-plots.

Linseed seed, straw and total dry matter (TDM) yield responded well to irrigation. Total dry matter production increased with irrigation from 509 g/m^2 to 763 g/m^2. The main effects of plant population on seed and straw yield were also significant. However, N and plant density did not influence TDM production.

The fibre yield/plant in irrigated plots was three times more than in rainfed plants. Without irrigation, fibre yield/plant did not respond to N. In irrigated plots, plants given 150 kg N/ha produced nearly twice as much fibre (0.8 g/plant) than plants which received no N (0.5 g/plant). Plant population influenced production of primary branches more in irrigated plants than in unirrigated plants. Seed yield components except for the thousand seed weight (TSW), responded favourably to irrigation. Addition of N had no effect on yield components except for seed yield/plant. Increasing the plant population reduced capsule production/plant. Under dryland conditions plant population had little effect on capsule number/plant and seed yield. However, there was a large effect in plants from irrigated plots.

Additional keywords: *Linum usitatissimum*, flax, irrigation, nitrogen, plant population.

Introduction

Linseed (*Linum usitatissimum* (L.) Griesb.). also known as flaxseed, is one of the most versatile and useful crops and has been grown for thousands of years (Genser and Morris, 2003). Linseed yields seed which is a rich source of both non-edible and edible oil. The industrial oil is an important ingredient in the manufacture of paints, varnishes and linoleum (Matheson, 1976) while edible linseed oil is used for human consumption and contains α-linolenic acid (ALA), a polyunsaturated fatty acid that is known to have nutritional and health benefits (Wood, 1997; Morris, 2005). Aside from ALA, linseed is becoming increasingly popular as a nutritional and functional food in the Western world due to its high content of health promoting substances such as ω 3 fatty acid, soluble and insoluble fibre and lignans (Morris, 2005).

In most countries, linseed is only cultivated for its seed which is processed into oil and a high protein stock feed after oil extraction (Martin *et al.*, 1976; Sankari, 2000; Flax Focus, 2004) with the linseed straw generated as a by-product (Sankari, 2000). The large amount of straw residue from the linseed industry (Sankari, 2000) causes an environmental problem for its disposal in major linseed producing countries (Akin, 2000). Linseed straw contains bast fibres which can be used for the production of paper, coarse textiles, rope, fibre board, moulded panels and as insulation material (Matheson, 1976; Wood, 1997; Flax Focus, 2004). Despite the potential uses of linseed fibre especially for composites and biobased industries (Akin *et al*., 2003) linseed fibre production is still economically marginal (Rennebaum *et al*., 2002). This may be due to the wide use of conventional linseed cultivars which produce a high seed and oil yield but low stem and fibre yields (Rennebaum *et al*., 2002). However, recently there has been increased interest in breeding and growing dual purpose linseed cultivars (Foster *et al*., 1997; Easson and Molloy, 2001) which can be harvested for both seed and fibre.

A significant number of studies have been published on linseed husbandry in other countries but there is limited information on linseed production in Canterbury, especially on the performance of dual purpose cultivars. In particular, information is not available on the response of linseed to such management strategies as irrigation, nitrogen (N) fertilisation and manipulation of the plant population to optimise seed and fibre yield.

Wood (1997) reported that linseed has a shallow root system thus needs sufficient moisture during the growing season. Linseed responds well to irrigation (Lisson and Mendham, 2000; Hassan and Leitch, 2001a) especially in areas with poor rainfall distribution (Lisson and Mendham, 2000). Couture *et al.* (2002) further noted that water stress limited growth by hastening physiological maturity. Several reports claimed that the plant was susceptible to drought at flowering (Foster *et al.,* 1998) and during early seed development (Martin *et al.,* 1976; Green *et al.,* 1994; Growing Flax, 2004).

Reported responses of linseed to N are diverse and conflicting. Several reports indicated a favourable response to N (Dybing, 1964; Hocking *et al*., 1987; Hocking and Pinkerton, 1991; Hocking, 1995) especially when soil N was low (Marchenkov *et al.,* 2003). At other times N had no effect on seed yield or oil content (Woodhead, 1976) or there was a poor response to N (McGregor, 1960; Hocking *et al.,* 1997; Rossini and Casa, 2003). Matheson (1976) suggested that variable responses to N could be due to other factors such as the initial soil N level, soil moisture or the season.

Recommended optimum seeding rates for the crop vary depending on environmental and management factors (Hocking and Pinkerton, 1991). For seed production a population of about 400 plants/m^2 was proposed to promote branching and capsule/seed production while maximising straw yield and reducing lodging losses (Turner, 1991; Easson and Long, 2001). Information on the optimum plant population in Canterbury is inadequate. Thus, there is a need to establish the optimum plant population which will maximise returns.

Linseed used to be grown on a commercial scale as an oil crop in New Zealand, mainly in mid Canterbury (Woodhead, 1976). However, the popularity of the crop declined due to limited markets and low profitability (Keating, 1975). Relegated to a minor status, little attention has been given to the crop especially in the areas of research and development. Considering the benefits and increased popularity of linseed, especially in the Western world, this study was conducted to assess linseed's performance in the absence of new information on its agronomy under Canterbury conditions.

Specifically, the objectives of the study were:

1. To determine the influence of irrigation, N and plant density on seed and fibre yield.
2. To investigate yield responses of linseed to a range of plant populations and their interaction with irrigation and N.

Materials and Methods

A linseed (cv. *Hinu*) field trial was carried out on a Wakanui silt loam from 10 December 2003 to 12 April 2004 at the Horticultural Research Area, Lincoln University (43^o 39' S, 172^o 28' E, 11 m above sea level), Canterbury. The experimental design was a split plot with irrigation as main plots and factorial combinations of N and plant density as sub-plots. Plots were 10 m long by 2.5 m wide. The land was harrowed, ploughed and rolled prior to sowing.

Plots were sown with an Öyjord cone seeder in rows 15 cm apart. The seeding rates were 540, 1,080, 1,620 and 2,160 seeds/m^2 to achieve target plant populations of 250, 500, 750 and 1000 plants/m^2. After sowing all plots were given a pre-emergence irrigation. For irrigated plots, overhead irrigation was applied when the soil moisture deficit was approximately at/or below 50 % of field capacity. Measurements were made with a Time Domain Reflectometer (TDR) to a depth of 200 mm to determine crop water use. Nitrogen fertiliser was applied as urea, at 150 kg/ha, two weeks after emergence. Weeds were controlled by hand as required. Mesurol, which contains 750g/kg methiocarb, was sprayed at 1 kg/ha and a bird scarer was used to keep away birds.

Plant height was determined by measuring five randomly selected plants from each plot. Plants were measured from ground level to the uppermost capsule before final harvest. Harvests were carried out every 2 weeks using a randomly placed 0.2 m^2 quadrat for plant biomass and stand density assessment. The number of plants was counted in each treatment to determine plant population and their dry weight was measured after drying the samples in a forced draught oven at 70 ^{o}C for 72 h. Final plant density was determined one day before final harvest by hand pulling and counting plants in a 0.2 m^2 quadrat. Plant height was determined by measuring five randomly selected plants from each plot. Plants were measured from ground level to the uppermost capsule before final harvest.

The final harvest for seed yield was taken when more than 50 % of the capsules had turned brown and seed rattled in the capsules when they were shaken (Matheson, 1976). Final harvest for biomass and seed yield was by hand pulling plants from a 1 m^2 quadrat. After harvest, plants were air dried for about 15 – 30 days. Seeds were threshed manually. The seeds were then cleaned and weighed for yield determination. Seed and stem dry weights were measured after drying seed in an oven at 70 ^{o}C for 72 h.

The number of capsules/plant was estimated from counts on five sample plants/plot. Capsules were removed by hand, seed was manually extracted and cleaned and the total weight and number of seeds/sample plant recorded. Similarly, the number of primary branches on each sample plant was counted and the stem diameter measured using a precision calliper at 3 cm from the base of the plant. Main stem length was measured from ground level to just below the first apical branch. After removal of the capsules and leaves stems were air-dried and weighed. Stems were retted by soaking them in water for four weeks. Fibres were manually extracted from each sample, dried at room temperature and their weights were determined.

All data were subjected to analysis of variance (ANOVA) using GENSTAT to identify main effects and interactions in response to irrigation, N and plant density. Differences among means were determined using LSD at the 5 % level of significance.

Results

Climatic condition

Rainfall over the growing season was only 68 % of the long tem mean (LTM) (Table 1). The first month of the growing season was one of the driest on record in Canterbury and rainfall was only 2 % of normal. Evapotranspiration was 17 % higher than the LTM. The second month was also dry with Canterbury receiving only 40 % of normal rainfall. April was wet with 24 % more rain than normal and 53 % less evapotranspiration than the LTM for the month. The mean temperature during the growing season was 0.5 ^{o}C lower than the LTM of 15 ^{o}C.

Table 1. Climatic conditions at Lincoln from December 2003 - April 2004.

	Rain (mm)		Air Temp °C						Penman (mm)	
Month	LTM*	total	LTM	max	LTM	min	LTM	mean	LTM	total
2003 Dec	50.0	1.2	20.9	21.8	10.2	10.0	15.4	15.8	143.7	172.9
2004 Jan	51.3	21.0	21.9	23.6	11.4	12.8	16.5	17.9	148.0	153.7
2004 Feb	40.6	43.6	21.8	20.2	11.3	11.0	16.3	15.2	117.4	115.7
2004 Mar	50.4	36.8	20.1	20.0	9.7	8.9	14.7	14.0	99.9	99.6
2004 Apr	46.0	60.4	17.3	16.2	6.9	4.2	12.0	9.7	62.9	29.3
Total/Mean	238.3	163.0	20.4	20.4	9.9	9.4	15.0	14.5	571.9	571.2

* Long Term Mean

Table 2. The effect of irrigation, nitrogen and plant density on linseed population and biomass at final harvest (125 days after sowing).

Treatment		Population[1*] plt/m²	Dry Matter (g/m²) Seed	Straw	Other[2*]	TDM
Irrigation (I)						
	nil	478	132	220	154	506
	full	492	242	321	197	760
S.E.		14.1	12.4	5.1	9.6	21.4
Significance		ns	**	**	*	**
Nitrogen (N) (kg/ha)						
	0	498	182	266	177	625
	150	471	192	275	174	640
S.E.		10.6	6	10.7	6.8	16.8
Significance		ns	ns	ns	ns	ns
Density (plants/ m²)						
	540	238	183	310	163	655
	1080	379	200	279	183	662
	1620	583	198	241	177	616
	2160	769	166	252	180	598
S.E.		14.9	8.5	15.1	9.6	23.8
Significance		**	*	*	ns	ns
CV (%)		6.1	17.9	14.2	8.8	11.1
Significant interactions		nil	nil	nil	nil	nil

1* Only flowering/fruiting plants were counted
2* Others include leaves, capsule fractions
* ** *** significant at P < 0.05; 0.01; 0.001 respectively

Table 3. The effect of irrigation, nitrogen and plant population on linseed plant height and stem characters (125 days after sowing).

Treatment		Plt height (cm)	Stem Length (cm)	Stem wt/plt (g)	Fibre wt/plt (g)	Branches /plant	Stem Diameter (cm)
Irrigation							
	nil	40.3	29.3	1.5	0.3	1.2	0.15
	full	58.9	40.9	4.2	1.0	2.5	0.22
S.E.		0.48	0.33	0.16	0.04	0.13	0.026
Significance		**	**	**	**	**	**
Nitrogen (N) – kg/ha							
	0	47.6	33.9	2.6	0.5	1.8	0.18
	150	51.6	36.3	3.5	0.8	1.8	0.19
S.E.		0.71	0.59	0.27	0.06	0.14	0.06
Significance		**	**	*	**	ns	ns
Density (plants/ m^2)							
	238	52.3	34.5	3.4	0.6	2.4	2.0
	379	49.7	35.7	3.1	0.6	2.0	0.2
	583	48.9	36.0	2.8	0.7	1.8	0.18
	769	47.5	34.2	2.8	0.6	1.1	0.19
S.E.		1.01	0.83	0.38	0.09	0.19	0.09
Significance		*	ns	ns	ns	**	ns
CV (%)		6.9	6.6	7.3	9.4	18.2	5.5
Significant interactions							
I x N		Ns	ns	ns	**	ns	ns
S.E.		0.86	0.68	0.31	0.07	0.2	0.07
I x D		Ns	ns	ns	ns	*	ns
S.E.		1.32	1.02	0.49	0.12	0.28	0.011
CV (%)		1.9	1.9	10.3	11.3	14.7	2.7

Establishment and early growth

The final plant population was lower than the target population densities in all treatments (Table 2). Germination tests gave 90-95 % germination but seed establishment was slow especially under rainfed conditions. Seedling emergence was poor and ranged from 34 to 44 %.

Dry matter yield

There was a highly significant effect of irrigation on seed, straw and TDM yield (Table 2). Total dry matter increased with irrigation from 509 g/m^2 to 763 g/m^2. Plant population affected both straw and seed yield.. Higher yields were obtained from low population plots. At the lowest seed density, seed yield was 183 g/m^2. It reached a plateau at 349 and 583 plants/m^2 and then decreased at the highest density. There was a negative relationship between straw yield, and increased density.

Both the lowest straw (252 g/m^2) and seed (166 g/m^2) yields were obtained at the highest density of 769 plants/m^2. Nitrogen and plant population had no significant effect on TDM.

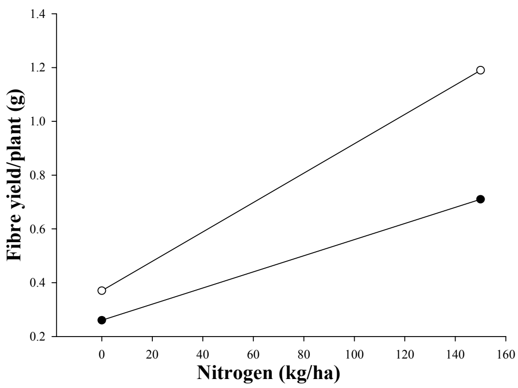

Figure 1. The interaction of irrigation (● nil; ○ full) and nitrogen on linseed fibre weight/plant (g).

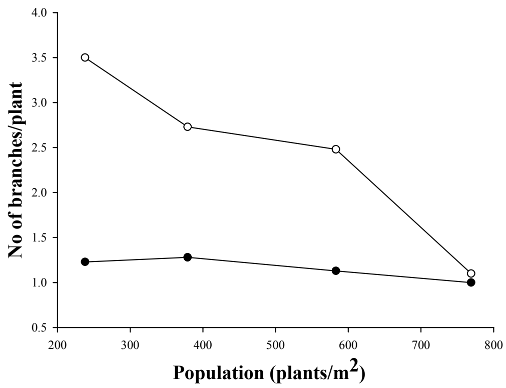

Figure 2. The interaction of irrigation (● nil; ○ full) and plant population on number of basal branches in linseed.

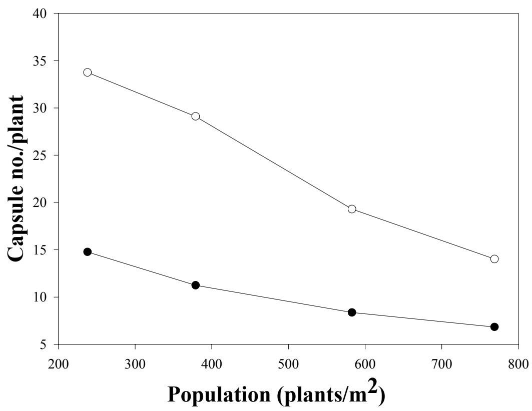

Figure 3. The interaction of irrigation (● nil; ○ full) and plant population on capsules/plant.

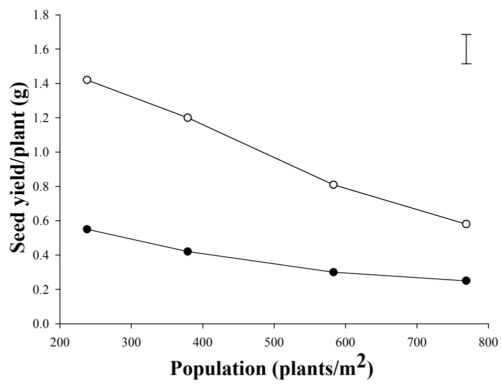

Figure 4. The interaction of irrigation (● nil; ○ full) and plant population on linseed seed yield/plant. Error bar indicate LSD at P < 0.05.

Stem Characteristics

There were highly significant responses, of all measured stem characters in response to irrigation (Table 3). Irrigated plants were 46 % taller (58.9 cm), had twice as many branches (2.5), had a 47 % greater diameter (0.22 cm) and produced more than double the fibre (1 g/plant) than unirrigated plants. Nitrogen also enhanced stem growth giving taller plants with longer and heavier stems and higher fibre production. The N treated plants were 8 % taller, with the main stem 7 % longer and gave 35 % more seed and stem (Table 3). However, there was no response to nitrogen in branches/plant and stem diameter to N. Increased plant density had a negative effect on plant height. The tallest plants were from the lowest density plots. Branching was inhibited in both rainfed and in high density plots.

Significant interactions showed that without irrigation, fibre weight/plant did not respond to nitrogen (Figure 1). However, in irrigated plots, N fertilised plants produced nearly twice as much fibre as unfertilised plants. The combination of irrigation and N yielded the most fibre (1.19 g/plant) while rainfed plants that received no N produced the least fibre/plant (0.26 g).

Increased plant population affected basal branch production on irrigated plants but had little effect on rainfed plants (Figure 2). Basal branch production was increased with irrigation at the lower plant densities. However, at 769 plants/m^2 branch production was inhibited. Similarly, basal branches were inhibited under rainfed conditions at all plant populations.

Table 4. The influence of irrigation, nitrogen and plant population on linseed yield components (125 days after sowing).

Treatments		Capsules/plant	Seeds/capsule	TSW (g)	Seed yield/plant (g)
Irrigation (I)					
	nil	10.3	7.1	5.1	0.4
	full	24	8.2	5.1	1.0
S.E.		0.66	0.23	0.02	0.02
Significance		**	*	ns	**
Nitrogen (N) (kg/ha)					
	0	16.1	7.6	5.1	0.6
	150	18.3	7.6	5.2	0.7
S.E.		0.89	0.05	0.05	0.03
Significance		ns	ns	ns	*
Density(plants/ m^2)					
	238	24.3	7.8	5.2	1
	379	20.2	7.6	5.1	0.8
	583	13.8	7.6	5	0.6
	769	10.4	7.4	5.2	0.4
S.E.		1.26	0.07	0.08	0.04
Significance		**	*	ns	**
CV (%)		14.3	6.5	0.07	17.5
Significant interactions					
I x D		**	ns	ns	**
S.E.		1.7	0.2	0.1	0.1
CV (%)		7.6	6.1	0.9	6.4

Seed yield and yield components

All of the components except for thousand seed weight (TSW) responded favourably to irrigation (Table 4). Irrigated plants produce more than twice the number of capsules and seed yield/plant and had 15 % (8.2) more seeds/capsule than rainfed plants. Nitrogen had no effect on yield components except for seed yield/plant. There was a negative relationship between plant population and capsule production/plant but the latter was positively correlated with yield. Increased plant population reduced per plant capsule production and hence seed yield. There was no effect of plant population on TSW and seeds/capsule.

Plant population had a major effect on the number of capsules/plant on irrigated plants but little effect on rainfed plants (Figure 3). The combination of low density (238 and 349 plants/m^2) and irrigation promoted capsule production but rainfed high density plants had depressed capsule production. At 249 plants/m^2, irrigation more than doubled capsule production when compared to rainfed plants. The lowest number of capsules per plant was in the rainfed high density of 583 and 769 plants/m^2.

The effect of plant population on seed yield/plant of unirrigated plants was minimal, compared with the large effect on irrigated plants (Figure 4). At high density irrigated plants produced the most seed at 1.4 g/plant compared with unirrigated plants, which only produced 0.25 g/plant.

Establishment and growth

The recommended population for linseed varies between 350-500 plants/m^2 (Freer, 1993; Canadian Flax Council, 1996). Seed germination is usually between 93-98 % (Freer, 1993) but field seedling emergence rates of only 50-60 % are normal (Canadian Flax Council, 1996). The final plant populations in this study were much lower than the desired target densities. This is similar to the results of Easson and Molloy (2000) and Sankari (2000). Poor emergence gave a variable plant stand. The sensitivity of linseed to water stress during establishment (Casa, 1999) made it difficult to obtain the target densities. Moreover, some seeds may have been buried too deep in the soil thus delaying emergence and giving uneven crop development and asynchronous ripening (Freer, 1993; D'Antuono and Rossini, 1995). O'Connor and de Gupta (1994), showed that seed sown at 4 cm deep took 33 % longer to emerge than seed sown at 2 cm.

Plant stand was best in irrigated, N fertilised, low density plots. Sankari (2000) reported that in linseed, fastest vegetative growth is between establishment and flowering. Sufficient water (Hassan and Leitch, 2001), more available N (Diepenbrock *et al*., 1995, Hocking, 1995); and other resources such as other nutrients and light for the growth of individual plants are available at low plant populations (Khan, 1976). This could be the reasons for the robust growth and more even plant stand observed in these plots.

Yield response to irrigation

There were significant yield responses to irrigation. This conforms with the results of other studies on linseed (Dybing, 1974; Singh *et al*., 1974; Drewitt, 1975; Foster *et al*., 1998; Lisson and Mendham, 2000; Hassan and Leitch, 2001). The TDM values obtained here are within the range of values reported in several studies ranging from 70 to 704 g/m^2 (Hocking *et al*., 1997; Rossini and Casa, 2003; Coutere *et al.,* 2004). The seed yield of 132 g/m^2 from unirrigated plants and 242 g/m^2 with irrigation are considerably higher than the yields of 109 and 162 g/m^2 by Lisson and Mendham (2000) for unirrigated and irrigated plants in south-eastern Australia. The higher seed yield from irrigated plots was attributed to higher capsule numbers and more seeds/capsule with irrigation (Lisson and Mendham, 2000) and on increased seed size (Drewitt, 1975).

The straw yields were lower than reported by Lisson and Mendham (2000), who obtained 586 g/m^2 from unirrigated plots and 771 g/m^2 under irrigation. The lower straw yield increases from irrigation may be partly accounted for by the abundant rain late in the growing season which prolonged vegetative growth and caused secondary growth (Keating 1975; Green *et al*., 1994) giving greater TDM (Hassan and Leitch, 2001) and biomass partitioning in favour of stems (D' Antuono and Rossini, 1995; Sankari, 2000) rather than seed (Diepenbrock and Porksen, 1993).

Further, the high rainfall late in the season caused secondary flowering and uneven ripening. This produced a larger number of immature, partly filled capsules in unirrigated plots, partly explaining the wide difference in seed yield and capsule production in the two treatments.

Water supply was severely restricted at the early stage of crop growth. Wood (1997) reported that linseed is shallow rooting and needs water in the 0 – 10 cm soil layer. Among a number of crops studied, Hocking *et al.* (1997), showed that linseed was the first crop to be affected by water stress due to poor root development. Gupta and Agrawal (1977) showed that most of the moisture in the 0-10 cm layer of a black clay soil sown to linseed is lost within the first 60 days after sowing under unirrigated conditions. Thus, although plants were irrigated immediately after sowing it was probably not sufficient to sustain plant growth during the following dry months.

During the crop growing season, Canterbury had only 2% of normal rainfall in the first month and 40% in the second month (Table 2). At the same time evapotranspiration was 17% higher than the long term mean in the first month of the growing season. The Canadian Flax Council (1996) reported that crop water use of linseed can be as high as 410 mm. During the seedling stage, water use will vary from 2 to 3 mm/day increasing to as high as 7 mm/day during flowering. Although there was adequate rain during the critical stages of plant growth which are from flowering to just prior to seed ripening (Canadian Flax Council, 1996; Foster *et al.,* 1998), the limited amount of moisture available during early phase plant growth had a marked effect on production later in the season and affected yield (Coutere *et al*., 2002).

Kramer (1983) suggested that yield losses caused by drought are considerably larger than those caused by any other environmental or management constraints. The amount of dry matter produced is considerably reduced through the effect of drought on photosynthesis and respiration (Hassan and Leitch, 2001). Our results show that plants subjected to water stress performed poorly in terms of biomass production and yield. Water stressed plants were much shorter, had fewer branches, a smaller stem diameter and produced less fibre. In addition, they produced fewer capsules and seeds/capsule. Seed yield/plant was one third the value of irrigated plants.

Effect of nitrogen

There was a limited response of seed, straw and TDM yield to N. This supports the results of McGregor (1960), Keating (1975), Hocking *et al.* (1997) and Rossini and Casa (2003). However, yield per plant was 7.4% more in N treated plants than in no N plants. The lack of response to N could be due to the high rates of N applied. Freer (1993) reported that the N requirement of linseed was less than for other crops. Positive yield responses to N at 20- 60 kg/ha have been reported by Dybing (1964), Singh and Singh (1978), Hocking *et al*. (1987), Hocking and Pinkerton (1991) and Hocking (1995), particularly when soil N levels were low (Marchenkov *et al.,* 2003).

The combined effects of the slight increases in seed yield components due to N, though not significant in themselves, may have contributed to increased seed yield/plant. Some reported that the dominant effect of N stress on yield was a reduction in the number of capsules/plant (Dybing, 1964; Hocking and Pinkerton, 1991; Hocking *et al.,* 1997). However, we did not have this result probably because soil N was not limiting for capsule growth. The observed non-significant effect on TSW and seeds/capsule was similar to the results of Hocking and Pinkerton, (1991) and the claim made of Khan and Bradshaw (1976) that, in linseed, these characters are moderately stable.

The main effect of N in this work was to promote plant height and produce longer and heavier stems which could partially account for the greater fibre yield from N fertilised plants

(Easson and Molloy, 2000). Irrigation increased the effect of N on fibre yield/plant giving up to a 60% increase.

Although there were no significant interactions among treatments lodging was common in plants from irrigated, high density, N fertilised plots. Koshta and Battawar (1981) reported that more than 60 kg N/ha resulted in extensive crop lodging due to rain and reduced yield. Lodging in N fertilised irrigated plots, especially at the higher seeding rates, may have accounted for the poor seed yield/unit area in this work. Yield losses due to bird damage may have also impacted on yield/unit area.

Effect of density

Seed yield/unit area was affected by plant population over the range tested. This conforms with the results of past studies on linseed (Khan, 1976; Turner, 1991; Diepenbrock and Porksen, 1993; Easson and Molloy, 2000), but contrasted with results of Albrechtsen and Dybing (1973), who found no significant yield difference in flax stands ranging from 100 to 700 plants/m^2.

Plant stand determines the effectiveness of a leaf canopy (Diepenbrock *et al.,* 1995). Better performance at low plant populations was shown to be based on a longer leaf duration, greater LAI and a higher net-assimilation-rate (Diepenbrock and Porksen, 1993; Filippo, 1995). At high plant populations, leaf senescence occurred much earlier and affected capsule formation and growth. Diepenbrock and Porksen (1993) demonstrated a greater partitioning of assimilates in favour of seeds and capsules at lower populations (200 and 400 seeds/m^2) although higher populations gave a higher TDM production. Consequently, low plant density may give a comparatively high capsule yield/unit area, which is similar to our findings.

The negative relationship between population density and straw yield was also reported by Sankari (2000) who obtained the highest stem yield at low stand densities. Lisson and Mendham (2000) indicated that a higher stem yield was obtained when the seeding rate was increased from 390 seeds/m^2 to 530 seeds/m^2. However, there was a higher incidence of lodging. In this study, lodging only occured at the highest population which may partly explain the decreased stem yield at this population (Lisson and Mendham, 2000).

On a per plant basis, seed yield at the lowest plant population was more than double the yield at the highest population. The large increase in the number of capsules/plant between the lowest and highest population plots was similar to the results of Turner (1991), who also reported a doubling of seed yield. Variation in seed yield was mostly due to differences in the number of capsules/plant. Differences in the seeds/capsule and seed weight had little influence on seed yield (Dybing, 1964; Leitch and Sahi, 1999; Lisson and Mendham, 2000). In addition, seeds/capsule and TSW of the linseed cultivar used in this study showed no response to varying plant density. Similar responses have been observed in other linseed varieties (Khan and Bradshaw, 1976; Hocking *et al*., 1983). This suggests that the responses are governed by independent genes (Khan and Bradshaw, 1976), which are the result of natural selection. The significant irrigation by population density interaction of capsules/plant supports the results of Diepenbrock and Porksen (1993) who observed that capsule growth was promoted by low plant density and an abundant moisture supply.

Linseed can compensate for low plant stands through extensive branching and increased size when sown at wider spacings (Khan and Bradshaw, 1976; Gubbels, 1978; Hassan and Leitch, 2001b). Seed yield has been shown to be linearly related to the number of fruiting branches thus branching is desired for increased seed yield per plant (Hocking, 1995). Furthermore, Diepenbrock and Iwersen (1989) showed that growth and development in linseed stems was largely influenced by the available space for individual plants.

As with the results of Hassan and Leitch (2001b), in this study, as plant density increased, plant growth was restricted, with increasingly shorter stems, smaller leaves and fewer branches and capsules. In contrast with the findings of Leitch and Sahi (1999) and Hassan and Leitch (2001b), the increased numbers of plants at higher populations did not compensate for reduced individual plant size, accounting for the non significant effect of population on DM production.

Conclusions

Linseed yield varied greatly in response to irrigation and plant population but showed little response to N. Seedling emergence was poor due to drought early in the growing season. Seed yield response to irrigation was high and was mainly due to high capsule production. Although responses to N were lacking, the combined effect of slight increases in seed yield components, though not in themselves significant, may have contributed to increased seed yield. The main effects of N were to promote stem growth, and to increase fibre yield/plant. The TSW and number of seeds/capsule showed little or no response to varying environmental conditions showing a degree of stability in these characters. The seed yields obtained are comparable to results obtained in other studies, confirming the potential of linseed as a crop in Canterbury.

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